To cite this article: HUA K, ZHAO W B, WU D F. Sea states effects on fatigue damage of large ship prone to springing effect [J/OL]. Chinese Journal of Ship Research, 2021, 16(6). http://www.ship-research.com/EN/Y2021/V16/I6/176.

DOI: 10.19693/j.issn.1673-3185. 02134

Sea states effects on fatigue damage of large ship prone to springing effect

HUA Kang[*], *ZHAO Wenbin, WU Dingfan*

Shanghai Merchant Ship Design and Research Institute, Shanghai 201203, China

Abstract: [**Objectives**] This paper aims to study the fatigue damage problem of large ships prone to the springing effect. [**Methods**] The tested fatigue damage of two-generation 400 000 DWT very large ore carriers (VLOCs) is compared by the ship model test method, and the relationships of sea states and fatigue under the springing of hull girders are analyzed. According to the recursion method, a classical sea state is selected from a series of model test sea states. [**Results**] The results show that the fatigue damage magnification effect has trend relationships with significant wave height and encounter period. The concept of "dominant sea state" is proposed by the inductive recursion method, and the formula of the fatigue damage magnification factor is improved. The springing effect varies significantly according to different sea states, and the fatigue damage magnification effect of wave-induced loads increases very rapidly as significant wave height and encounter period decrease. [**Conclusions**] Replacing multiple typical sea states with a dominant sea state could allow a relatively accurate fatigue damage magnification factor to be ascertained rapidly. As such, this paper can provide references during the initial design period.

Key words: ship structure; springing; fatigue; ship model test

CLC number: U661.4

0 Introduction

The springing of large ore carriers has attracted attention from researchers since the 1960s. As the needs of global shipping constantly grow, ships have become larger and more specialized. Due to the increases in ship size and load capacity, the proportion of high-strength steel rises, which makes ships structures relatively flexible and their natural frequencies much lower than those of regular ships. As a result, the springing effect intensifies obviously, and its influence on the fatigue of hulls cannot be ignored.

Generally, ship springing refers to the continuous vibration of hulls when the excitation frequencies of waves encountered by ships are close to the natural frequencies of hull girders. According to further research, springing also occurs when wave excitation frequencies are n or $1/n$ times of the natural frequencies of hull girders (n is a positive integer). This is generally called a multi-frequency or sub-frequency response.

Springing usually happens to large ships with low natural frequencies (less than 0.5 Hz) and high speeds (more than 20 kn) and is mainly in bending and torsional modes. It is commonly seen on large container ships with large openings. Due to their low cross-sectional moments of inertia and large ratios of length to molded depth, very large ore carriers (VLOCs) have low vertical natural frequencies and are thus prone to springing too. The above-mentioned phenomenon has been confirmed by both real VLOC monitoring and ship model tests[1]. Since fatigue loads of ship structures increase obviously under continuous vibration of hull girders caused by springing, springing has become a problem to which due attention should be paid in the current design of large ships.

Received: 2020－10－05 **Accepted**: 2020－12－22

Supported by: High-tech Ship Research Program of the Ministry of Industry and Information Technology ([2017]614)

Authors: HUA Kang, male, born in 1983, master's degree, senior engineer
ZHAO Wenbin, male, born in 1982, master's degree, senior engineer
WU Dingfan, male, born in 1982, senior engineer

