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# Bulk Carrier's Motion Analysis with Sloshing Effect in Water Ballast Cargo Hold

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**Abstract:** Since a ship in the voyage may encounter severe environment conditions, the ballast water should be adjusted to enhance navigational stability, maneuverability and safety. For a bulk carrier in a normal ballast condition, the most common operation is to load additional ballast water into an empty dry cargo hold. In the intermediate process of loading ballast water, a large free surface exists in the cargo hold and the sloshing behavior may influence ship motion. Therefore, the ship's motion behaviors between normal ballast condition and heavy ballast condition in sever environment are investigated. The analyses in this article are divided into two parts: discussion of the ship's motion with varied loading conditions and calculation of the ship's motion with different liquid filling heights in the water ballast cargo hold. The later part assumes the ship sails with a partially filled tank during the ballasting process and compares the motion with that sailing with a fully filled water ballast cargo hold. A three-dimensional panel method coupling with the tank sloshing flow model is applied to analyze bulk carrier's motion in frequency domain. The results are obtained using the real sea state with the application of Pierson – Moskowitz spectrum and show that the ship motion, especially in roll motions, under varied loading conditions and sloshing effect can be significant affected.

**Key words:** ship motion; seakeeping/sloshing coupling; spectrum analysis; 3D panel method

## 0 Introduction

The loading ballast water can increase a ship's safety and stability in severe environments, such as preventing the cavitation of propellers and great slamming of ships. The state of loading ballast water fully filled in the cargo hold of a bulk carrier is called heavy ballast condition. For investigating the seakeeping performance after loading ballast water, the first part of computations in this paper discusses ship motions with different loading conditions, namely normal ballast condition, heavy ballast condition and design load condition. Additionally, it is possible for a tank filling ballast water partially in the ballasting process. The second part of computations analyzes seakeeping with the free liquid moving in the cargo hold and discusses with different filling heights in the tank.

The sloshing motions may interact with ship motions seriously as the cargo hold is very large. Thus, to enhance the strength of tank structure, studying free liquid motions in the cargo hold is very important. For the purpose of investigating a ship's motion in this paper, the complicated problem of the nonlinear liquid motion inside tanks will be carefully simplified to a linear problem. Computations are established by a three-dimensional panel method, and implemented by coupling seakeeping and sloshing flow models. The formula is based on the frequency domain and assumed as a linear problem. Both discussions of different loading conditions and different filling heights in tanks are presented in the following sections. All the numerical results are carried out in both regular waves and irregular waves, which are real sea states, by applying the Pierson – Moskowitz spectrum.

## 1 Numerical Methods

The numerical computations are simulated in frequency domain by using the commercial code HydroSTAR, which is developed by Bureau Veritas. Seakeeping formula is associated with a sloshing flow model for considering the free liquid motion. Due to computations with the linear theory approach, the roll damping should be modified properly as regards the viscous effect. Ikeda Himeno semi-empirical formula [1] was introduced to adjust the roll damping for ships using appendages, like bilge keels and skegs. As the results, the predicted roll motion will be more reasonable.

For coupling seakeeping and sloshing, six-degree-of-freedom motions of tanks are considered in the interior boundary value problem. Then, the additional added mass and damping caused by the tank are substituted to the seakeeping formula for combining the interior and exterior flows. Due to the basis of linear potential theory, there's no damping induced by the liquid motion in tanks. Thus, HydroSTAR used the artificial damping term to prevent the unrealistic value around the resonant frequencies. The artificial damping is treated in the boundary condition in the tank walls, which is regarded as the energy dissipation when liquid moving in tanks. About the detail theory of seakeeping coupling with sloshing effect and the decision of artificial damping coefficient can refer to the references [2] and [3].

