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Comparative study of the effect of hull-girder stiffness on springing behaviors

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Abstract: With the large scale development trend, the lengths of ships are constantly increasing. As a result, high strength steel is widely used due to the demand of lightweight design of ship structures. hull-girder of the ship, in particular, becomes much more flexible than those of small and medium-sized ships. This results in different characteristics of springing behaviors of ship structures when the ship sails on the sea. In this paper, a large engineering ship is taken as the research subject in order to study its low- and high-frequency wave induced load responses in waves. Two kinds of steel girders with different transverse-section moments of inertia are used to simulate original and changed stiffness in a segmented model. The 3D hydroelasticity theory is employed to predict responses of the ship in waves, and comparison analysis is also conducted between experimental and theoretical results. It is shown that springing behavior is prone to happen with low hull-girder stiffness, and continual springing behavior will result in serious fatigue damage to ship structures. The necessity of considering the hull-girder stiffness as an important parameter in the structural optimization design of large ships is thus verified as the effect of hull-girder stiffness on springing behaviors cannot be neglected.

Key words: hull-girder; stiffness; springing; model test; 3D hydroelasticity theory

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0 Introduction

In the international shipping market, in order to reduce production costs, the main scale of ships is constantly developing towards the large-scale direction. For example, the length of "Zheng He" super-large container ship made in China is close to 399.9 m, which is 70 m longer than the "Nimitz" class nuclear-powered aircraft carrier of America. On the other hand, to reduce the weights of ship structures, designers began to use lightweight design of structures. Therefore, high strength steel has been widely used in the ship structures, making the ship structures more and more flexible. In view of the transverse-section stiffness of ship structures, the hull-girder stiffness of large-scale ships is relatively lower compared with that of traditional small and medium-sized ships. The hull can produce a resonance phenomenon even under low sea condition—springing behavior. The springing phenomenon may become more serious with the increase of the ship's main scale, and the contribution of the hull Vertical Bending Moment (VBM) to the total load caused by the springing behavior can even far exceed the wave frequency components. The continual springing behavior will result in fatigue damage to ship structures, thus affecting the safety and maintenance costs of ship structures.

In the past 20 years, the elastic resonance of springing behavior has been studied more and more, with the means of model test and theoretical analysis, and even the real ship test. The segmental keel beam model test technology was widely used in the research of springing model test. It can be not only

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used to study the distribution law of wave loads along the length of the ship, but also used to further verify the theoretical analysis method. Through the segmental keel beam model test method, the characteristics of the springing behaviors of a super-large oil tanker were studied by Lin[1]. The occurrence mechanism was explained and its effect on the overall longitudinal strength and the fatigue damage was discussed finally. Based on the model test and theoretical method, the higher-order harmonic components of the VBM in the wave were studied by Gu et al.[2]. They found that the higher-order components may cause nonlinear springing behavior if the higher-order components of the bending moment are equal to the characteristic frequencies of the hull-girder. Through researches, Jensen et al.[3] considered that for traditional ships, if the bending stiffness is low, the speed is high and the non-linear excitation is serious, the springing behavior may be more serious. Through the springing and flutter model tests of a ultra-large ore carrier, it was found by Wang et al.[4] that the springing behavior existed both in regular and irregular waves for this ship. For the container ship, the existence of large structure openings made the transverse and torsional loads of the ship as important as the vertical loads. With an open aluminum square tube used as the keel beam, the vertical, horizontal and torsional stiffness of a very-large container ship hull was simulated by Zhu et al.[5], and through the study of vertical, horizontal and torsional vibration responses in regular and irregular waves, the characteristics of springing behaviors of the super-large container ship were analyzed. It was found that when the ship encountered large wave height, the non-linear springing behaviors were often coupled with the slamming flutter, but it was difficult to separate them by technical means, which was also described in Reference[4].

Although there were large amounts of related references on the springing phenomena of large-scale ships, the number of references studying on the influence of the hull-girder stiffness on the characteristics of springing behaviors was not large. Though References[6-7] involved contents of this aspect, they did not illustrate completely from the view of the effect of the hull-girder stiffness change on the springing behaviors. In this paper, a large engineering ship was chosen as the research object, and the segmental model tests of two kinds of hull-girder stiffness were carried out. Combined with the prediction of 3D linear hydroelasticity theory, the vertical wave load characteristics of the ship subjected in waves were analyzed, and the effect of the hull-girder stiffness change on the springing behaviors was studied.