***Corresponding author**: HUA Kang

At present, the springing of large ships is mainly studied through numerical calculation, ship model tests, and model-ship comparisons. Safety of ship structures can be guaranteed by using these methods as needed in ship design. By research, Cleary et al. [2] found that springing-induced fatigue damage was the dominant factor for VLOC fatigue problems. Lewis[3] was the first to propose a "multi-section ship model" and used it to measure wave-induced bending moment. This method was used to evaluate the springing effect by Dudson et al.[4] in 2001. According to their test results, fatigue damage caused by wave-induced loads accounts for 30%−45% of the total damage in the case of head sea, while that in the cases of beam and following seas is small. Considering the difficulty in accurately predicting the nonlinear motion response of ships through numerical analysis, Storhaug et al. [5] analyzed the springing effect experimentally. Moreover, they carried out engineering applications and developed a complete evaluation system. By monitoring 18 000−255 000 DWT bulk carriers, Moe et al. [6] verified the gain effects of the additional springing-induced fatigue stress on traditional wave-induced loads in the hull fatigue strength. Moreover, a standard formula was developed through regression of relevant data by the response matrix method to serve as a reference for the fatigue strength design of ships of the same scale. Wang et al. [7] also studied the influence of hull-girder stiffness on springing experimentally. From their studies, large ships are of relatively low stiffness and are thus more likely to be affected by springing during navigation.

The ship model test is another reliable method in ship design to simulate the influence of sea states on wave-induced loads. However, constrained by test periods and costs, ship model tests generally use representative combinations of sea states and speeds with large contributions to fatigue damage as typical test conditions. Comparison between test results and real-ship data shows that results under typical test conditions can truly reflect the actual states of ships during navigation.

Taking the two generations of 400 000 DWT VLOCs designed by Shanghai Merchant Ship Design & Research Institute (SDARI) as the research object, this paper carried out model tests of springing to analyze the relationships of springing-induced fatigue damage with sea-state factors such as significant wave height H_s and encounter period T_e. Moreover, by inductive recursion, the paper determined dominant sea states among many typical test conditions to replace complicated typical test conditions and thereby truthfully reflect springing with short test periods and low costs. This also provides a method of evaluating predicted wave-induced loads and fatigue damage at the initial stages of design.

1 Ship model test

1.1 Test scheme

Input conditions of a model test mainly include hull form, natural frequency of the hull girder, cross-sectional moment of inertia of hull girder, and test sea states. The hull form, natural frequency, and moment of inertia can be provided directly at the initial stages of design and are thus not discussed here. This paper focuses on the selection of sea states for test schemes.

Sea states are defined in light of the global spectral wave climate atlas. However, a complete wave climate map shows multifarious sea states, and it is thus impractical in terms of the test period and cost for model tests to cover all those states. Therefore, the test sea states selected in this paper are defined by several typical short-term sea states composed of significant wave height H_s and zero-crossing period T_z. Specifically, sea-state selection should ensure that the fatigue damage under all actual sea conditions is covered as much as possible by limited typical sea states, also known as the principle of maximum contribution to fatigue damage. As the numerical calculation is adopted to predict springing during the selection of typical conditions, engineering experience from previous tests is necessarily drawn on for adjustment.

According to the numerical calculation results, the typical sea states selected in this paper are a 4 × 4 matrix composed of H_s = 2.5, 4.5, 6.5, and 8.5 m and T_z = 7, 9, 11, and 13 s. The occurrence probability of this group of typical sea states in wave climate maps is about 39%. However, the corresponding fatigue damage of a ship in a ballast condition can reach 89% of the calculated value under all sea states, and that under a full-load condition takes a similar proportion. This indicates that ships are prone to fatigue damage under the selected typical sea states. In this paper, the simulation of most of the damage is achieved with various short-term sea states, which means these states are highly representative and thus meet test requirements.

Tables 1 and 2 present the 16 typical sea states for two generations of 400 000 DWT VLOCs and their corresponding speeds respectively.

Table 1 Sea states for two generations of 400 000 DWT VLOCs

No.	First generation		Second generation	
	H_s/m	T_z/Hz	H_s/m	T_z/Hz
1	2.5	7.5	2.5	7
2	2.5	9.5	2.5	9
3	2.5	11.5	2.5	11
4	2.5	13.5	2.5	13
5	4.5	7.5	4.5	7
6	4.5	9.5	4.5	9
7	4.5	11.5	4.5	11
8	4.5	13.5	4.5	13
9	6.5	7.5	6.5	7
10	6.5	9.5	6.5	9
11	6.5	11.5	6.5	11
12	6.5	13.5	6.5	13
13	8.5	7.5	8.5	7
14	8.5	9.5	8.5	9
15	8.5	11.5	8.5	11
16	8.5	13.5	8.5	13