Demonstration ship is a bulk carrier with 93000 MT deadweight capacities. The water ballast cargo hold is the fourth cargo hold amidship. The dimensions of ship in different load conditions are described in Table 1. The case 1, case 2 and case 3 are in normal ballast, heavy ballast and design load conditions respectively. Comparing to the heavy ballast condition (case 2), it is allowable for the ship sailing with partially filled tank in the ballast process. Therefore, in the second part calculations, the ship draughts are changed to partially filled tanks, and parameters are based on case 2. There are three filling heights for studying: 40%, 50% and 60%. The relevant parameters are presented in Table 2 and Fig. 1. All the seakeeping analyses are simulated at a ship speed of 5 knots. And the discrete panels of the vessel with water ballast tank are illustrated in the Fig. 2.

## 2 Computational Results

### 2.1 Ship motion analysis in different loading condition

The comparisons of different loading conditions are presented in this section. To validate the computational results obtained by HydroSTAR, results are compared with the well-known software, SMP (Ship Motions Program). SMP is based on the strip theory, and is widely known to be reliable in simulating ship motions. The verifying sample is case 3 defined in Table 1, and RAO (Response Amplitude Operators) results are shown in Fig. 3. The heading definitions for head seas are 180 degree and for beam seas at starboard side are 90 degree. Comparisons show that HydroSTAR (three-dimensional panel method) is well consistent with SMP (strip theory), except the roll motion around resonant frequencies. Because of the different numerical methods adopted in both tools and the complex phenomenon of roll motions, the quantity of roll responses may be quite different in both simulations for the resonant frequency. However, the trend of HydroSTAR results is similar to SMP results, and it is reasonable for using HydroSTAR to analyze seakeeping characteristics.

The RAOs in different loading conditions are illustrated in Fig. 4. Results of the heave, pitch and surge RAOs in head seas show a similar trend. On the other hand, in beam seas, the heave and roll motions may be influenced by different displacements and transversal metacentric heights. It is apparent that seakeeping characteristics of roll motions are varied with amplitudes and resonant frequencies. Comparing with normal ballast condition and heavy ballast condition, the amplitude in the resonant frequency of case 2 is larger than case 1.

For practical purpose, those roll motions are carried out in real seas (irregular waves) by applying the wave spectrum. Considering the North Atlantic sea state, the Pierson–Moskowitz spectra are used to investigate. Since the RAO characteristics in roll motions are different, trends in irregular seas may be varied even with the same sea state. The responses of roll motions in 18 sea states are presented by significant responses (double amplitude in 1 meter wave height) (see Fig. 5). And results show the higher roll evaluations are case 1 in short wave periods and case 3 in large wave periods. It means the higher responses occur as the wave distribution and RAO distribution match. For investigating in severe environments, the 5 meter wave height is assumed. According to wave data from IACS [4], the most common wave periods in 5 meter wave height are approximately in 12 to 16 seconds. Comparing the results in beam seas (see the symbols in Fig. 5 right part), the significant responses (in 1 meter wave height) in heavy ballast condition are almost greater than in the normal ballast condition. Since motions are analyzed in the linear approach, in this case, the bulk carrier in 5-meter wave height may cause larger roll motions for changing the normal ballast condition to the heavy ballast condition.

### 2.2 Ship motion analysis with sloshing effects in partially filled tank

Due to the assumption of loading ballast water partially in cargo holds, sloshing motions shall be generated by the free liquid moving in tanks. Accordingly, interior liquid motions may alter ship motions as well as the ship motions excite tanks since the dimension of tank is very large here. For investigating the interaction between seakeeping and sloshing, 40%, 50% and 60% filling heights are calculated, and results are compared with the fully filled case (case 2). From computational results (see Fig. 6), the heave and pitch motions are similar in different filling heights while roll motions are apparently influenced by sloshing motions. Two peaks appear as sloshing happens, and Clauss [5] have pointed out the property of these two peaks: for the peak in lower frequency is induced by the rigid body; in higher frequency is related to the transversal resonant sloshing. Moreover, to confirm the resolution of HydroSTAR, the added mass of tanks in transversal direction are obtained and compared with the formulated solution quoted from Faltinsen [6], who also modified for the prismatic tank. Both results of formula and HydroSTAR are consistent with each other (see Table 3 and Fig. 6). From roll motions results in Fig. 6, the peak in higher frequency also shows a good agreement with the tank natural frequency in trends. But, in quantities, ship motions are located in higher frequencies. The reason may be that tanks are not in phase with ship motions as tanks resonate, and ship motions would not be in resonant until both movements of interior and exterior are consistent.

