Study on the Wave Loads and Structural Stresses of Container Ship

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Abstract. In this article ship motions and wave loads are analyzed by using three dimensional motion of the ship program. As an example of a 5500TEU container ship, the heading angles of maximum motions and loads, amplitude of movement under the action of unit regular wave, load conversion functions, conditions and RAO of middle section at different angles have been gotten. The maximum dominant load parameters are also obtained. Then the long-term wave loads are calculated through the spectrum theory, and the results are compared with the values of classification rules. At the end forces and stresses distribution of the ship hull structure under dominant wave loads are also calculated by the dynamic load method with ANSYS software. The conclusions can be used to analyze ultimate loads of the container ships, and can also be the reference of ship structural design.

1. Introduction

Container ship is a kind of ship with large openings. In addition to the vertical bending moment in the design process, we must also consider the torque and horizontal bending moments produced by the oblique waves on the hull. At present, the structure of the general merchant ship is designed according to the standard of the classification societies. Because of the data and the formula of the classification rules are based on the statistical data, existing practice experiences and basic theory, which did not fully take into account the specific hull lines, size, speed, sea conditions and other factors, so the calculation according to standard out of the hull bending moment and shear force and torque is not very accurate. If the calculated value is too large, the hull structure designed according to this will cause material waste and dead weight reduction. On the other hand, if the calculated value is too small, the strength of the hull structure designed based on this will not be enough. Therefore, it is necessary to calculate the wave load of the specific ship first, then estimate the limit value according to the long term analysis, and finally use the dynamic load method to analyze the structure. This method can be more accurate than the empirical formula, and can also reduce the cost of hull structure design while improve the design efficiency.

There are two main methods for the study of three-dimensional hydrodynamic theory: the free surface Green function method and the Rankine source method [1]. In Green function method, velocity potential of flow field is determined by distributing sources and sinks in the wet hull surface, the Green function can satisfy all boundary conditions except the surface conditions. By using the
Green second formula, the velocity potential is expressed as the sum of the area integration of the distribution source along the wet surface of the hull and the line integration of the water surface with the hull line. The Rankine source method is a calculation method, which distributes singular points on both the body surface and the free surface. The method is simple in calculating the distribution singularity, and the ship's speed effect can be considered. These two methods have made some progress in recent years. The performance of Bessho form translating-pulsating source Green's function is discussed and a numerical integration method was proposed by Yao Chaobang et al. [2]. A 3D time domain program based on transient Green function method was developed by Sun Wei et al. [3]. The precise integration method and some mathematical derivations were employed to evaluate the memory part of the transient Green function and its derivatives. Program used to solve the initial boundary value problem based on hybrid Green function method was proposed by Tang Kail et al. [4,5]. Method of Rankine source theory combined with three dimensional hydroelastic theory to solve medium and high speed condition was developed by Li Hui [6]. Aiming to predict ship performance such as wave drag, sinkage and trim, the steady ship wave problem was solved based on the high-order Rankine source method by Chen Xi et al. [7]. Linearized free-surface condition with respect to double body potential was adopted in the calculation. Parametric roll prediction for a large containership in head waves was performed by Zhao Chunhui et al. [8]. The commonly used software for prediction of ship's three-dimensional motion and wave load are SESAM, SCADIS and HSC etc.

The main work of this paper is to use ship three-dimensional motion program (HSC) to predict short-term and long-term wave loads on a 5500TEU container ship, and compare them with the calculated values of current classification rules. The program uses the free surface Green function method to calculate the motions in 6 degrees of freedom and wave loads of the ship.

2. Navigational Conditions Setting

The analysis object in this paper is a 5500 TEU container ship, it’s main parameters are presented in Table 1.

| LOA/m | LWL/m | LBP/m | B/m  | D/m  | Draft(Designed)/m | C_b   | C_w   |
|-------|-------|-------|------|------|-------------------|-------|-------|
| 277.350 | 268.657 | 266.000 | 40.000 | 24.000 | 12.000            | 0.6136 | 0.853 |

In order to get the maximum wave loads of the ship, main load parameters under different sea conditions and different heading angle combinations should be set up to analyze the structural response. As container ship with large openings, the most important load parameters are the vertical wave shear, vertical wave bending moment and wave torsional moment.

In order to get the maximum value of the main load parameters, the frequency response function of ship motion can be started with. It is assumed that the sine wave frequency range of unit wave height is 0.05 ~2.00 rad/s and meets the hull in different directions. The speed is assumed to be 75% design speed, then frequency response functions along the different angle of attack can be calculated. In this example, the navigation conditions are as follows: sailing speed is 9.6 m/s; heading angles are 0°, 30°, 60°, 90°, 120°, 150° and 180°; range of phase angles is -180°~180° and wave frequency is from 0.05 to 2.00 rad/s.

