Ship's Wave-enduarability Theory Application in Navigation

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Abstract: This paper reviews the development of ship wave-enduarability theory and summarizes its application in shipbuilding in the past half century, studies four aspects about wave-enduarability application in navigation technology: route optimization design, intelligent ship driving, non-standard heavy cargo lashing and ship motion state and short-term forecast, and tries to provide valuable reference for the development of navigation technology.

INTRODUCTION

Ship navigation performance includes: buoyancy and stability, heavy resistance, strength and rapidity, maneuverability and wave resistance on the deck, clap bottom resistance and water resistance propeller, and even ship's equipment, instrument and human adaptability. Broadly speaking, shipwave-enduarability can be understood as a guarantee of the ship safe navigation at sea, and various integrated navigation performance to maintain a complete all basic operating tasks. Ship's wave-enduarability theory provides a way and method to predict the motions of ships on the sea.

A REVIEW ON HALF A CENTURY'S DEVELOPMENT OF SHIP WAVE-ENDUARABILITY THEORY

In 1952, Dennis and Pearson [1] applied the theory of radio noise to waves, and probability statistics method and spectrum analysis were the basic tool and method for irregular waves research, and ship motion began to be read as a response to the waves. Before that, scholars mainly researched ships motion (waveform as the cosine curve) in static water and regular wave. Pearson wave model links irregular wave and regular wave. The wave rises

$$\zeta(x,t) = \int_0^\infty \cos(\omega^2 g^{-1} x - \omega t + \varepsilon) \sqrt{A^2(\omega)d\omega} \qquad (1)$$

In it, ωandε are regular wave's frequency and random phase respectively (0 ~ 2π); A (ω) is wave amplitude spectrum; g is acceleration of gravity. This model shows irregular waves can be expressed with an infinite number of random phase superposition of different frequency regular wave, and at the same time, it also shows that the transient wave rise of ocean waves obeys normal distribution, which can prove that the amplitude and wave height of ocean waves obey Rayleigh distribution. By the method of probability theory, the maximum design wave height can be calculated to meet the required safety assurance requirements, which will be the main basis of estimated ship waves force and movement.
Wave wave spectrum shows the internal structure. Different frequencies regular waves energy, according to the principle of linear system response, has the following relationship with ship motion spectrum.

$$S(\omega) = |H_1(i\omega)|^2 S_\zeta(\omega) \quad (i = \sqrt{-1}) \qquad (2)$$

In it, S_ζ（ω）is wave spectrum;H_1（iω）is called system frequency response function, which represents the characteristics of input and output of the ship. Apparently, system frequency response function can solve the movement problem of ship in irregular waves. In 1955, Cowen. G Laniidae, based on fluid dynamics theory, put forward "slice theory" for ship heave and pitch movement calculation. Later, with HuiHong Watanabe, Gerry Hereby, Tasai Fuzao continuous improvement, in the 70 s, new "slice theory" had become the main tool to forecast ship in wave oscillation properties. Therefore, the frequency response function of the ship can be got not only from the model test, but by using theoretical calculation method. According to ship motion spectrum, all kinds of characteristics of ship motion parameters can be forecasted. This is the thought of spectral analysis method applied to ship motion research.

Wave bending distance is the key problem to determine the ship’s longitudinal bending moment in waves. In the past, the intensity specification is based on standard wave to calculate wave force on the ship (temple valley waveform as the standard waveform). In fact, while ship is sailing in random waves, wave bending moment is random, so more accurate method is to adopt the method of probability theory to determine wave bending moment distribution law along the ship and maximum possible wave bending moment value. In 1967, Moor [2] published ship model test results of wave bending moment, and in 1972, the calculation formula of amplitude wave bending moment with amplitude was published. Later, Lewis, Orchy and others estimated the biggest spectral density value of wave bending moment in vessel life cycle according to wave bending moment distribution as probability design criteria of hull longitudinal strength failure we can accept [3]. At present, this method has been adopted by classification society, and become the theoretical basis of hull structure design.