Because characteristics are changed in ship motions with partially filled tanks, ship behaviors in sea states may be different. From computational results shown in Fig. 8, ship motions with fully filled tanks are larger than those with partially filled tanks in the sea states, and motions are smaller as the less filling water in tanks. As previous approach, in the severe environment of 5-meter wave height, seakeeping may be better for ships with sloshing effects in the computations applying Pierson–Moskowitz spectrum (see the symbols in Fig. 8 right part). Therefore, to sum up, sloshing motions can truly affect the seakeeping characteristics, and make the ship resonates away from the frequencies of realistic sea states sometimes.

## 3 Conclusions

The linear potential flow analysis is carried out to investigate both normal ballast condition and heavy ballast condition in severe environments. Computational results show the different loading conditions and sloshing effects may alter the seakeeping characteristics, especially in the roll motions. Due to the dual mass system generated by the partially filled tank, the sloshing motions make the roll motions with two resonant frequencies. And after studying, in this case, the seakeeping in the heavy ballast conditions is worse than that in the normal ballast condition as the ship voyage in 5-meter wave height and beam seas. In addition, for the ship with partially filled tank, the less ballast water loads in the tank, the better seakeeping performance it has. Although the seakeeping is better for ships with a partially filled tank, the damage in tank structures, which is caused by sloshing motions, should be considered carefully.

## References


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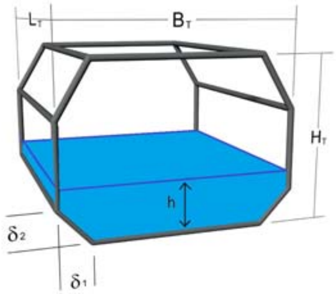
Table 1 Ship dimensions in varied loading conditions

| Parameter | case1 | case 2 | case 3 |
|---|---|---|---|
| Length (m) | 235 | | |
| Breadth (m) | 38 | | |
| Height (m) | 20 | | |
| Draught (m) | 6 | 8.07 | 13.5 |
| Displacement | 40102.6 | 59925.8 | 96752.7 |
| KG (m) | 10.630 | 10.074 | 10.764 |
| $GM_L$ (m) | 572.534 | 419.681 | 302.386 |
| $GM_T$ (m) | 11.795 | 7.330 | 5.088 |

Table 2 Tank parameters with different filling heights

| Parameter | 40% f.h. | 50% f.h. | 60% f.h. |
|---|---|---|---|
| Tank length $L_T$ | 26.6 m | | |
| Tank breadth $B_T$ | 38 m | | |
| Tank height $H_T$ | 17.899 m | | |
| $\delta_1$ | 5.605 m | | |
| $\delta_2$ | 5.768 m | | |
| Filling height $h$ | 7.16 m | 8.95 m | 10.74 m |
| Draught | 6.90 m | 7.11 m | 7.35 m |



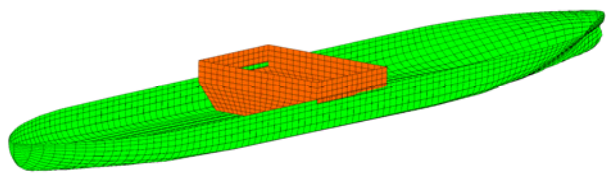



Fig. 1 Tank illustration with relevant parameters [5]    Fig. 2 Ship panels with tank of 60% filling height

