The Simulation of Ship Motion in Marine Environment

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Abstract. According to analyze the identity of ocean wave, the theory of wave energy spectrum was used to compute the wave elevation in some sea state. Based on establishing ship motion equations, the strip theory of the ship was used to simulate ship motion in different situation. The result showed the change of significant wave height badly influenced the amplitude of the ship motion, but it light influenced the periods of the ship motion. The change of degree of abaft the beam badly influenced the amplitude and periods of pitch, it mainly influenced periods of heave and amplitude of roll. The change of ship speed influenced the amplitude and periods of pitch, it mainly influenced periods of heave and roll.

Introduction

The work of protect the trade ocean route for Chinese navy will be more and more in the future. So Chinese navy ship will more and more cruise on the western Pacific Ocean and Indian Ocean. The wind and ocean wave of those areas are very strong. The Solid Rocket Motor (SRM) in ship will endure the loading which is caused by ship motion. How to compute the SRM's damage and evaluate its life caused by these loading have been an important research problem. (M. Xu, 2008, J.S. Xu, 2009)

It is the basic work to analyze the loading on SRM for damage calculation. Only exact prediction the ship motion, the life of SRM maybe evaluate which is difficult to solve. The ship strip theory is advanced (B. V. Korvin Kroukovsky, 1995, B.V. Korvin, 1957, W.Z. He, 1998), which is the available way to solve this problem. The ship strip theory is applied to simulate ship motion in different Navigation condition.

Research on Wave Spectra

Because real seas are never monochromatic, a statistical approach is needed to random seas. A common spectrum used is the Bretchneider Spectrum.

The Bretchneider Spectrum (C.L. Bretscheider, 1961) has the form:

$$S_\zeta(\omega)=\frac{1.25}{4}\frac{\omega_m^4}{\omega^5}H^2e^{-1.25\left(\frac{\omega_m}{\omega}\right)^4} \tag{1}$$

This spectrum requires two parameters, H is the significant wave, ω_m and is the modal frequency. For fully developed storms, the frequency is related to the significant wave height by the equation:

$$\omega_m=0.4\sqrt{\frac{g}{H}} \tag{2}$$

g Is the acceleration of gravity in the equation?

The energy density of the sea wave can be calculated by the equation:

$$E=\rho g\sum_{i=1}^{freq}\frac{A_i^2}{2}=\rho g\int_0^\infty S_\zeta(\omega)d\omega \tag{3}$$

ρ Is the sea density, and A_i is the wave amplitude in some frequency in the equation. It can be calculated by the equation:

$$A_i = \sqrt{2S_\zeta(\omega_i)\Delta\omega} \qquad (4)$$

Adding in a random phase angle, random seas may be simulated by:

$$\zeta(t) = \sum_{i=1}^{freg} A_i \cos(\omega_i t + \psi_i) \qquad (5)$$

An example of the record of a random sea in Sea State Five ($H = 7m$) is shown in figure 1. The sea state was generated using 500 discrete frequencies equally spaced from 0 to 2.5 radian/second, calculated every 0.01 seconds.

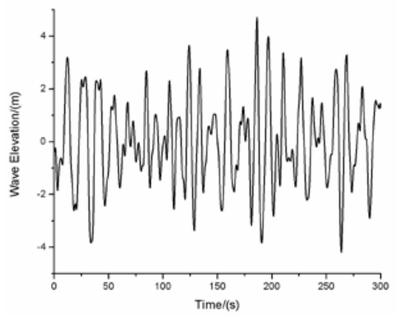

Figure 1. Fully developed Bretscheider spectrum for sea state seven

Ship Motion Model

In order to research on the ship motion, the ship coordinate need be established.

The Foundation of Ship Motion. In order to research on the ship motion in the sea wave, the two coordinates are usually applied as flowing. Both of the coordinates are right coordinates.

(1) Ship motion balance coordinate system $O - xyz$ .The center of gravity position is as origin of coordinate O, when the ship is balance motion. Ox coordinate axe is parallel with horizontal plane, and point to the ship motion. Oy coordinate axe and Oz coordinate axe are apeak. Oz coordinate axe is apeak with horizontal plane (shown in figure 2). The coordinate directions don't change, when the ship motion's speed is constant.

(2) Ship motion coordinate system $G - x'y'z'$. The center of gravity position is as origin of coordinate G, which is the same with ship motion balance coordinate system. Gx' coordinate axe lies in the endlong middle section, point to the ship heading. Oy coordinate axe is apeak with endlong middle section, and point to larboard. Gz' coordinate axe lies in the endlong middle section, point to the ship above (shown in figure 2).

