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Numerical simulation of wave loads over a large container ship on mooring state

锚泊状态下大型集装箱船波浪载荷的数值模拟

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Abstract –**In this paper, the mooring dynamic loads and the motion responses of a large container ship in irregular waves with steady wind and current is investigated based on the commercial software AQWA. Comparisons between the time-history motion responses of a large container ship and the change of the mooring line tension in three different cases, non-mooring case, V-type mooring case and I-type mooring case are discussed. The result shows that there is a long-period surge and sway motion response to the large container ship because of two-order drift loading, and the two-order drift loading has a strong effect on the response of large container ship system because of close low frequency between ship and wave. Both I-type mooring case and V-type mooring case can obviously reduce the surge and sway caused by second-order drift loading in typical sea conditions; conditions that each mooring line carries too much stress can be avoided by changing the mooring configuration in sea conditions. As expected, the relevant feature can provide a valuable base for the analysis of large container ships mooring in typical sea conditions.**

Keywords –**Second-order drift loading, mooring line tension, motion responses.**

I. INTRODUCTION

Recently, with the development of global ship transport, it has been a tendency to build larger container ship. Under this condition, the safety of large ship becomes an important research subject. Especially on mooring state, if the ship bears high environmental loading, it’s highly possible to be an accident caused by insufficient strength of mooring lines.

Researches on ship motion response of large ship on mooring state and the tension of mooring line are very difficult. The typical ship motion response of large container ship on mooring system not only includes first-order response which has the same frequency as the wave, but also contains two-order drift response. Even though the value of the two-order drift force is much smaller than the first-order force, it has a strong effect on the response of the large container ship system because of close low frequency between ship and wave (Dai and Duan, 2008). As the horizontal restoring force is very small, the natural oscillation periods long, which may leads to the resonance with low-frequency wave force. Wanget al (2007) used SESAM to analyze the static force and dynamic force of ship on SPM (single point mooring) state. After calculating different combinations of wind, wave and current, they found that on SPM state the tension of mooring line is very sensitive to the variation of wind and current while the surge and sway of ship has the biggest influence on the tension of mooring line.

The time-domain 3-D potential theory and segmental catenary theory have been used and the simulation model of the mooring system has been set up. Under the typical environmental condition, the motion response and tension of mooring line are analyzed under two different mooring states to get the curves of time-domain motion response of large container ship and tension of the mooring line over time, which can be a reference for the mooring of similar ships.

II. CALCULATION PROCESS AND BASIC THEORY

Calculation Process

The computations are carried out based the ANSYS-AQWA following the process illustrated in Fig.1. Firstly, the 3-D potential theory is used to calculate first-order, second-order wave loading, added mass and radiation damping caused by wave radiation and diffraction. Then the tension of the mooring line is carried out using the elastic catenary method. Under typical ocean environmental condition, the tension of the mooring line and the time-domain motion response with coupling of large container ship and the mooring lines are analyzed to obtain motion statistics and maximum.

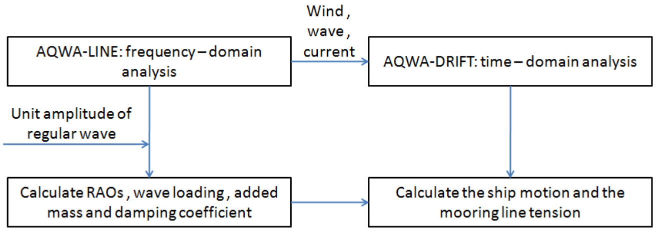


Fig.1 Calculation Process.

Basic Theory

Frequency-domain and Time-domain Motion Response Equation

The frequency domain analysis is carried out for regular waves of unit. Laplace’s equation [*L*] is used as the governing equations. Boundary conditions are set up for lineared free surface boundary condition[*F*], the impenetrable body surface condition[*S*], the bottom condition at depth h [B] and the radition condition at infinity[*R*], as shown in Eq.(1).