Table 2 Speeds of two generations of 400 000 DWT VLOCs

No.	Speed of the first generation/kn		Speed of the second generation/kn	
	Ballast	Full load	Ballast	Full load
1	14.5	14.5	15.4	14
2	14.5	14.5	15.4	14
3	14	14	15.4	14
4	14	14	15.4	14
5	12	12	13	12
6	12	12	13	12
7	11	11	13	12
8	11	11	13	12
9	9	9	11	10
10	9	9	11	10
11	8	8	11	10
12	8	8	11	10
13	6	6	8	7.3
14	6	6	8	7.3
15	5	5	8	7.3
16	5	5	8	7.3

1.2 Test process

As shown in Fig. 1, five flexible connectors were used in the model to produce vertical vibration modes similar to those of a real ship. These connectors were adjusted to the extent that the stiffness and damping of the model are close to those of a real ship. This ensures that real springing can be obtained under the 16 typical sea states.

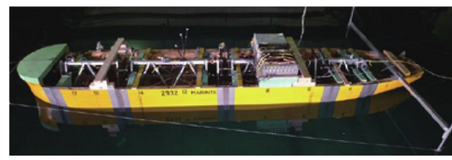

Fig. 1 VLOC test model

The variation trends of responses under the various short-term sea states can be obtained experimentally. Fig. 2 shows the time histories of typical wave-induced vertical bending moments. In this case, H_s = 2.5 m, spectral peak period T_p = 10.6 s, and speed U = 14.5 kn. In Fig. 2, the two curves refer to the wave-induced vertical bending moments (VBMs) with/without springing considered respectively. Filtering was performed by setting a cut-off frequency [8].

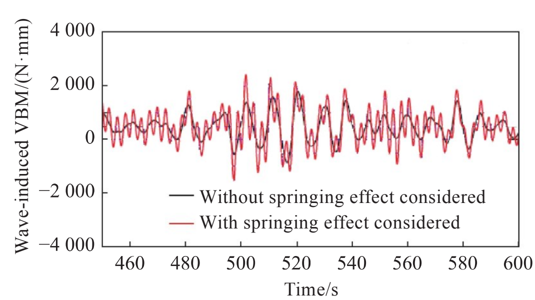

Fig. 2 Time histories of typical wave-induced VBM

On the basis of the time histories obtained experimentally, hot-spot stress ranges and fatigue damage rates can be calculated by rainflow counting. In this way, wave-frequency-induced fatigue damage (WF) and high-frequency-induced fatigue damage (HF) of ships in full-load and ballast conditions under various typical sea states can be obtained respectively. Considering that the fatigue damage at midship is obviously more serious than that at bow and stern, this paper focuses on the influence of springing on the fatigue damage of longitudinal ribs at midship sections.

2 Analysis of test results

2.1 Fatigue damage magnification factor

As described in Section 1.2, WF and HF were calculated respectively under ballast and full-load conditions. Specifically, the former represents fatigue damage D_{wave} caused by wave-induced loads alone, while the latter represents springing-induced fatigue damage D_{HF}. The sum of the two is total fatigue damage D_{total}. In this paper, the ratio of springing-induced fatigue damage to the total fatigue damage, i.e., D_{HF}/D_{total}, is used to evaluate the proportion of fatigue damage caused by the springing effect in the total damage.

Through the model test data, we can obtain a fatigue damage magnification factor F_{vib} as follows.

$$F_{vib} = \frac{D_{total}}{D_{wave}} \tag{1}$$

Finally, the springing-induced F_{vib} of two generations of 400 000 DWT VLOCs was obtained (Table 3).