1 Model test

1.1 Main parameters and segmentation of the model

The main parameters of the large engineering ship are shown in Tab. 1. In order to study the influence of the hull-girder stiffness change on the springing behavior, the steel hull-girder in the ship model can be replaced, but the shape of the ship model needs to be consistent with the reduced scale. The ship model is divided into 10 segments along the L_{PP} direction, and the segmental positions are located at the 2nd, 4th, 6th, 8th, 10th, 12th, 14th, 16th and 18th station transverse-sections, respectively. All the segments are connected to each other into a whole by two same measure girders. When the ship model is moving in the wave, the vertical wave bending moments at each segmental position can be measured and recorded at the segmental gaps by means of strain sensors mounted on the girders.

Table 1 Main parameters of the large engineering ship

Parameter	Value
Total length L_{OA}/m	301.0
Length between perpendiculars L_{pp}/m	285.0
Water line width B/m	44.0
Molded depth H/m	32.4
Bow draught T_f/m	7.40
Stern draught T_a/m	9.41
Displacement Δ/t	78 647.0
Height of center of gravity Z_g/m	11.92
Longitudinal position of center of gravity X_g/m	−4.42

The similar relation of the real ship and the model stiffness EI is converted according to the fifth power of the reduced scale. When designing the model, the stiffness of the small hull-girder stiffness is obtained by reducing the theoretical value of the first-order vertical vibration frequency of the original hull-girder stiffness shrunk by a third. At this time, the stiffness of the small hull-girder stiffness is about 11% of the original stiffness. Considering the first-order vertical vibration frequency of the hull-girder, the small hull-girder stiffness actually simulates a ship with the main scale much larger than the prototype. The photographs of the segmental model of the large engineering ship and the hull-girders with two kinds of stiffness are shown in Fig. 1.

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(a) Segmental model

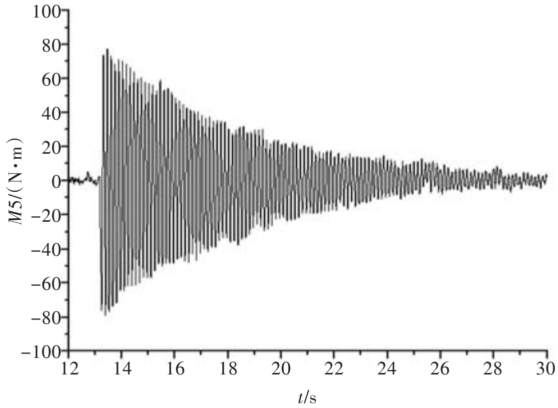
(b) Original stiffness hull-girder (c) Small stiffness hull-girder

Fig.1 Photos of the segmental model and hull girders

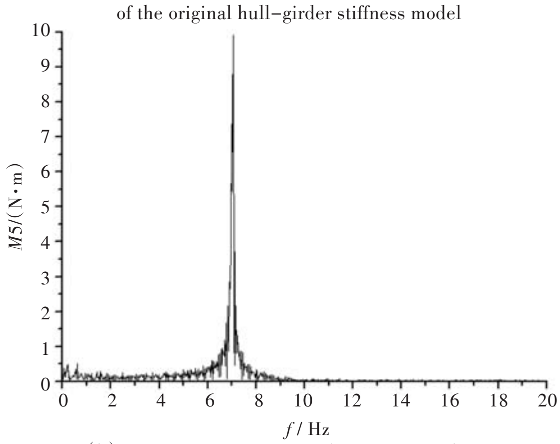
1.2 Analysis of model test results

Through the hammering test in still water of the models, the first several-order wet mode frequencies of the two kinds of hull-girder stiffness models can be obtained respectively. The VBM decline curves of the midship section and its frequency spectrum analysis figures obtained from hammering tests of the original hull-girder stiffness model and small hull-girder stiffness model are shown in Fig. 2. As can be seen from the figure, frequencies of the two-node vertical vibrations of the two stiffness models are 7.03 and 2.70 Hz respectively; frequencies of the three-node and four-node vertical vibrations of the small hull-girder stiffness model are 6.29 and 10.42 Hz, respectively, while frequencies of the three-node and four-node vertical vibrations of the original hull-girder stiffness model are not significant. As can be found, compared to the original hull-girder stiffness model, the wet mode frequencies of the small hull-girder stiffness model are reduced sharply, which reflects that the hull-girder of the latter becomes more elastic, making springing behavior more prone to happen to the ship when it is sailing in waves.