(3)

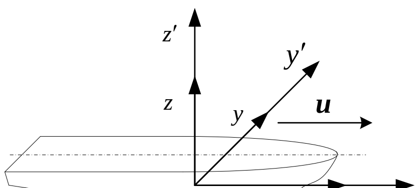

Figure 2. Ship motion balance and ship motion coordinate

Ship Motion Equations. The ship motion equations are established in the ship motion balance coordinate. The ship motion can decompound six species motion. The six motion are as flowing: surge, sway, heave, roll, pitch and yaw.

Note that η_1 is surge and was measured along the ship's centerline with positive forward, η_2 is sway and measured athwartships with positive starboard, and η_3 is heave with positive downwards. Looking into these axes, a positive rotation is counterclockwise. So roll η_4 is positive when the starboard side of the vessel is moving downward, pitch η_5 is positive when the bow is moving upwards, and yaw η_6 is positive when the bow is moving to starboard.

Most seakeeping analysis starts with the assumption that the motions of a ship are linear in nature. This a reasonable due to the small wave slopes experienced during most normal operating scenarios. The linearized seakeeping equations of motion for the six degrees of freedom may be written in short as (V.B. Scott, 2007):

$$\sum_{k=1}^{6}\left[\left(M_{jk}+A_{jk}\right)\ddot{\eta}_k+B_{jk}\dot{\eta}_k+C_{jk}\eta_k\right]=F_j e^{i\omega t} \qquad j=1,2,\cdots 6 \tag{6}$$

$$\mathbf{M}=\begin{bmatrix} m & 0 & 0 & 0 & mz_c & 0 \\ 0 & m & 0 & -mz_c & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & -mz_c & 0 & I_{44} & 0 & -I_{46} \\ mz_c & 0 & 0 & 0 & I_{55} & 0 \\ 0 & 0 & 0 & -I_{46} & 0 & I_{66} \end{bmatrix} \mathbf{A}=\begin{bmatrix} A_{11} & 0 & A_{13} & 0 & A_{15} & 0 \\ 0 & A_{22} & 0 & A_{24} & 0 & A_{26} \\ A_{31} & 0 & A_{33} & 0 & A_{35} & 0 \\ 0 & A_{42} & 0 & A_{44} & 0 & A_{46} \\ A_{51} & 0 & A_{53} & 0 & A_{55} & 0 \\ 0 & A_{62} & 0 & A_{46} & 0 & A_{66} \end{bmatrix} \mathbf{B}=\begin{bmatrix} B_{11} & 0 & B_{13} & 0 & B_{15} & 0 \\ 0 & B_{22} & 0 & B_{24} & 0 & B_{26} \\ B_{31} & 0 & B_{33} & 0 & B_{35} & 0 \\ 0 & B_{42} & 0 & B_{44} & 0 & B_{46} \\ B_{51} & 0 & B_{53} & 0 & B_{55} & 0 \\ 0 & B_{62} & 0 & B_{46} & 0 & B_{66} \end{bmatrix} \mathrm{C}=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & C_{33} & 0 & C_{35} & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & C_{53} & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Expanding the equations (6) with all coefficients in them shows a very interesting phenomenon. Because of the symmetrical zeroes in each matrix, the whole system divides into two sets of three coupled equations; one set consisting of surge, heave, and pitch, and the other set describing sway, roll, and yaw. This can further be simplified, as Salveson (N. Salveson, 1970) point out, by noting that the surge force and the surge response, are very small compared to the other forces and motions. The equations of motion for each fixed frequency are then:

$$\begin{aligned} &(M+A_{33})\ddot{\eta}_3+B_{33}\dot{\eta}_3+C_{33}\eta_3+A_{35}\ddot{\eta}_5+B_{35}\dot{\eta}_5+C_{35}\eta_5=F_3(t)e^{i\omega_e t} \\ &A_{53}\ddot{\eta}_3+B_{33}\dot{\eta}_3+C_{53}\eta_3+(I_{55}+A_{55})\ddot{\eta}_5+B_{55}\dot{\eta}_5+C_{55}\eta_5=F_5(t)e^{i\omega_e t} \end{aligned} \tag{7}$$

$$(I_{44}+A_{44})\ddot{\eta}_4+B_{33}\dot{\eta}_4+C_{44}\eta_4=F_4(t)e^{i\omega_e t} \tag{8}$$

The equations (7) and (8) are the heave, pitch and roll equations in some frequency. Solving these equations can get the ship motion in the regular sea wave.

Solving Ship Motion Equations. The coefficients of the equations are lied on the ship dimension, direction and speed. The ship basic parameters are shown in table 1.