In bad weather, problems appear such as waves on deck, clap bottom and propeller water. In order to guarantee the safety of the ship, artificially reduce the speed or change direction. The statistic characteristics of ship deck waves, bottom water and propeller events in bad weather can be forecasted with the method of seakeeping theory. In sailing, the above phenomenon depends on the relative speed of the wave and the ship, and there is a minimum critical velocity. At the ship critical speed estimation aspect, Orchy, Michael, Lewis, Etison, Kitazawa and Hosoda put forward some estimate formulas [4]. These formulas are basically on the basis of the probability beyond a certain limit of rough seas on deck, clap bottom and propeller water. For example, Kitazawa and Hosoda put forward that container ships: deck wave probability limit is 0.01; The boundaries of clap bottom probability is 0.02; The boundaries of propeller emergence idling probability is 0.1.

Due to the deep development of offshore oil development, mooring ships and floating drift of marine structures become focus problems. In fact, this is a nonlinear problem of interaction between waves and objects. Since the 70 s, the problem became a new hotspot of ship's seakeeping theory research [5].

Since the 60 s, many countries have successively established ship seakeeping pool. Now some questions that is not clear in theory, such as ship capsized in following waves and tail of oblique waves, mainly still need to be studied through model test.

Taken together, the development of ship seakeeping theory mainly manifests in two aspects: the development of ship fluid dynamics theory and the widely application of probability and mathematical statistics theory. Now, theoretical calculation method is already applied to predict ship sailing on actual movement performance. Ship's seakeeping design proposed by the owner is feasible in technology.

SHIP'S WAVE-ENDUARABILITY THEORY APPLICATION IN NAVIGATION

Ship's wave-enduarability theory application in navigation will be various. Below regards the ship's wave-enduarability theory applied in navigation.

A. Route optimization design

According to long-term ocean climate data, currents and waves, design a route for ship with the combination of ship navigation performance and loading condition. The route has the optimal performance index: shortest voyage time, minimum fuel consumption, and minimum damage and damage. The route is not the same as the great circle route with the shortest distance between two points on the surface of the earth. The reason is that energy saving should consider to make full use of ocean currents and sea wind in order to improve the speed of the ship, at the same time, avoid too large swing of the ship, deck wave, and the danger of bottom and propeller water. Route optimization design can use dynamic programming to establish optimization mathematical model. Their specific mathematical forms include three parts: ship motion equation in earth coordinate system, ship's in wave speed calculation formula and optimal value function.

The ship motion equation in earth coordinate system is [6]

$$\phi_{k+1} = \phi_k + (V_k\cos\alpha_k + U_N)\Delta t_K/R, \quad \theta_{k+1} = \theta_k + (V_k\sin\alpha_k + U_E)\sec\alpha_k\Delta t_K/R \qquad (3)$$

In it, （ϕ，θ）is the shipping location (latitude and longitude); (UE，UN) is the current speed of east and north direction component; α is ship course angle; Δ t is time interval; V is for speed; R is for the earth's average radius.

In ship speed calculation in wave is

V＝V0（p）－VW(h,δ，p）　　（4）

In it, V0 (p) is ship's static water speed while power is p (B.H.P.); h is YiBo high; δ is relative wave angle; VW is the correction term of ship wave speed after meter and power, wave height, and relative wave angle. Many calculation formula put forward can be found in relevant information.