Table 3 F_{vib} of two generations of 400 000 DWT VLOCs

	Fatigue damage magnification factor F_{vib}	
	Ballast condition	Full-load condition
First generation	2.41	2.04
Second generation	5.85	2.61

2.2 Factors affecting F_{vib}

F_{vib} is affected by many factors. The internal factors mainly include damping coefficient, hull-girder stiffness, and natural frequency, while the external ones are wave period, significant wave height, and speed. For a hull, a smaller damping coefficient and lower stiffness and natural frequency result in more obvious springing. However, as inherent elements in ship design, they are not the focus of this paper.

Among the above factors affecting F_{vib}, sea state and speed are the ones that affect ship springing greatly in the daily operation of ships. Their influences can be reduced by artificial adjustments, such as avoiding harsh sea states and actively reducing speed. Therefore, studying the external factors is of great significance for large ships at sea to ensure personal and property safety.

The two generations of 400 000 DWT VLOCs have similar design elements such as total dimensions, hull-girder stiffness, and natural frequency. For this reason, their differences in these internal factors can be ignored and only the influences of external variables including H_s, T_z, and speeds on the springing effect are considered in comparative research.

To study the influences of sea state and speed on the variation trend of F_{vib} more accurately, this paper calculated the F_{vib} of these two generations of VLOCs under typical sea states. Table 3 reveals a great difference in the F_{vib} of the two generations of VLOCs in the ballast condition. Therefore, analysis results under this condition are presented in Tables 4 and 5 respectively. Moreover, results under the full-load condition are similar to those under the ballast condition.

Table 4 F_{vib} of the first-generation 400 000 DWT VLOC in ballast condition

H_s/m	F_{vib}					
	T_z=8.0 s	T_z=9.0 s	T_z=10.0 s	T_z=11.0 s	T_z=12.0 s	T_z=13.0 s
2.5	12.0	5.1	2.9	2.2	1.7	1.3
3.5	9.4	4.5	2.8	2.0	1.5	1.4
4.5	9.2	4.5	2.8	1.9	1.5	1.5
5.5	5.4	2.9	2.2	1.8	1.5	1.4
6.5	3.7	2.4	2.0	1.7	1.5	1.4
7.5	2.7	2.0	1.7	1.5	1.4	1.3
8.5	2.3	1.8	1.6	1.4	1.3	1.3

Table 5 F_{vib} of the second-generation 400 000 DWT VLOC in ballast condition

H_s/m	F_{vib}					
	T_z=8.0 s	T_z=9.0 s	T_z=10.0 s	T_z=11.0 s	T_z=12.0 s	T_z=13.0 s
2.5	46.8	21.4	7.8	2.2	2.0	1.6
3.5	27.3	12.5	7.0	3.7	2.8	2.0
4.5	25.8	11.8	6.9	3.9	2.9	2.0
5.5	19.0	9.6	5.8	3.6	3.1	2.5
6.5	16.9	8.9	5.5	3.5	3.1	2.7
7.5	7.5	5.0	3.5	2.6	2.3	2.0
8.5	3.7	3.1	2.5	2.0	1.9	1.7

2.3 Influence of sea state on springing

Ship speed is not an independent factor affecting springing in actual navigation. For example, speed is close to the maximum design value under good sea states. However, harsh sea states reduce speed, and ships even have to slow down actively under such states. Therefore, speed can be regarded as a variable related to sea state, and research on the relationship between speed and springing still comes down to that on sea states.

The influence of sea state on ship vibration can be divided into two aspects. One is that large ships are prone to springing during navigation under low sea states. As the hull structure is a system with small damping, springing can last for a long time and ultimately result in fatigue damage of the hull structure. According to the test results, HF is likely to become the main source of ship fatigue damage, and its proportion even exceeds that of wave-induced fatigue damage. The other is whipping, which caused by the ship bow prone to wave slamming under high sea states, resulting in flutter accompanied by nonlinear resonance. Due to its low frequency and instantaneousness, whipping basically belongs to the research category of ship ultimate strength. Therefore, it will be considered seriously during the investigation of high-speed ships with large flares (such as large container ships). However, as for large fat ships at low speeds, whipping is hardly likely to occur, and it makes a smaller contribution to fatigue damage than that of springing. Thus, whipping can be considered as a secondary factor in such a case.