Distribution diagram of small shell of ship under water used by HSC program in this paper is shown in Figure 1.
Figure 1. Distribution diagram of small shell of ship under water.

3. Motion Amplitudes of Hull under the Action of Regular Wave in Unit Wave Amplitude ($\xi_0$)

Surge ($\xi_1$), sway ($\xi_2$), heave ($\xi_3$), roll ($\xi_4$), pitch ($\xi_5$) and yaw ($\xi_6$) amplitudes of the ship at different heading angles are presented in Figure 2 to Figure 7.

Figure 2. Surge amplitude of the ship at different heading angles.

Figure 3. Sway amplitude of the ship at different heading angles.

Figure 4. Heave amplitude of the ship at different heading angles.

Figure 5. Roll amplitude of the ship at different heading angles.
It can be seen from Figure 2 to Figure 7 that the heading angles corresponding to the maximum amplitudes of different motions are 0°, 90°, 30°, 60°, 30° and 30°.

4. Force Conversion Function and Response Amplitude Operator (RAO)

Phase spectrum of different force conversion functions such as longitudinal shear force (F1), transverse shear force (F2), vertical shear force (F3), torsional moment (F4), vertical bending moment (F5) and horizontal bending moment (F6) can be calculated by using ship three-dimensional motion program. Based on the results, it can be found that heading angles corresponding to each kind of maximum force are 60°, 60°, 180°, 60°, 180° and 120°.

After calculating the spectrum of ship motion in all directions and the force spectrum of the hull, it is necessary to select the Response Amplitude Operator (RAO) of the main load parameters. The main loads are vertical shear force (F3), torsional moment (F4) and vertical bending moment (F5). Because the RAO of ship’s three-dimensional motion program is divided into multiple segments along the Lbp, so the output data must be analyzed, and the location with the maximum amplitude of RAO can be selected. Through the analysis of data, the maximum vertical shear force (F3) occurs at 165m from after perpendicular (A.P.), the maximum torsional moment (F4) occurs at A.P.66m and the maximum vertical bending moment (F5) occurs at A.P.133m (amidship). In addition, the maximum amplitude, heading angle, frequency and phase angle of the maximum amplitude should be selected from the spectrum diagrams also.

Some important results are presented in Table 2.

| F3       | F4           | F5           |
|----------|--------------|--------------|
| Section  | 165m         | 66m          | 133m         |
| Head     | 180°         | 60°          | 180°         |
| w(freq)  | 0.55rad/s    | 0.5rad/s     | 0.45rad/s    |
| RAO(max) | 8.11×10^6 N  | 2.05×10^8 N·m| 5.71×10^8 N·m|
| Phase    | -0.627°      | 80.5°        | -179.87°     |
5. Long Term Wave Load Analysis

5.1. Long Term Wave Load Analysis
Ships may encounter various sea conditions during the whole service life (usually 20 years). Under rough sea conditions, although the operation time is short, the load response value can reach the extreme point. According to the statistics, the operating time of the ship in the rough sea condition accounts for about 5% of the total voyage [9]. Therefore, it is necessary for ship designers to pay attention to the maximum wave load that may occur during the whole life period of the ship. Wave spectrum and frequency should be selected during the analysis of the long-term wave load. In this paper P-M (Pearson-Moszkowicz) wave spectrum is chosen because a set of empirical formula are derived from the observation of the Atlantic open sea area, where is also the sailing route of 5500 TEU container ship. The wave frequency table recommended by IACS WP/S committee is selected to be used in the program calculation. After calculating, the loads of different directions along the length of ship can be obtained, as shown in Table 3.

Table 3. Loads in different directions along the length of ship by long term wave load analyses.