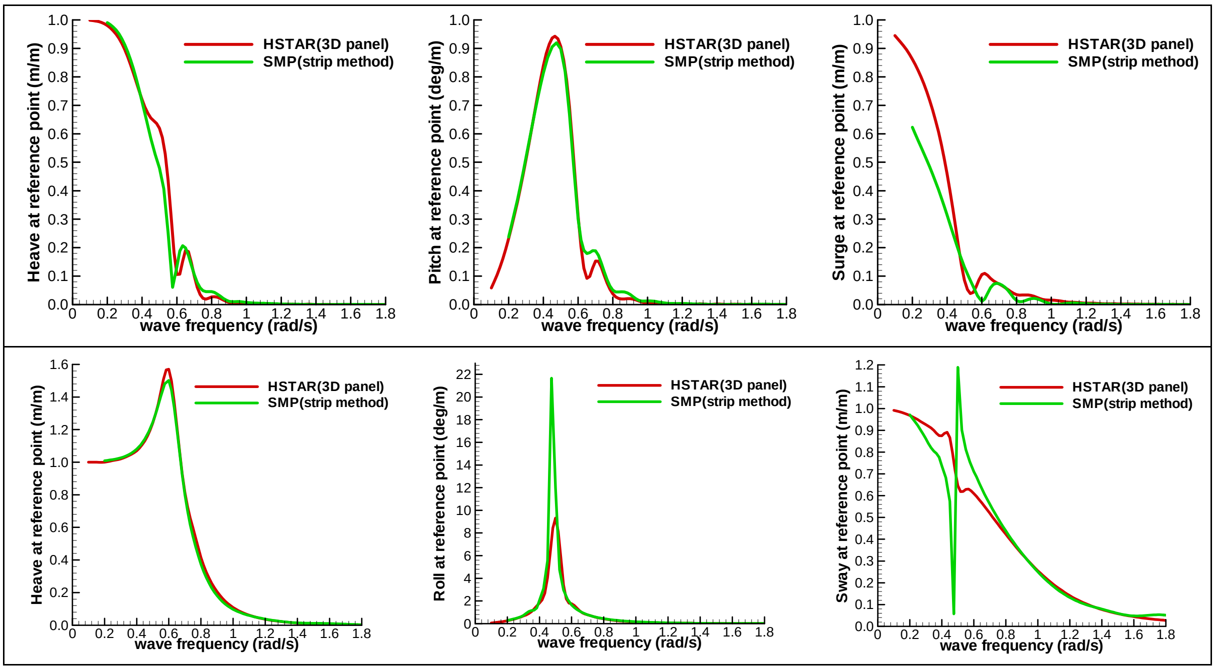



Fig. 3 Comparisons of HydroSTAR and SMP in head sea (top) and beam sea (bottom).