$$\begin{array}{ll} [L] & \nabla^2\Phi(x,y,z,t)=0,\ \text{In the fluid domain} \\ [F] & \dfrac{\partial^2\Phi}{\partial^2 t}+g\dfrac{\partial\Phi}{\partial z}=0,\ \ z=0 \\ [S] & \dfrac{\partial\Phi}{\partial n}=U_j n_j,\quad \text{at object plane} \\ [B] & \dfrac{\partial\Phi}{\partial n}\Big|_{z=-h}=0 \quad \text{or} \quad \lim\limits_{z\to-\infty}\nabla\Phi=0 \\ [R] & \text{infinity radiation condition} \end{array} \tag{1}$$

The total potential function in Eq. (1) can be expressed as follows:

$$\Phi(x,y,z,t)=\phi(x,y,z)e^{-i\omega t}=\left[(\phi_I+\phi_d)+\sum_{j=1}^{6}\phi_j x_j\right]e^{-i\omega t} \tag{2}$$

where ϕ_I: incident potential function,

ϕ_d: radiation potential function,

ϕ_j: velocity potential function caused by motion in j direction,

x_j: motion response in j direction and

ω: incident wave frequency.

Through frequency-domain calculation, the RAOs of structure under unit wave loading are obtained using Eq. (3) as follows:

$$[-\omega^2(M_s+M_a(\omega))-i\omega B+K]X(\omega)=F(\omega) \tag{3}$$

$$RAO=\frac{X(\omega)}{A} \tag{4}$$

where A: wave amplitude,

M_s: ship mass matrix,

M_a: added mass matrix,

B: damping matrix ,

K: hydrostatics stiffness matrix,

F: wave excitation vector and

X: motion response vector.

Time-domain motion equation is shown as follows:

$$M_s\ddot{X}(\mathrm{t})=F(\mathrm{t}) \tag{5}$$

F(t) refers to the total force action on float body, including the forces caused by wind, wave, current and the mooring lines.

Through impulse response method, the convolution integral form is as follows:

$$[M_s+M_a]\ddot{X}(\mathrm{t})+KX(t)+\int_0^t h(t-\tau)\dot{X}(\tau)d\tau=F(\mathrm{t}) \tag{6}$$

Calculation of Second-order Wave Exciting Loading

The near field solution of second-order wave exciting force is as follows (Pinkster,1980):

$$F_{\mathrm{strc}}^{(2)}=\sum_{i=1}^{N}\sum_{J=1}^{N}\left\{P_{ij}^{-}\cos[-(\omega_i-\omega_j)t+(\varepsilon_i-\varepsilon_j)]+P_{ij}^{+}\cos[-(\omega_i+\omega_j)t+(\varepsilon_i+\varepsilon_j)]\right\}$$
$$+\sum_{i=1}^{N}\sum_{J=1}^{N}\left\{Q_{ij}^{-}\sin[-(\omega_i-\omega_j)t+(\varepsilon_i-\varepsilon_j)]+Q_{ij}^{+}\sin[-(\omega_i+\omega_j)t+(\varepsilon_i+\varepsilon_j)]\right\} \tag{7}$$

Where P_{ij} and Q_{ij} are the in-phase and out-of-phase components of the time independent transfer function.

Supposing the sum frequency contribution can be ignored, the equation above becomes:

$$F_{\mathrm{strc}}^{(2)} = \sum_{i=1}^{N}\sum_{J=1}^{N}\left\{P_{ij}^{-}\cos[-(\omega_i-\omega_j)t+(\varepsilon_i-\varepsilon_j)]\right\} + \sum_{i=1}^{N}\sum_{J=1}^{N}\left\{Q_{ij}^{-}\sin[-(\omega_i-\omega_j)t+(\varepsilon_i-\varepsilon_j)]\right\} \tag{8}$$

where ω_i and ω_j are the frequencies of each pair of waves, a_i and a_j are the corresponding amplitudes, ε_i and ε_j are the radiation phase angles.