| Distance from A.P./m | Longitudinal Shear Force/N | Transverse Shear Force/N | Vertical Shear Force/N | Torsional Moment/N·m | Vertical Bending Moment/N·m | Horizontal Bending Moment/N·m |
|---------------------|-----------------------------|--------------------------|------------------------|-----------------------|----------------------------|-------------------------------|
| -5                  | 0.00                        | 0.00                     | 0.00                   | 0.00                  | 0.00                       | 0.00                          |
| 10.65               | 6.22×10^6                  | 3.17×10^6                | 2.72×10^7              | 9.83×10^7             | 1.95×10^8                  | 2.63×10^7                     |
| 24.35               | 1.92×10^7                  | 1.18×10^7                | 4.87×10^7              | 2.40×10^8             | 6.77×10^8                  | 1.22×10^8                     |
| 38.72               | 3.10×10^7                  | 1.77×10^7                | 5.78×10^7              | 3.34×10^8             | 1.39×10^8                  | 3.21×10^8                     |
| 56.7                | 4.20×10^7                  | 2.34×10^7                | 6.12×10^7              | 6.40×10^8             | 2.43×10^8                  | 6.96×10^8                     |
| 66                  | 4.70×10^7                  | 2.42×10^7                | 6.22×10^7              | 8.69×10^8             | 2.94×10^8                  | 8.99×10^8                     |
| 74.1                | 5.00×10^7                  | 2.38×10^7                | 5.88×10^7              | 1.03×10^9             | 3.47×10^8                  | 1.09×10^9                     |
| 88.94               | 5.36×10^7                  | 2.39×10^7                | 4.95×10^7              | 1.09×10^9             | 4.23×10^8                  | 1.40×10^9                     |
| 99                  | 5.57×10^7                  | 2.28×10^7                | 4.16×10^7              | 1.12×10^9             | 4.65×10^8                  | 1.60×10^9                     |
| 103                 | 5.67×10^7                  | 2.25×10^7                | 3.87×10^7              | 1.12×10^9             | 4.77×10^8                  | 1.66×10^9                     |
| 118                 | 5.74×10^7                  | 2.21×10^7                | 3.04×10^7              | 1.04×10^9             | 5.03×10^8                  | 1.81×10^9                     |
| 133.34              | 5.78×10^7                  | 2.05×10^7                | 3.04×10^7              | 1.02×10^9             | 5.07×10^8                  | 1.86×10^9                     |
| 148.14              | 5.57×10^7                  | 2.02×10^7                | 4.35×10^7              | 1.10×10^9             | 4.76×10^8                  | 1.78×10^9                     |
| 162.9               | 5.23×10^7                  | 2.11×10^7                | 6.21×10^7              | 1.21×10^9             | 4.10×10^8                  | 1.60×10^9                     |
| 165                 | 5.14×10^7                  | 2.12×10^7                | 6.44×10^7              | 1.22×10^9             | 3.98×10^8                  | 1.57×10^9                     |
| 177                 | 4.62×10^7                  | 2.24×10^7                | 6.22×10^7              | 1.31×10^9             | 3.11×10^8                  | 1.34×10^9                     |
| 192.54              | 3.87×10^7                  | 2.24×10^7                | 6.13×10^7              | 1.40×10^9             | 1.98×10^8                  | 1.05×10^9                     |
| 198                 | 3.53×10^7                  | 2.26×10^7                | 5.97×10^7              | 1.37×10^9             | 1.47×10^8                  | 9.23×10^8                     |
| 207.34              | 2.94×10^7                  | 2.16×10^7                | 5.23×10^7              | 1.27×10^9             | 9.62×10^8                  | 7.37×10^8                     |
| 222.14              | 2.05×10^7                  | 1.82×10^7                | 3.99×10^7              | 9.51×10^8             | 4.27×10^8                  | 4.58×10^8                     |
| 236.94              | 1.29×10^7                  | 1.36×10^7                | 1.59×10^7              | 4.91×10^8             | 4.80×10^8                  | 2.50×10^8                     |
| 250.7               | 7.93×10^6                  | 7.14×10^6                | 3.45×10^6              | 8.74×10^7             | 3.89×10^8                  | 1.64×10^8                     |
| 271.4               | 7.64×10^5                  | 1.18×10^6                | 2.63×10^6              | 5.89×10^7             | 3.76×10^8                  | 1.70×10^8                     |

5.2. Comparison between the Results of Long Term Wave Load Analysis and Classification Rules Formula
The vertical shear force values in the long-term wave load analysis are similar to those calculated by the formula in the ABS and CCS [10, 11]. The middle part of long-term load calculation by PM spectrum value (3.04×107 N) and the standard value (3.06×107 N) is very close, but at length range A.P.40~60 m and A.P.150~210 m long term load vertical shear force is significantly higher than the standard value (A.P.56.7 m for example, the long-term load value is 6.12×107 N, standard value is
3.25×107 N). From A.P.220 m to the bow, the standard value is higher than the vertical shear force predicted by long term load. Taking A.P.222.14 m as an example, the long-term load value is 3.99×107 N, the standard value is 4.38×107 N; in A.P.250.7 m, for example, the long-term load value is 3.45×106 N, and the standard value is 1.47×107 N.

The vertical wave bending moment in the long-term wave load analysis results can be compared with the calculated value of the standard formula of the classification society, and it can be seen that the vertical wave bending moment calculated by the two methods is basically the same distributing trend along the length. The difference at sagging condition results is 16.31% (long term load value is 5.07×10⁸ N·m, standard value is 4.243×10⁸ N·m), hogging condition difference is 32.46% (standard value of hogging condition is 3.424×10⁹ N·m). From A.P.40 to A.P.160m part of the ship at sagging, and from A.P.25 to A.P.175m at hogging condition, vertical wave bending moment standard value of these ship sections is smaller than the long-term wave load prediction value.