Table 1. Main parameters of some navy ship

tonnage $\forall$	length L	beam D	baseline B	Max speed U
6000t	153m	14.6m	6m	30knot

According to solve the equation (8), it can be changed as transfer function:

$$RAOH(\omega_e)=\frac{\eta_4}{kA}=\frac{C_{44}}{\sqrt{\left(C_{44}-(I_{44}+A_{44})\omega_e^2\right)^2+B_{44}^2\omega_e^2}} \tag{9}$$

In the equation, $\tan(\alpha)=\dfrac{B_{44}\omega_e}{C_{44}-(I_{44}+A_{44})\omega_e^2}$. $F_4=kAC_{44}$, ω_e is the wave encounter frequency, $\omega_e=\omega-Uk\cos\beta$, k is the wave number. $k=\omega^2/g$, ω is the wave frequency.

According to solve the equation (7), it can be derivated as flowing:

$$\hat{\eta}_3=\frac{\hat{F}_3 S-\hat{F}_5 Q}{PS-QR} \qquad \hat{\eta}_5=\frac{\hat{F}_5 P-\hat{F}_3 R}{PS-QR} \tag{10}$$

$P=C_{33}-\omega_e^2(M+A_{33})+i\omega B_{33}$, $Q=C_{35}-\omega_e^2 A_{35}+i\omega B_{35}$, $R=C_{53}-\omega_e^2 A_{53}+i\omega B_{53}$, $S=C_{55}-\omega_e^2(I_{55}+A_{55})+i\omega B_{55}$.

According to solve the equation (10), the transfer functions of heave and pitch can be acquired. The $RAOS(\omega_e)$ and $RAOZ(\omega_e)$ can be calculated according to the equations (11) and (12):

$$RAOS(\omega_e)=\frac{\eta_3}{A} \tag{11}$$

$$RAOZ\left(\omega_e\right)=\frac{\eta_5}{kA} \tag{12}$$

In the equations, η_3 and η_5 separately express the real part of the $\hat{\eta}_3$ and $\hat{\eta}_5$

Solving Ship Motion. It is difficulty to solve ship motion transfer function directly, until the ship strip theory is advanced. The software of Maxsurf was applied to solve the function, which is based on ship strip theory.

Firstly the ship model was established by the software, the main parameters of some navy ship are shown in Table 1. The model are shown in Fig.3.

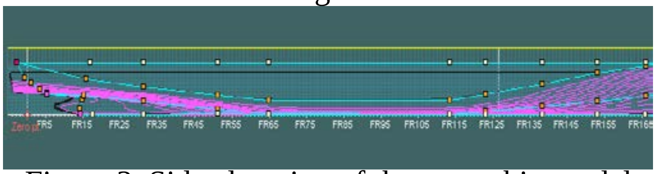

Figure 3. Side elevation of the navy ship model

After the model was established, the data of ship shape can be created by simulation. The data file can be imported to the SeaKeeper module of Maxsurf. The number of the ship strip is thirty. The ship was set to a speed of 14 knots, traveling in Sea State Five with seas 135 degrees abaft of the beam. The simulation results of the roll, pitch and heave's transfer function are shown in Fig.4.

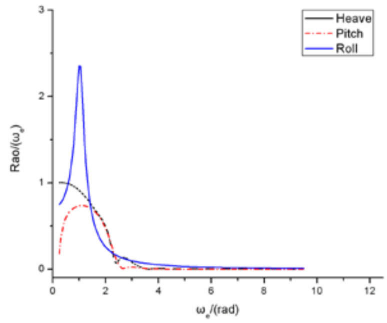

Figure 4. Amplitude-frequency response under some seakeeping scenario

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Acceding to curve of the roll, pitch and heaves transfer function, the motions expressions can be calculated:

$$\eta_3(t)=\sum_{i=1}^{freq}A_i RAOS(\omega_{ei})\cos(\omega_{ei}t+\varphi_m) \quad ; \quad \eta_4(t)=\sum_{i=1}^{freq}A_i k_i RAOH\left(\omega_{ei}\right)\cos(\omega_{ei}t+\alpha_i) \qquad \eta_5(t)=\sum_{i=1}^{freq}A_i k_i RAOZ(\omega_{ei})\cos(\omega_{ei}t+\psi_i)$$

(14)

Significant Wave Height Effect on the Ship Motion. The curve of roll, pitch and heave vs. time can be acqured in significant wave height, which are shown in Fig.5.