Jensen et al. [9] studied springing under random sea states and carried out theoretical calculations in light of the nonlinear quadratic strip theory in the frequency domain. The nonlinear effect caused by changes in additional mass, waterplane width, and damping were investigated. Moreover, they analyzed ship fatigue damage and ultimate load without considering whipping caused by slamming. Seen from the results, springing is more obvious in the cases of head sea, oblique bow wave, and small T_z, and springing peaks do not affect ultimate load greatly. By theoretical calculation and ship monitoring, Storhaug [10] analyzed the characteristics of springing-induced fatigue damage. Some of the conclusions drawn from the analysis are as follows: The springing effect under the ballast condition is more obvious than that under the full-load condition; fatigue damage decreases as T_z rises and increases with H_s; active speed reduction is an effective way to avoid springing under harsh sea states.

Short-term sea states are mainly described by T_z and H_s. The influence of changes in these two elements on F_{vib} can be observed from Tables 4 and 5, in which different H_s correspond to different speeds. This paper expects to avoid involving speed variables in analyzing sea-state factors and thereby eliminate external interference in determining the variation trend of F_{vib}. For this purpose, T_z is converted into the wave encounter period T_e to eliminate the influence of speed. The conversion formula is as follows:

$$\omega_z = \frac{2\pi}{T_z} \quad (2)$$

$$\omega_e = \omega_z - \frac{\omega_z^2 U}{g}\cos\beta \quad (3)$$

$$T_e = \frac{2\pi}{\omega_e} \quad (4)$$

where ω_z is zero-crossing frequency; ω_e is encounter frequency; β is a wave direction angle; g is the gravitational acceleration.

The T_e converted, H_s, and F_{vib} were plotted into 3D surface diagrams (Figs. 3 and 4):

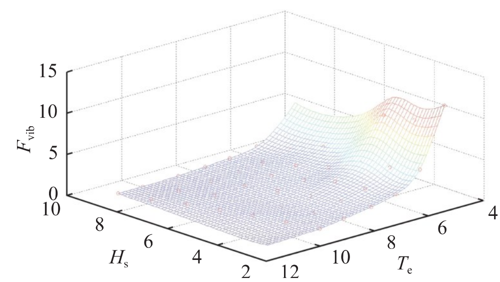

Fig. 3 F_{vib} of the first-generation 400 000 DWT VLOC

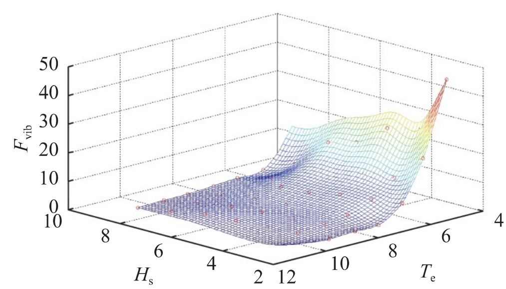

Fig. 4 F_{vib} of the second-generation 400 000 DWT VLOC

Figs. 3 and 4 show that F_{vib} increases as T_e and H_s decrease. Notably, the influence of H_s on F_{vib} is not in line with the trend obtained by Reference [10], which shows that "fatigue damage increases with H_s". In other words, an increase in H_s results in increased fatigue damage but decreased F_{vib}. The reason for the above trend difference is as follows: Compared with HF, wave-induced fatigue damage increases faster with H_s, leading to a decreased proportion of HF in the total fatigue damage under high sea states.