6. Analysis of Container Ship Hull Structure under Wave Load

6.1. Establishment of Dynamic Finite Element Model

The hull profile and rib lines plan are drawn by Autocad firstly, then the main node coordinates are input to ANSYS software. ANSYS is used to do the pre-processing work and to finish the establishment of hull dynamic finite element model, as shown in Figure 8.

![Figure 8. Dynamic finite element model (right half).](image)

After the establishment of the whole ship dynamic load model, it need to adjust the static state of weight distribution and buoyancy distribution according to the design of the original ship plan, and confirm that the model is consistent with the original ship.

The pressure load of ships in waves can be obtained by using HSC program, as shown in Table 3. Water pressure distribution and movement amplitude can be converted to nodal force of the dynamic load model through compiling external program, further more the movement of the ship caused by unbalanced force is converted to acceleration, exerted on each node as the form of inertial force in order to achieve the balance of force.

When the nodal forces are completely exerted, the appropriate boundary conditions are added to the model before the analysis is carried out according to the requirements of the relevant rules, including the rigid body displacement constraint, as shown in Figure 9.
6.2. **Analysis of Container Ship Hull Structure under Wave Load**

6.2.1. **Analysis of Vertical Shear Force (F3).** It can be seen from Table 3 that the maximum vertical shear force lies on A.P.38 m–A.P.88 m and A.P.162 m–A.P.198 m. Figure 10 and Figure 11 show the stress distribution diagram of the hull structure of A.P. 38 m–A.P.88 m. Figure 12 and Figure 13 show the stress distribution diagram of the hull structure of A.P.162 m–A.P.198 m.

![Stress distribution diagram at A.P. 38m–88m under vertical wave shear (Hogging).](image1)

![Stress distribution diagram at A.P. 38m–88m under vertical wave shear (Sagging).](image2)

![Stress distribution diagram at A.P. 162m–198m under vertical wave shear (Hogging).](image3)

![Stress distribution diagram at A.P. 162m–198m under vertical wave shear (Sagging).](image4)
6.2.2. Analysis of Wave Torsional Moment (F4). The maximum wave torsional moment lies on A.P.66m~A.P.103m and A.P.177m~A.P.222m by referring to Table3. Figure 14 shows the stress distribution diagram of the hull structure of A.P.66m~A.P.103m. Figure15 shows the stress distribution diagram of the hull structure of A.P.177m~A.P.222m.

![Figure 14](image1.png)  
**Figure 14.** Stress distribution diagram at A.P. 66m~103m under wave torsional moment.  

![Figure 15](image2.png)  
**Figure 15.** Stress distribution diagram at A.P. 177m~222m under wave torsional moment.

6.2.3. Analysis of Vertical Bending Moment (F5). From table 3 it can be found that the maximum vertical bending moment lies on A.P.103m~A.P.162m. Figure 16 and Figure 17 show the stress distribution diagram of the hull structure of A.P.103m~A.P.162m.

![Figure 16](image3.png)  
**Figure 16.** Stress distribution diagram at A.P. 103m~162m under vertical bending moment (Hogging).  

![Figure 17](image4.png)  
**Figure 17.** Stress distribution diagram at A.P. 103m~162m under vertical bending moment (Sagging).

7. Conclusion
The results of the above calculation and the analysis of the data can be concluded as follows:

1) The position and maximum value of the main load parameters and the corresponding navigation conditions are obtained through the analysis of ship motions and wave loads.

2) The results of long term wave load analysis and classification rules are compared, the vertical shear force of classification rules in the middle and the bow has reached 20 years of long-term load standard, but shear force near the stern is lower than 20 years standard. The vertical wave bending
moment of classification rules is less than 20 years standard, but in sagging condition the bending moment is close to 20 years standard.

(3) It can be seen from Von Mises stress distribution diagrams that when the hull structure is subjected to the vertical wave bending moment of twenty year long term wave loads, the stress will exceed the allowable stress of 22.2kg/mm² under hogging condition. The other ship's stress distribution state are still within the allowable stress range.

(4) According to the wave spectrum and sea state statistics recommended by the IACS WP/S Committee, the long-term load values are greater than the loads calculated by the current classification society formula, and it is conservative to predict the wave load according to that sea state. From the perspective of comparative strength of hull, in order to coordinate with the IACS standard, if the long-term prediction is made by using wave spectrum and sea state recommended by IACS to calculate the wave load value, the allowable stress may be appropriate to increase or the probability level used to forecast the wave load values can be adjusted from 10⁻⁸ to 10⁻⁵.⁵.

Acknowledgments
This work was financially supported by the Natural Science Founds of Fujian Province (No. 2018J01493).

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