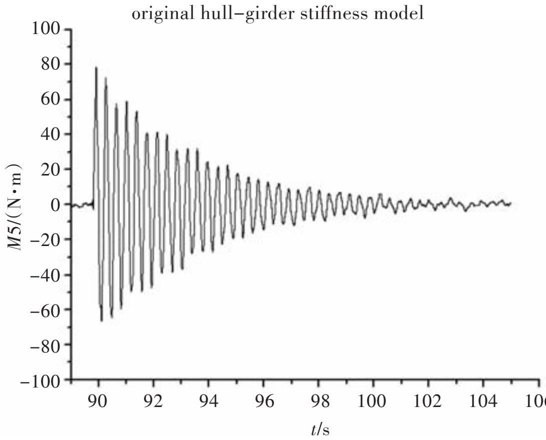
The Response Amplitude Operators (RAOs) of VBM of the original hull-girder stiffness model and the small hull-girder stiffness model are shown in



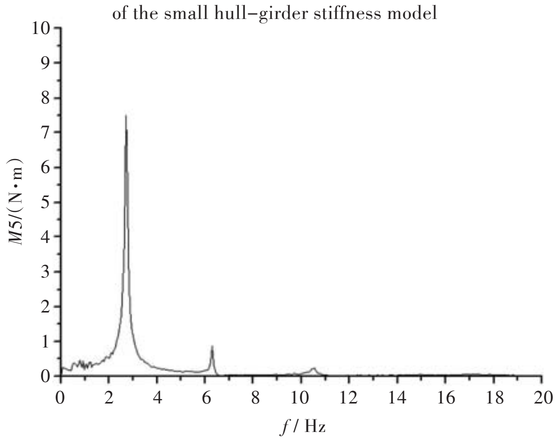
(a) VBM decline curves of the midship section of the original hull-girder stiffness model



(b) Frequency spectrum analysis figure of the original hull-girder stiffness model



(c) VBM decline curves of the midship section of the small hull-girder stiffness model



(d) Frequency spectrum of the small hull-girder stiffness model

Fig.2 The time history curves and frequency spectrums of the vertical bending vibrations by hammering test in still water of the two models

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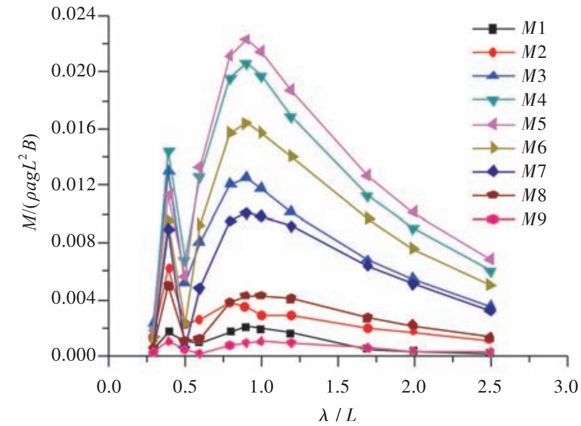
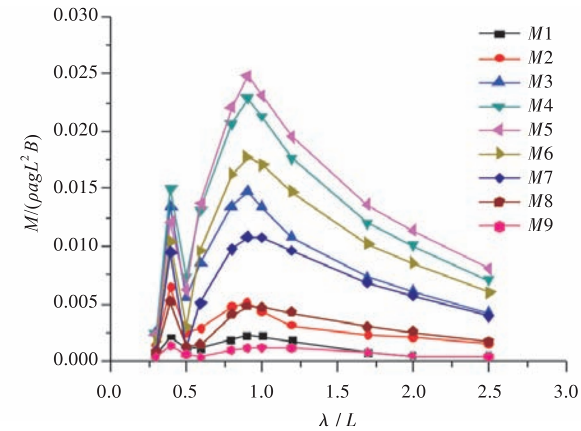
Fig. 3 and Fig. 4 respectively. In the figures, the sailing speed is 19.5 kn; the wave direction is the heading wave; $M1$ to $M9$ are the VBMs of the 2^{th}, 4^{th}, 6^{th}, 8^{th}, 10^{th}, 12^{th}, 14^{th}, 16^{th} and 18^{th} station transverse-sections of the ship model respectively. The synthetic components (*CM*) of the VBM M contain the wave frequency component (*WM*) and the high-frequency component (*HM*). $M/(\rho a g L^2 B)$ is the dimensionless result of the VBM M, where ρ is the density of the water (it is the freshwater density in the model test and sea water density in the theoretical calculation), a is the wave height, g is the gravity acceleration, L is the length of the ship and B is the water line width. As shown in the figure, each RAO has two peaks which are located at the ratio of wave length to ship length (λ/L) of 0.4 and 0.9, among which the small peak is the contribution of the two-node vertical vibration frequencies of the hull-girder to the RAO. At different wavelengths, the ratios of high-order moments to wave moments are all less than 1.2. The stiffness change of the hull-girder has little effect on the wave frequency components of RAO of VBM, but the small stiffness makes the peak of the synthetic bending moment increase by 30%.