2.4 Research of dominant sea state

The test scheme in this paper involves 16 typical sea states totally. In this section, the reliability of F_{vib} under simplified sea states was studied by recursion. The F_{vib} of the first-generation 400 000 DWT VLOC in Table 3 was taken as an example. The original table was divided into four equal quadrants, each of which is a 3 × 3 matrix (Table 6). Then, the F_{vib} at each matrix center was used for weighted averaging, and an equivalent fatigue damage magnification factor F_{vib_eq4} = 2.35 under the four sea states was obtained. Subsequently, a F_{vib_eq4} of 5.65 was acquired in a similar way for the second-generation VLOC of the same scale in the ballast condition. The actual F_{vib} of the two generations of VLOCs obtained from the model tests was 2.41 and 5.85 respectively. By comparison, F_{vib_eq4} is close to the test results in Table 3.

Table 6 F_{vib_eq4} of the first-generation 400 000 DWT VLOC

H_s/m	F_{vib_eq4}					
	T_z=8.0 s	T_z=9.0 s	T_z=10.0 s	T_z=11.0 s	T_z=12.0 s	T_z=13.0 s
2.5	12.0	5.1	2.9	2.2	1.7	1.3
3.5	9.4	4.5	2.8	2.0	1.5	1.4
4.5	9.2	4.5	2.8	1.9	1.5	1.5
5.5	5.4	2.9	2.2	1.8	1.5	1.4
6.5	3.7	2.4	2.0	1.7	1.5	1.4
7.5	2.7	2.0	1.7	1.5	1.4	1.3
8.5	2.3	1.8	1.6	1.4	1.3	1.3

According to the above division, the F_{vib} obtained under the four simplified typical conditions is within a small error to the values calculated under 16 typical sea states. On this basis, this paper proposed a concept of "dominant sea state", namely the condition with the greatest contribution to wave-induced fatigue damage. In fact, spectral analysis of fatigue damage in unit time under each short-term sea state in the wave climate map can be performed to obtain the sea state corresponding to the maximum fatigue damage, also known as the "dominant sea state". This condition is considered to be the central sea state of the 16 typical sea states input in the tests. As mentioned above, the factors H_s and T_z of the dominant sea states for the two generations of VLOCs should be H_s = 5.5, T_z = 10 and H_s = 5, T_z = 10 respectively. The F_{vib} obtained under a dominant sea state is called dominant fatigue damage magnification factor $F_{vib\_dominant}$. The $F_{vib\_dominant}$ of the two generations of VLOCs was 2.2 and 5.8 respectively, which is also close to the F_{vib} obtained from the model tests. Similar conclusions were obtained from the analysis of the two generations of VLOCs in a full-load condition. In addition, the analysis of test data on a 325 000 DWT VLOC shows that its $F_{vib\_dominant}$ is similar to the tested F_{vib} as well, and they were 2.84 and 2.71 respectively [11].

Det Norske Veritas (DNV) provided an empirical formula for preliminary estimation of F_{vib} for large fat ships [12]:

$$F_{vib} = \frac{A_w^4 + A_{vib}^{3.7}}{A_w^4} \tag{5}$$

$$A_w = 18.5 \times 10^{-6} \frac{B(C_B + 0.7)L_{pp}^{1.9}}{Z} \tag{6}$$

$$A_{vib} = 2.3 \times 10^{-8} \frac{V^2 B(C_B + 0.7) L_{pp}^{1.9}}{\left(\frac{T}{L_{pp}}\right)^{0.4} Z} \tag{7}$$

where A_w is a coefficient of wave-induced fatigue; A_{vib} is a coefficient of high-frequency induced fatigue; B is molded breadth, m; C_B is a block coefficient; L_{pp} is the length between perpendiculars, m; Z is the section modulus of hull girders, m^3; V is the maximum service speed under the designed draft, kn; T is designed draft, m.

Formula (7) takes the square of service speed as a variable. However, the test results of two generations of VLOCs reveal that the springing effect is not always of a square relationship with speed, which is especially true for the F_{vib} under the ballast condition in Table 3. Moreover, sea states with the greatest contribution to fatigue are not those corresponding to the maximum service speed. Therefore, taking the square of service speed as an input variable for evaluation is unable to well explain the springing-induced magnification factor physically.