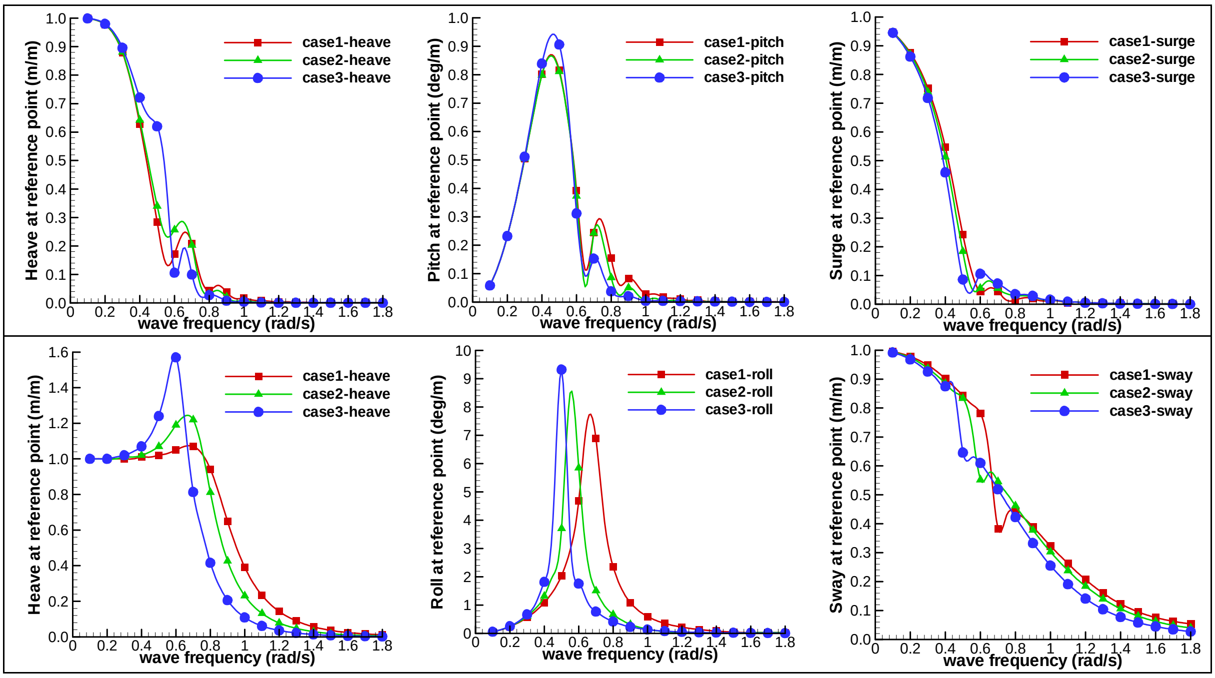



Fig. 4 Seakeeping characteristic in different loading conditions in head sea (top) and beam sea (bottom).

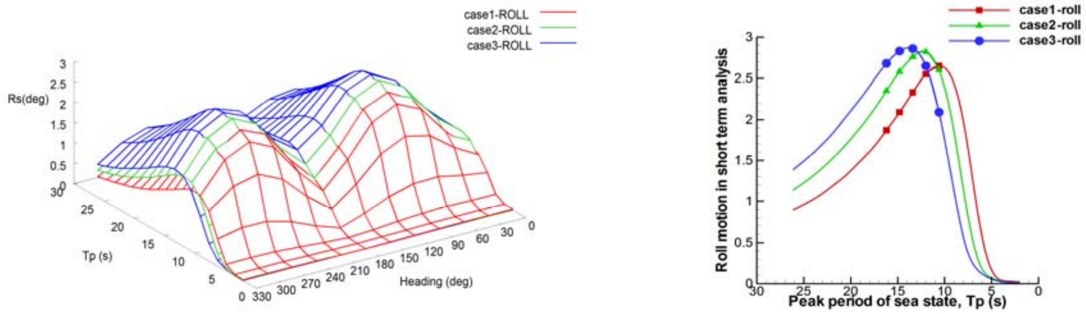



Fig. 5 Significant responses of roll motions in different wave incident angles (left); Roll motions take from left figure in 90 degree heading (right).