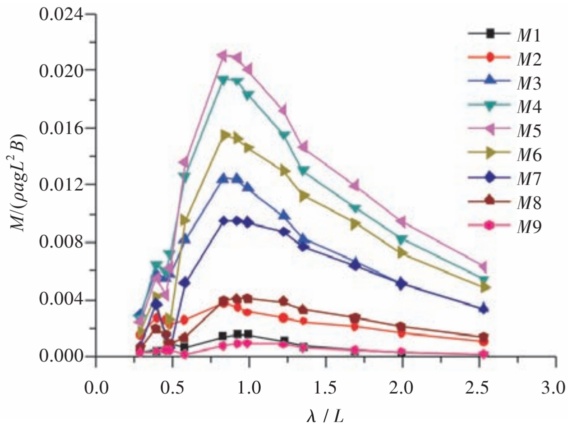


(a) Wave frequency component RAO of VBM

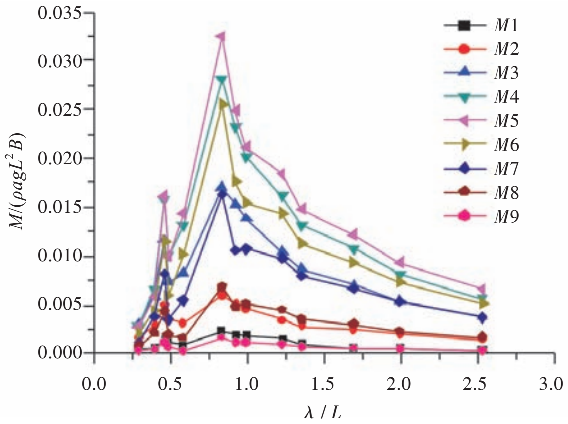


(b) Synthetic component RAO of VBM

Fig.3 RAOs of VBM of the original hull-girder stiffness model



(a) Wave frequency component RAO of VBM



(b) Synthetic component RAO of VBM

Fig.4 RAOs of VBM of the small hull-girder stiffness model

The ratio of the *HM* and *WM* of the VBM is shown in Fig. 5. As shown in the figure, when $\lambda/L = 0.465$, *HM/WM* of the small stiffness condition increases sharply, with the maximum value even reaching 12. Analyzing the reason, it is because that the reduction of the hull-girder stiffness results in the sharp increase of the water elastic effect of the hull, and it resonates with the two-node vertical vibration of the hull-girder, causing the serious springing behavior of the small hull-girder stiffness, which is similar to the phenomenon mentioned in the Reference[1].

Subsample of the time history curves and frequency spectrums of the midship section VBM of the original hull-girder stiffness model and the small hull-girder stiffness model are shown in Fig. 6. They are all model values in the figure, and the corresponding λ/L of original stiffness and small stiffness are 0.4 and 0.465 respectively. As can be seen in the figure, under the original stiffness, the *WM* is the main contribution of the bending moment synthetic component. Under the same wave height, the amplitude of the VBM with small stiffness increases sharply, and the first-order vertical vibration component is the main contribution of the synthetic bending mo-