According to the above discussion, the dominant sea state is closely related to springing. Thus, by replacing speed in the original expression with dominant sea state, we can describe the springing-induced fatigue magnification factor F_{vib} more accurately. The modified expression is as follows:

$$F_{vib} = \frac{A_w^4 + A_{vib}^{3.7}}{A_w^4} \tag{8}$$

$$A_w = 18.5 \times 10^{-6} \frac{B(C_B + 0.7)L_{pp}^{1.9}}{Z} \tag{9}$$

For the ballast condition:

$$A_{vib\_ballast} = 0.128 \frac{B(C_B + 0.7)L_{pp}^{1.9}}{T_e^{2.7} H_s^{2.7} (T_b/L_{pp})^{0.4} Z} \tag{10}$$

For the full-load condition:

$$A_{vib\_cargo} = 7.37 \times 10^{-4} \frac{B(C_B + 0.7)L_{pp}^{1.9}}{T_e^{1.5} H_s (T_c/L_{pp})^{0.4} Z} \tag{11}$$

where $A_{vib\_ballast}$ is a coefficient of high-frequency-induced fatigue under the ballast condition; A_{vib_cargo} is a coefficient of high-frequency-induced fatigue under the full-load condition; T_b is ballast draft; T_c is full-load draft.

Here, with the first-generation 400 000 DWT VLOC as an example, Table 7 and Fig. 5 compare the F_{vib} obtained from the model tests, the modified formula, and the original formula. As can be seen from the comparison, the calculation results of the modified formula are more consistent with the test ones, which means the modified formula can correct the original one.

Table 7 Calculated F_{vib} of the first-generation 400 000 DWT VLOC

Condition	Fatigue damage magnification factor F_{vib}		
	Model test	Modified formula	Original formula
Ballast	2.41	2.41	2.32
Full load	2.04	2.03	1.38

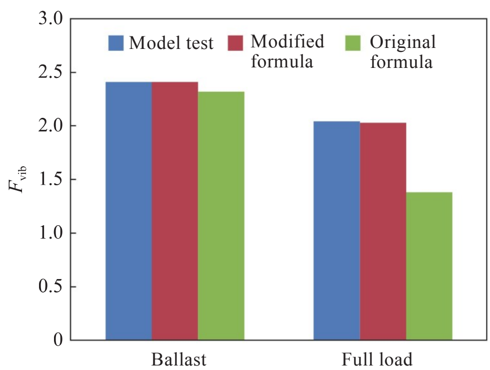

Fig. 5 Comparison of F_{vib} of the first-generation 400 000 DWT VLOC calculated by three methods

According to the above analysis, replacing multiple typical sea states with a dominant sea state is feasible in terms of reliability. The application significance of a dominant sea state is as follows. Although conventional methods of typical conditions are systematic, they involve long periods of tests and subsequent processing, thus failing to make predictions and provide guidance at the initial stages of ship design. By inductive recursion, this paper obtained dominant sea states through gradual simplification of sea states. On this basis, relatively accurate evaluation values of F_{vib} can be obtained in a short time both during the estimation with the empirical formula and during experimental verification. In this way, requirements at the initial stages of design can be met, and structural modification due to over-large F_{vib} at later stages of design can be avoided.

3 Conclusions

This paper compared the model tests on two generations of 400 000 DWT VLOCs and analyzed the input conditions and results of the tests. Moreover, it discussed the relationships of springing-induced fatigue damage with sea-state factors including significant wave height and encounter period. On this basis, the following conclusions were drawn.

1) Springing of VLOCs occurs in ship model tests and real ship monitoring, and it is more likely to occur under a ballast condition. Wave-induced loads affect the fatigue damage of ship structures significantly.

2) The degree of springing varies greatly with sea states. The magnification effects of wave-induced loads on fatigue damage increase with the decreases in encounter frequency and significant wave height.

3) Inductive recursion reveals that relatively accurate fatigue damage magnification factors can be obtained in a short time by using a dominant sea state instead of multiple typical ones. This is of guiding significance for the initial stages of design.