According to Newman (1974):

$$P_{ij}^{-} = \frac{1}{2}a_i a_j\left(\frac{P_{ii}^{-}}{a_i^2}+\frac{P_{jj}^{-}}{a_j^2}\right), Q_{ij}^{-} = 0 \tag{9}$$

Thus Eq. (8) can be simplified to:

$$F_{\mathrm{sv}}(t) = \sum_{i=1}^{N}\sum_{j=1}^{N}\left\{P_{ij}^{-}\cos[-(\omega_i-\omega_j)t+(\varepsilon_i-\varepsilon_j)]\right\} \tag{10}$$

III. COMPARISON BETWEEN EXPERIMENTAL DATA AND NUMERICAL SIMULATION

Before using AQWA to analyze the problem, it’s necessary to certify the validity of the theory. In this section, two cases are used to exam the theory. One is a mooring box-type floating breakwater case (Dong et al, 2009), and the other is a three anchors buoy system (Miao et al, 2003).

Experiment Parameter

CASE ONE

The box-type floating breakwater mooring system is composed of four mooring lines. The main geometrical parameters are listed in Tab. 1. The model is built in the AQWA-Line, shown as Fig.2.

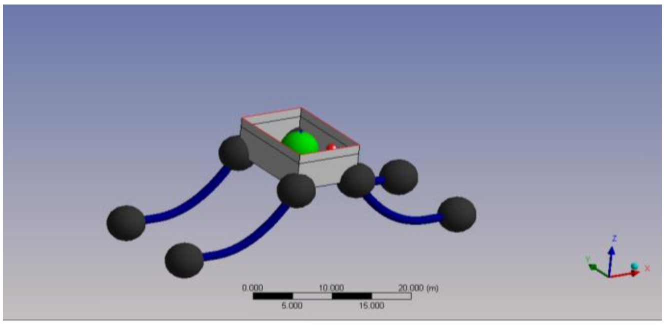


Fig.2 Box-Type Floating Breakwater System.

Table 1. The principal dimensions of floating breakwater system.

Name	Parameter	Value
Breakwater	Wide /m	0.3
	Moulded depth T/m	0.18
	Designed draft T/m	0.135
	Scale Ratio /m	1/30
Mooring line	Length/m	13.0

CASE TWO

The buoy system is composed of three parts: buoy, pontoon and the mooring lines. The main geometrical parameters and wave parameters are listed in Table 2 and Table 3, respectively. According to the offsets of the buoy system, the model is built and meshed which is shown as Fig.3:

Table 2. The geometrical characteristics of buoy system.

Item	Parameter	Value
Buoy	Diameter D_1 /m	10.0
	Depth T /m	2.2
	Designed draft T /m	1.00
	Mooring point height /m	0.72
Pontoon	Diameter D /m	3.4
	Height H /m	1.62
	Mass M /kg	5000
Mooring line	Short anchor chain length /m	37.5
	Long anchor chain length /m	165.0
	Overall length/m	202.5

Table 3. Wave parameters.

Wave direction /°	180
Wave height /m	4.0
Period /s	1.98

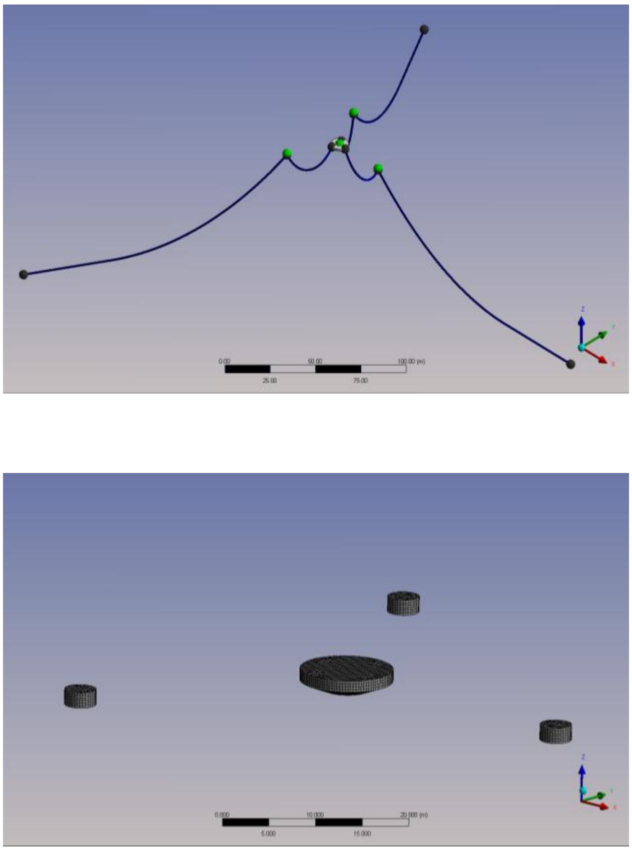


Fig.3 Buoy Displacement and Mesh.