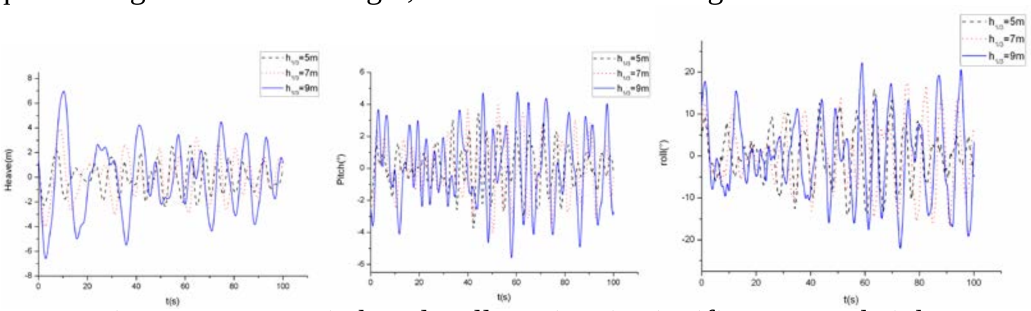

Figure 5. Heave Pitch and Roll vs. time in significant wave height

The simulation figure is shown: Change the beam degree effect on the heave's, pitch's and roll's amplitude and period.

The Shipping Degree Effect on the Ship Motion. The curve of roll, pitch and heave vs. time can be acqured in different shipping degrees, which are shown in Fig.6.

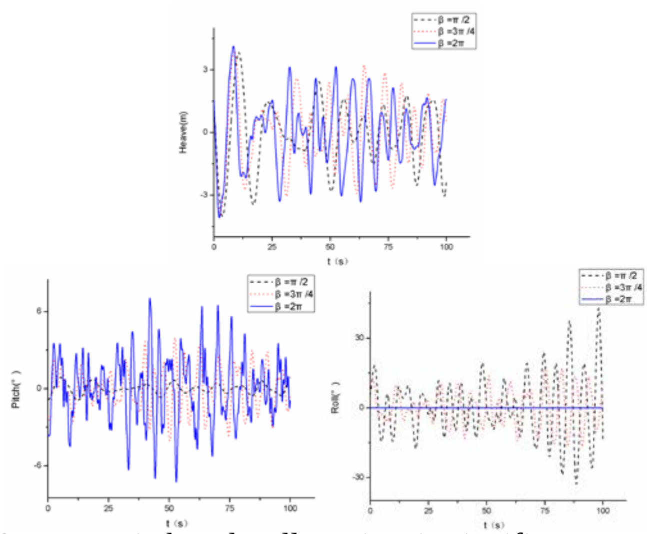

Figure 6. Heave Pitch and Roll vs. time in significant wave height

The simulation figure is shown: Change the beam degree effect on the pitch's amplitude and period, heave's period and roll's amplitude.

The Shipping Speed Effect on the Ship Motion. The curve of roll, pitch and heave vs. time can be acquired in different shipping degrees, which are shown in Fig.7.

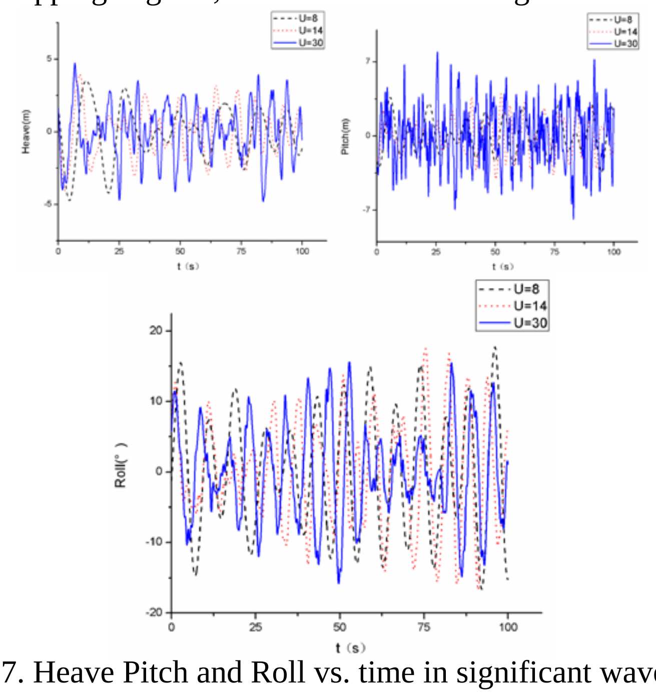

Figure 7. Heave Pitch and Roll vs. time in significant wave height

The simulation figure is shown: Increase the shipping speed can make heave and roll's period shorten. These can make pitch's amplitude increase and period shorten.

Summary

According to the ship strip theory, the ship motion laws in different navigation conditions are researched. The conclusion can be summarized as flowing:

1) The change of significant wave height badly influenced the amplitude of the ship motion.

2) The beam degree effect different on ship three motion (heave, pitch and roll). Changing the beam degree effects on the pitch's amplitude and period, heave's period and roll's amplitude.

3) The shipping speed effect different on ship three motion (heave, pitch and roll). Increase the shipping speed can make heave and roll's period shorten. These can make pitch's amplitude increase and period shorten.

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