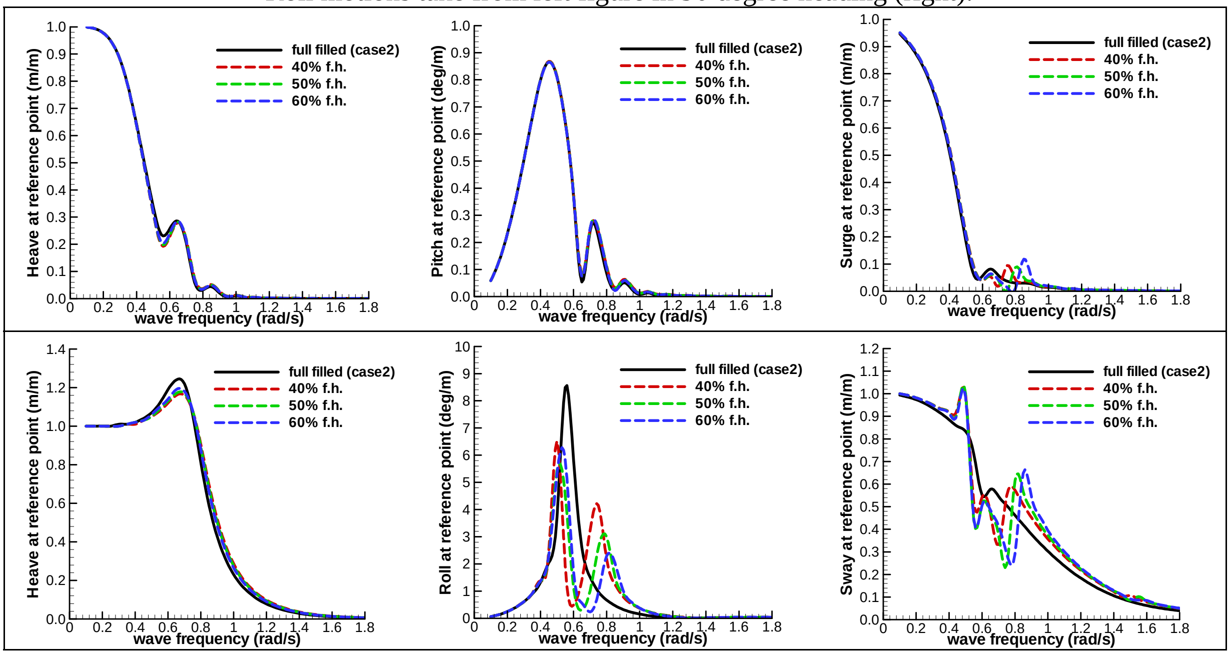



Fig. 6 Seakeeping characteristic for different filling heights tank in head sea (top) and beam sea (bottom).

Table 3 The 1st mode of sloshing natural frequency in tank transversal direction

| filling height | natural frequency |
|---|---|
| 40% | 0.6541 |
| 50% | 0.7125 |
| 60% | 0.7577 |

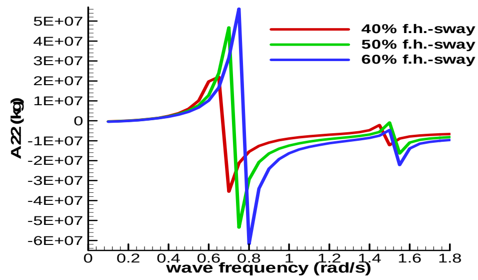



Fig. 7 The added mass in transversal direction

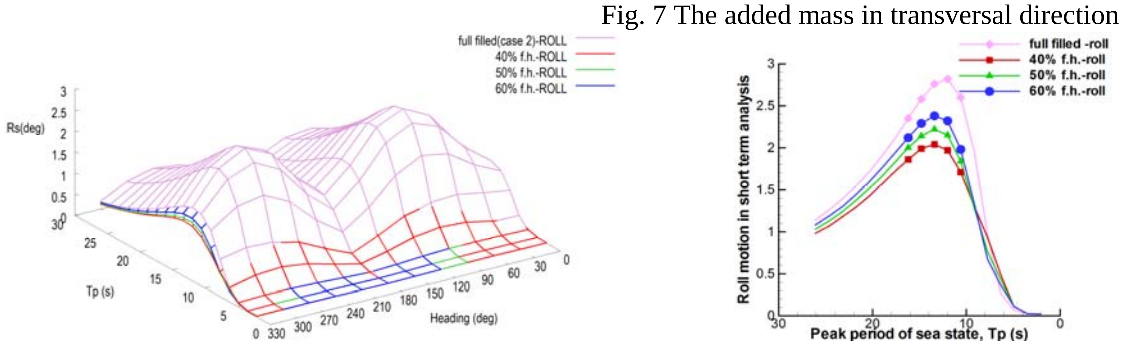



Fig. 8 Significant responses of roll motions with different sloshing effect in different wave incident angles (left); Roll motions take from left figure with different sloshing effects in 90 degree heading (right).