Result Analysis

Comparison between experiment and numerical calculation of box-type floating breakwater and buoy motion response and mooring line tension, are listed in Tab.3 and 4, respectively. The tested and simulation results of the box-type floating breakwater system and the buoy system are shown in Fig.4 and 5. The comparison shows that the calculation results agree well with experiments. This indicates that modeling errors and settings of parameter, when using the software, are acceptable and the simulation method is feasible and reliable.

Table 4. Comparison between tested and simulation results of Box-Type Floating Breakwater System.

Period(s)	Calculated	Experimental	Error
5	0.85	0.77	10.39%
6.028	0.85	0.9	5.56%
7.0144	0.99	1	1.00%
7.99	0.95	0.79	20.25%
8.49	0.88	0.81	8.64%

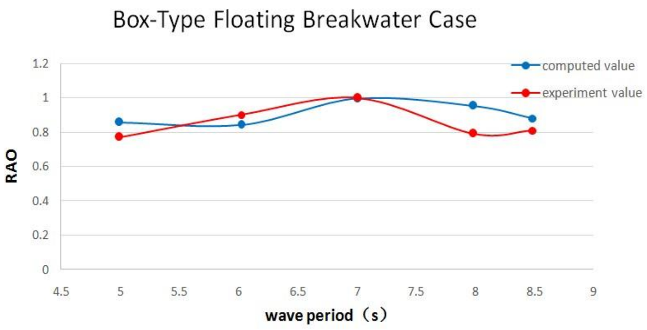


Fig.4 Box-Type Floating Breakwater System.

Table 5. Comparison between tested and simulation results of Buoy system in head waves.

item	measured value 1	measured value 3	surge	heave	pitch
Simulation result	0.729	1.666	3.58	1.87	9.05
Tested result	0.687	1.57	3.48	1.82	8.5
Relative error	6.10%	6.10%	2.9%	2.7%	6.50%

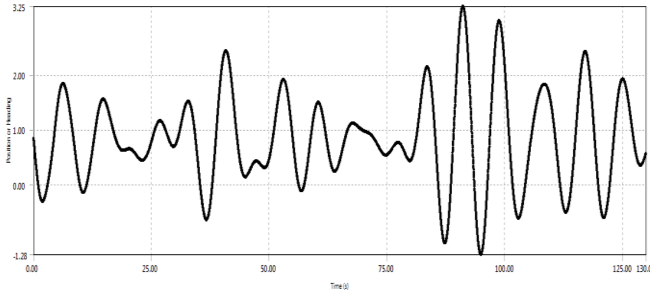


Fig.5 Time History of Buoy Heave Motion Response.

IV. MOORING MODEL OF LARGE CONTAINER SHIP

In this paper, three different cases are considered, i.e., non-mooring case, V-type mooring case and I-type mooring case. The time-history motion responses and the changes of the tension of the mooring line are calculated. The mesh and displacement of fairlead are shown as Fig. 6, 7 and 8. Parameters of environmental condition and the mooring lines are as Tab. 6 and 7.

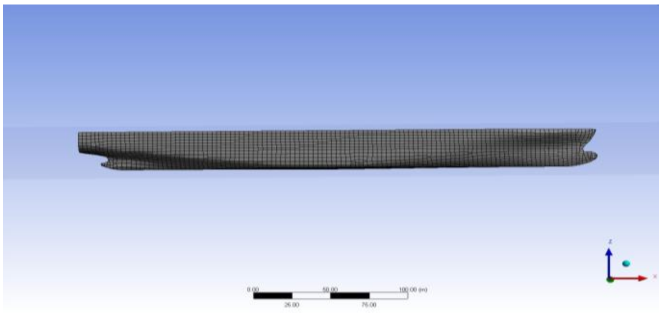


Fig.6 Mesh.