Take the shortest sailing time as the optimal value function and its recursive form is

$$f_K(\phi_K,\theta_K) = \min\{\sum_{j=1}^{K-1}\Delta t_j\} \qquad f_{K+1} = \min(f_K + \Delta t_K) \qquad (5)$$

When calculation, select shipping routes starting point and end point, connect with great circle line, and decorate several great circle lines in both spacing, establish a computing grid, and set the ship speed constant within time interval from a ship grid node to next grid node. Obviously, one of the key problems is to determine the ship speed in the wave. From the angle of ship's seakeeping, a great deal of research have been made. The research results show that when wave YiBo high is under a certain limit, the speed will decrease with the increase of resistance and wind resistance in waves, which is called shipping stall in the wave; When YiBo high is above a certain limit, the speed of main wave is limited by deck wave and clap bottom limit, and decreases with increasing of high YiBo. Then determine the maximum allowable speed of the ship at this time. Use ship's wave-enduarability theory to estimate or model test method to get high YiBo limit with parameters that influence speed, and the size of stall and maximum allowable speed. Obviously, with wave spectrum and its limitation in application of spectrum analysis, the actual route should be properly corrected according to recent weather and wave forecast.

B. Intelligent ship driving

Computer aided decision system is an important part of ship automation driving. Ship navigation safety evaluation system can be got by absorbing the rich research results of ship's seakeeping and combining fuzzy logic judgment. In this respect, the author has made some meaningful study [7], and the method of the evaluation model is set up.

Ship capsizing risk mainly occurs in tail oblique wave or following sea conditions. First of all, determine the risk factors of occurring topple, choose four risk factors causing ship capsizing: wave direction angle, speed, high wave energy concentration ratio and transverse stability, and divide risks into four grades based on the specific situation. The most important thing is to identifymembership function of risk factors to dangerous degree. Due to random wave, ship capsizing must also be random events, various factors causing ship capsizing statistical probability can be obtained from the model ship capsized series test. In most cases, membership function has the characteristics of normal distribution, and its mathematical form is

$$u_i(x) = \exp[-(x-a)^2/b^2] \qquad x = P_i(\xi) \qquad (i = 1 \sim 4) \qquad (6)$$

In it, a, b are undetermined coefficients; Pi (ξ) is probability distribution function. Due to the influence degree of each risk factor in the evaluation is different, weighted coefficient of each factor should be configured differently, called weight.Weighted average is adopted for the evaluation model.

$$b_i = \sum_{i=1}^{4} a_i r_{ij} \quad (j = 1 \sim 4) \qquad c = 0.1b_1 + 0.45b_2 + 0.8b_3 + 0.95b_4 \qquad (7)$$

In it, ai is weight; rij is for evaluating matrix (I is the i factor, j stands for four risk ratings), select the appropriate probability value as a threshold to dangerous level; C is for comprehensive evaluation parameter, take 0.70 for critical value.

For ship safety problems caused by multiple factors, mainly including ship structure safety, loading (discharging) safety, navigation safety in stormy waves, etc., in principle, the above mentioned methods can be used to set up security evaluation model. However, due to very large modeling workload, good results were rare.

C. Non-standard heavy cargo lashing

Non-standard heavy goods refer to offshore oil field derrick, large industrial equipment, rolling stock, high-speed vessels, large transformers. The common characteristics of the goods is big weight and big size. Improper lashing will cause slip, dumping goods, and major accident. The key technologies determining lashing and securing intensity is to calculate the size of motion inertia force and direction acting on the goods. Due to motion inertia force depends on the motion performance of ship in waves, therefore, wave resistance theory provides the corresponding theoretical basis and experience formula to solve such problems. From a security perspective, people are only interested in the possible maximum, such as wave height, rolling and pitching angle and maximum heaving amplitude. Ship's wave-enduarability theory can obtain the maximum probability estimates, and the author has discussed on the problem [8].

Synthesis movement inertial force applied to goods gravity is

$$F_x = F_{\varphi\tau x} + F_{\varphi n x} \quad F_y = F_{\theta\tau y} + F_{\theta n y} \quad F_z = F_{\theta\tau z} \pm F_{\theta n z} + F_{\varphi\tau z} \pm F_{\varphi n z} + F_{zz} \qquad (8)$$