4) The research work in this paper is based on test data on VLOCs. Relevant conclusions may not be necessarily applicable to ships with high speeds, large openings, and large bow flare angles such as large container ships. The applicability of the conclusions needs to be further verified.

References

[1] Lloyd's Register. Structural design assessment: Guidance notes on the assessment of global design loads of large container ships and other ships prone to whipping and springing [S]. London: Lloyd's Register, 2014.

[2] CLEARY W A, ROBERTSON J B, YAGLER A. The results and significance of the strength studies on the Great Lake bulk ore carrier Edvard L. Ryerson [C]// SNAME Symposium on Hull stresses in Bulk Carriers. Ottawa: [S. n.], 1971: 412−426.

[3] LEWIS E. Ship model tests to determine bending moments in waves [J]. The Soc. of Naval Arch. and Marine, 1954: 62.

[4] DUDSON E, RAMBECH H, WU M. Determination of wave bending loads on a 40 knot, long slender open topped containership through model tests and hydrodynamic calculations with particular reference to the effects of hull flexibility on fatigue life [C]//The 6th International Conference on FAST Sea Transportation. London: The Royal Institution of Naval Architects, 2001: 177−190.

[5] STORHAUG G, VIDIC-PERUNOVIC J, RÜDINGER F, et al. Springing/whipping response of a large ocean going vessel-a comparison between numerical simulations and full-scale measurements [C]//Proceedings of Hydroelasticity in Marine Technology. Oxford: the University of Oxford, 2003: 117−131.

[6] MOE E, HOLTSMARK G, STORHAUG G. Full scale measurements of the wave induced hull girder vibrations of an ore carrier trading in the North Atlantic [C]//RINA International Conference, Design and Operation of Bulk Carriers. London: [S. n.], 2005: 57−85.

[7] WANG X L, GU X K, HU J J. Comparative study of

the effect of hull-girder stiffness on springing behaviors[J]. Chinese Journal of Ship Research, 2016, 11 (5): 55−62, 77 (in Chinese).

[8] Norwegian Marine Technology Research Institute (Marintek). Evaluation of fatigue damage rates based on model tests for the 400, 000DWT ore carrier [R]. Norge: Marintek, 2010.

[9] JENSEN J J, DOGLIANI M. Wave-induced ship full vibrations in stochastic seaways [J]. Marine Structures, 1996, 9 (3/4): 353−387.

[10] STORHAUG G. Experimental investigation of wave induced vibrations and their effect on the fatigue loading of ships [D]. Norway: Norwegian University of Science and Technology, 2007.

[11] Shanghai Merchant Ship Design and Research Institute (SDARI). Evaluation of fatigue damage rates based on model tests for the 325, 000DWT ore carrier [R]. Shanghai: SDARI, 2017.

[12] DNV GL. Fatigue assessment of ship structures: DNV GL-CG-0129 [S]. [S. l]: DNV GL, 2014.

海况对大型船舶波激振动疲劳损伤的影响

华康*,赵文斌,吴定凡

上海船舶研究设计院,上海 201203

摘　要:［目的］针对大型船舶波激振动效应下的疲劳损伤问题进行研究。［方法］通过船模试验方法,比较两代400 000 DWT 超大型矿砂船(VLOC)疲劳损伤的试验结果,分析船体梁波激振动效应下海况与疲劳的关系。通过递推方法,研究系列模型下的典型海况影响。［结果］结果表明,波激振动对疲劳的放大效应与有义波高和遭遇周期存在趋势关系。通过归纳递推方法,提出"主导海况"的概念,对疲劳损伤放大因子公式进行了修正;波激振动程度随海况的变化明显,波激载荷对疲劳损伤的放大效果随遭遇频率和有义波高的减小而增大。［结论］以"主导海况"代替多典型海况,可以在较短时间内获取相对准确的疲劳损伤放大因子,这在船舶设计初期具有指导意义。

关键词: 船舶结构; 波激振动; 疲劳; 船模试验