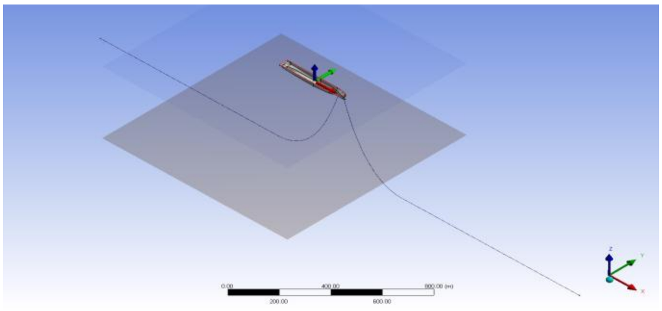


Fig.7 I-type mooring case.

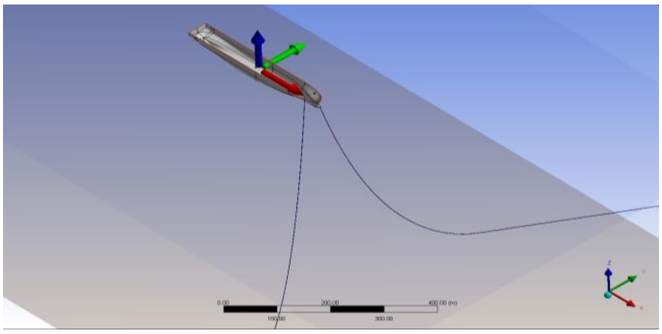


Fig. 8 V-type mooring case.

Table 6. Wave, wind & current parameters .

parameter		value
wave	Significant wave height /m	6.75
	Zero-crossing period /s	8.38
wind	Speed /m·s^{-1}	20
current	Velocity /m·s^{-1}	0.5
Angle between ship and wave, wind and current /°		180°& 145°

Table 7 mooring line parameters .

Line	Item	Value
	Number	2
	Overall length /m	1600
Section 1	Length /m	400
	Diameter /mm	108
	Unit weight/kg·m^{-1}	150
	Stiffness EA/N	600000000
	Max tension /N	7500000
Section 2	Length /m	500
	Diameter /mm	108
	Unit weight/kg·m^{-1}	120
	Stiffness EA/N	600000000
	Max tension /N	7500000
Section 3	Length /m	700
	Diameter /mm	108
	Unit weight/kg·m^{-1}	170
	Stiffness EA/N	600000000
	Max tension /N	7500000

V. TIME-DOMAIN ANALYSIS OF LARGE CONTAINER SHIP ON MOORING STATE

Wave Condition of Head Sea (The angel between Ship and wave, wind, current is 180 degree.)

Analyzing the effect of second-order drift loading on large container ship, the motion response and the tension of the mooring line on different mooring state in typical environmental condition are obtained. The comparisons are shown as Fig. 9, 10 and 11. The results are listed in table 8.

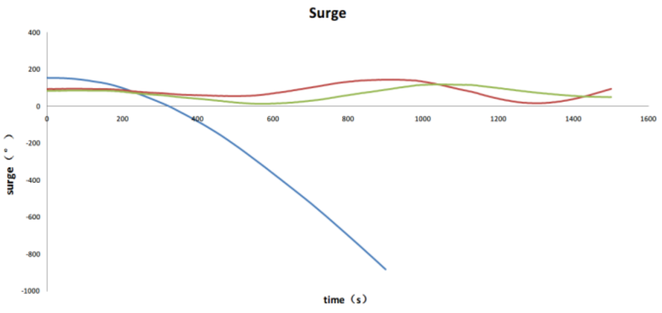


Fig.9 Ship Motion.