In it, Fx, Fy are respectively inertia force parallel to the deck along longitudinal and transverse; Fz is for inertia force of deck vertical direction. Calculate formula of unit weight of each component is espectively

$$F_{\varphi\tau x} = 0.07024\varphi_m l_z T_\varphi^{-2} \quad F_{\varphi n x} = 0.00123\varphi_m^2 l_x T_\varphi^{-2} \quad F_{\varphi\tau z} = 0.07024\varphi_m l_x T_\varphi^{-2}$$

$$F_{\varphi n z} = 0.00123\varphi_m^2 l_z T_\varphi^{-2} \quad F_{\theta\tau y} = 0.07024\theta_m l_z T_\theta^{-2} \quad F_{\theta n z} = 0.00123\theta_m^2 l_y T_\theta^{-2}$$

$$F_{\theta\tau z} = 0.07024\theta_m l_y T_\theta^{-2} \quad F_{\theta n z} = 0.00123\theta_m^2 l_z T_\theta^{-2} \quad F_{zz} = 4.0243 z_m T_z^{-2}$$

In it, φ_m,θ_m are maximum pitch and roll angle respectively; T_φ, T_θ are maximum pitching and rolling period respectively; Lx, ly, lz are respectively coordinates distance from a center of goods to ship gravity center; Tz, zm are maximum heaving cycle and amplitude, respectively. The ship motion parameters can be determined according to the theory of seakeeping. The benefits of theoretical method calculating inertia force are to get not only the size and direction of force obtained, but also estimate the probability, and thus prepare for the strength reliability analysis of the lashing structure, and this is what other computing methods lack. Of course, theoretical calculation have drawbacks, such as more calculation steps, but in increasingly powerful computer performance today, these defects will not affect the promotion and use of theoretical calculation method.

D. Ship motion state very short-term forecast [5]

By plane aircraft carrier landing, put forward very short-term prediction of ship motion elements in the future. Study on the modern control theory in ship's seakeeping application causes widespread attention. The problem ship motions very short-term forecast need to solve is that according to the historical records of ship motion, accurately forecast ship’s amplitude, velocity and acceleration of the movement in a few seconds later and more than ten seconds. Using adaptive filtering techniques can excuse ship motion prior statistical knowledge, and automatically adjust the parameters. The mathematical model of adaptive filter is

$$x_k = a_1 x_{k-1} + a_2 x_{k-2} + \cdots + a_m x_{k-m} + b_1 \varepsilon_{k-1} + b_2 \varepsilon_{k-2} + \cdots + b_n \varepsilon_{k-n} + w_k \qquad (9)$$

In it, $\varepsilon_{k-i} = x_{k-i} - \hat{x}_{k-i}, \hat{x}_{k-i}$ is k - I moment estimation value. The type (16) can make use of recursive least square method, using new value instead of the old values for identification, and the recursive form is

$$\hat{B}_{k+1} = \hat{B}_k + P_{k+1} A_{k+1}^T (x_{k+1} - A_{k+1} \hat{B}_k)$$

$$P_{k+1} = P_k - P_k A_{k+1}^T (A_{k+1} P_k A_{k+1}^T + I)^{-1} A_{k+1} P_k$$

$$B^T = (a_1, a_2, \cdots, a_m, b_1, b_2, \cdots, b_n) \quad A = (x_{k-1}, x_{k-2}, \cdots, x_{k-m}, \varepsilon_{k-1}, \varepsilon_{k-2}, \cdots \varepsilon_{k-n})$$

In it, P is state transition matrix.

Using phase difference GPS technology, the measurement of ship motion parameters can be realized. Combined with the application of adaptive filter, ship motion state very short-term forecast accuracy and reliability will be radically improved. It is believed that the technology will play an important role in automated driving and ship offshore operation.

CONCLUSION

Only according to the author's knowledge and understanding of the above discussions, in fact there are some places not involved. We are about to enter the 21st century, the review for half a century of the development of ship seakeeping theory and its application in the shipbuilding industry achievements will have a very good reference value for absorbing and using ship's wave-enduarability theory research results in navigation technology development process. At the same time, we also believe that ship's wave-enduarability theory will also pay close attention to the application in the field of navigation in the next 50 years of development.

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