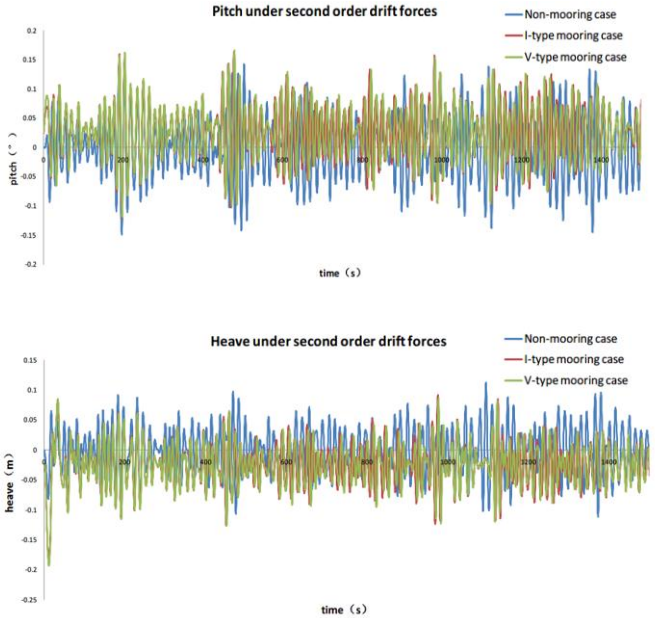


Fig.10 Ship Motion under Second Order Drift Force.

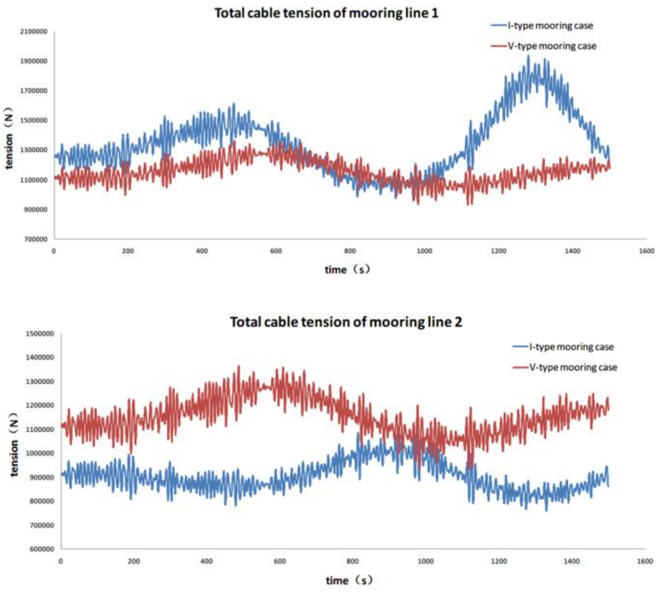


Fig.11Mooring Line Tense

Table 8 Significant results under 180°.

	Non-mooring case	I-type mooring case	V- type mooring case
Surge /m		34	45
Heave /m	0.443	0.444	0.441
Pitch /°	0.546	0.579	0.575
Heave under second order drift forces/m	0.055	0.027	0.026
Pitch under second order drift forces/°	0.059	0.094	0.095
Tension(line 1)/N		1760062	1240864
Tension(line 2)/N		1034329	1240222
Tension(line 1 section)/N		988000	437225
Tension(line 2 section)/N		232206	361698

Through the comparison we can get:

(1) As shown in Fig.9 and Tab.8, there is the long-period surge motion response of large container ship caused by two-order drift loading. Both of the two kinds of mooring ways can reduce the surge of ship, but I-type mooring case performs better relatively.

(2) According to Tab. 8, in head seas condition, there are almost no differences between the heave and the pitch motion whether the ship moors.

(3) In Fig.10 and Tab. 8, the influence of second-order drift loading plays nearly 10 percent proportion in motion responses on non-mooring state . V-type and I-type mooring case can obviously reduce the heave motion caused by second-order drift loading while increase the pitch about 5%.

(4) As shown in Fig.11 and Tab.8, in head seas condition, the tension of the mooring line is below the safety standard. However, the difference between two mooring line is relatively great in the I-type mooring case. It has a good chance that the dragging will happen.

It may be concluded that in head sea conditions, the V-type mooring case performs better.

Wave Condition of Bow Sea (The angel between Ship and wind, wave, current is 145 degree.)

Under the condition of bow sea, 145 degree, the comparisons of the motion response and the tension of the mooring line are as Fig.12, 13, 14 and 15. The results are listed in Tab. 9.

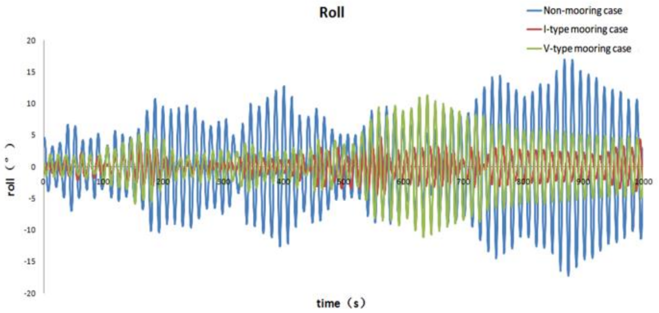


Fig.12 Ship Motion (roll).

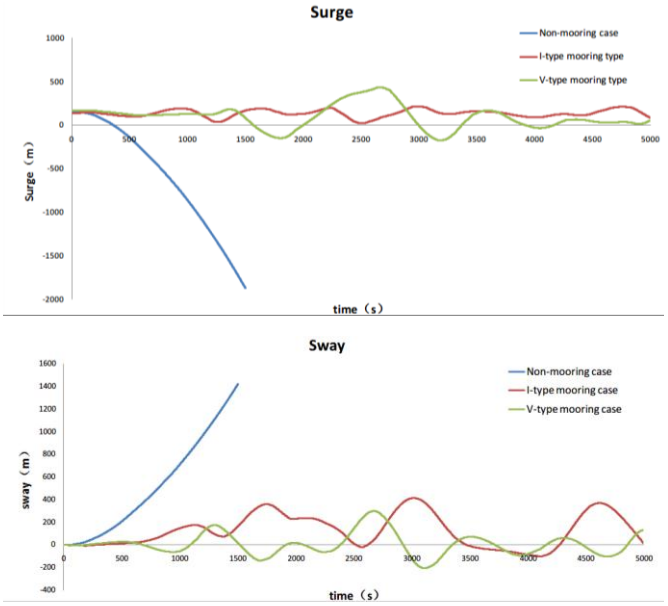
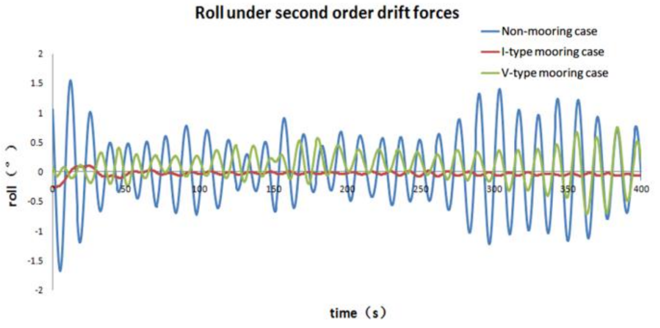


Fig.13 Ship Motion (surge and sway).



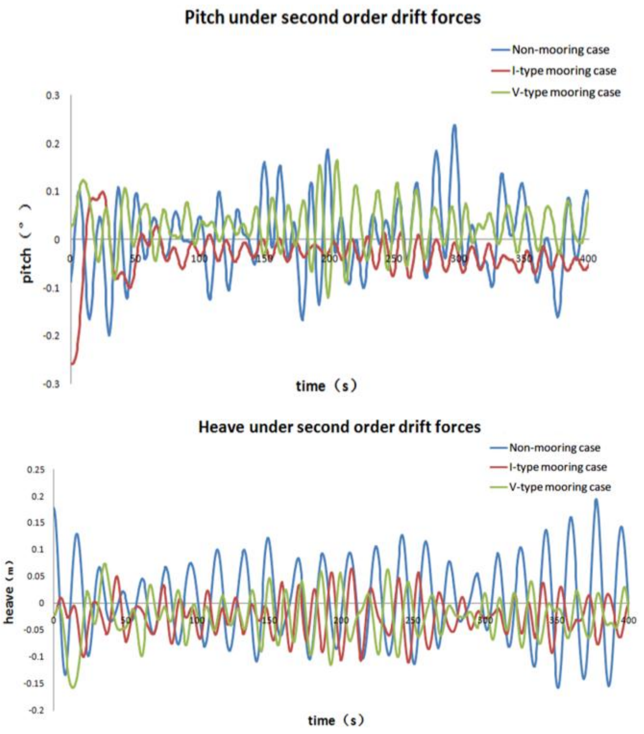


Fig.14 Ship Motion under Second Order Drift Force.

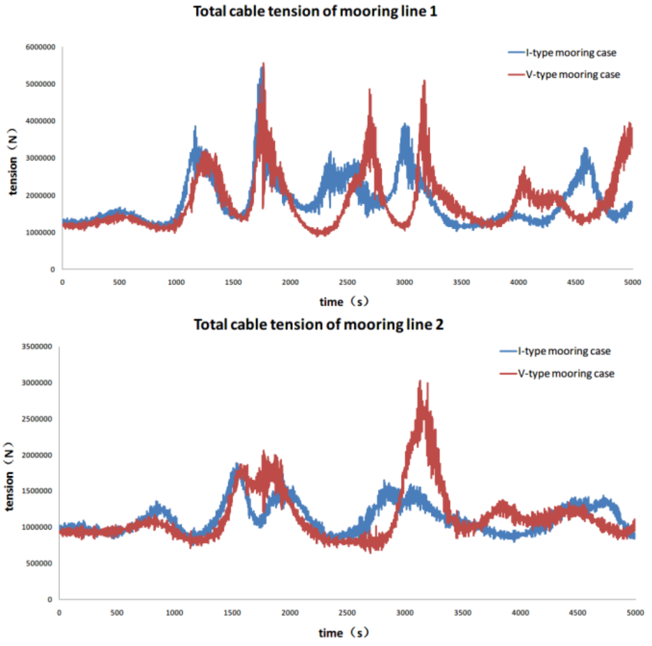


Fig.15 Mooring Line Tense.

Through the comparison it can be observed that:

(1) According to Fig.12 and Tab.9, in bow seas condition, there is an obvious roll, so the I-type mooring case and V-type mooring case can both provide some restoring force to the ship, reducing the roll effectively. However, through the comparison of the data, it can be found I-type mooring case performs better.

Table 9 Significant results under 145°.

	Non-mooring case	I- type mooring case	V- type mooring case
Surge /m		45	69
Sway /m		228	167
Heave /m	0.485	0.485	0.497
Roll /°	12.848	3.159	5.349
Pitch /°	0.846	0.650	0.661
Heave under second order drift forces/°	0.106	0.031	0.034
Roll under second order drift forces/°	1.573	0.1ome15	0.129
Pitch under second order drift forces/°	0.177	0.105	0.107
Tension (line 1)/N		2610385	2643026
Tension (line 2)/N		1381797	1551427
Tension/N (line 1section)		1878906	1911516
Tension/N (line 2 section)		590118	767629

(2) By comparing the influence of I-type mooring case and V-type mooring case on ship motion response, it's obvious that I-type mooring case performs better on reducing surge but worse on sway which are all caused by second-order drift force. The effectiveness depends on the angel between the mooring line and environmental loadings, i.e., wave, wind, current loadings.

(3) The loading conditions are almost the same between I-type mooring case and V-type mooring case. As the angle between environmental loadings and each mooring line is different in both two ways, there is always one mooring line carrying larger force than the other one in both two ways.

It can be concluded that in bow seas condition, the best mooring way depends on the specific conditions.

VI. CONCLUSION

In this article, a tentative conclusion is reached that the container ship motion response and the tension of the mooring line on two different mooring states in two different environmental conditions, 180/145 degree between the ship and wind, wave and current.

The results are as follows:

(1) Both I-type mooring case and V-type mooring case can dramatically reduce the surge and sway caused by second-order drift loading in head sea and bow sea conditions compared with non-mooring case.

(2)Results show that the second-order drift loading in our study case plays nearly 10 percent proportion in motion responses on non-mooring state. Its impact on the ship can be highly reduced on mooring state.

(3) According to Tab.8 and Tab.9, it can be learned that when the angle between the two mooring lines is large, it can effectively restrict the ship movement in one direction (for example, I-type mooring case in both cases can effectively limit the surge motion of the ship), but also easily lead to one mooring line carries much higher environmental loading. In order to ensure the safety of the mooring line it is important to come up with an appropriate mooring way to avoid the condition that one of the mooring lines to bear too much force.

VII. ACKONWLEDGMENTS

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