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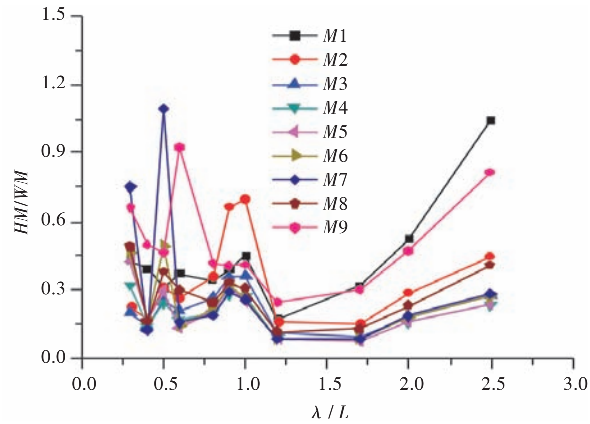
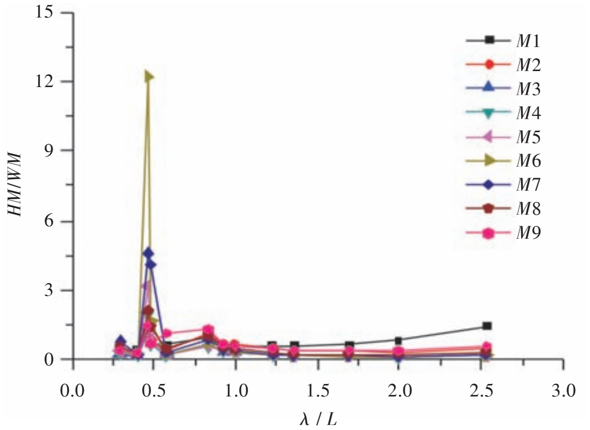


(a) Rotio of *HM* and *WM* of the original hull-girder stiffness model



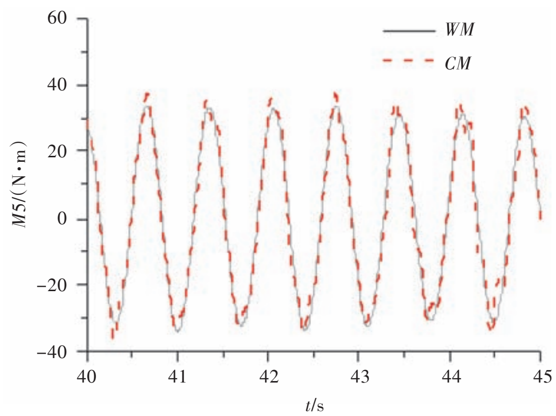
(b) Rotio of *HM* and *WM* of the small hull-girder stiffness model

Fig.5 Ratio of *HM* and *WM*

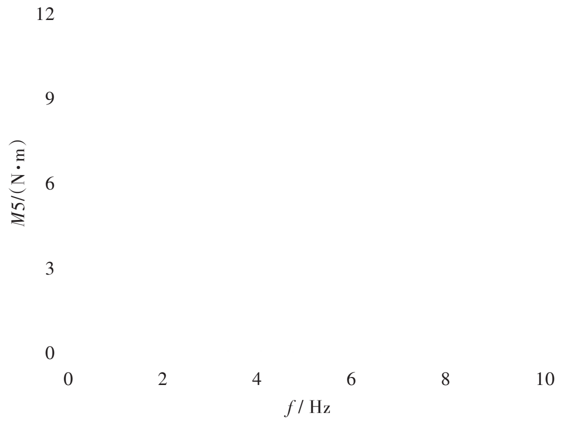
ment. It is worth noting that the first-order vertical vibration frequency (2.58 Hz) of the hull-girder is twice that of the wave component frequency (1.29 Hz), which is the obvious springing behavior caused by the frequency multiplication.

2 Theoretical prediction and comparison

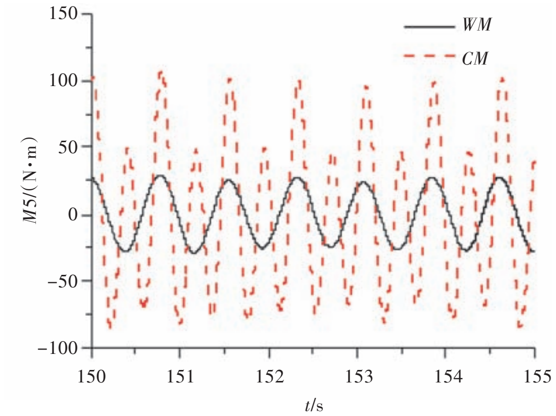
Since the mid-1970s, with the development of computer technology, the 3D hydrodynamic method has been developed rapidly and applied in the analy-



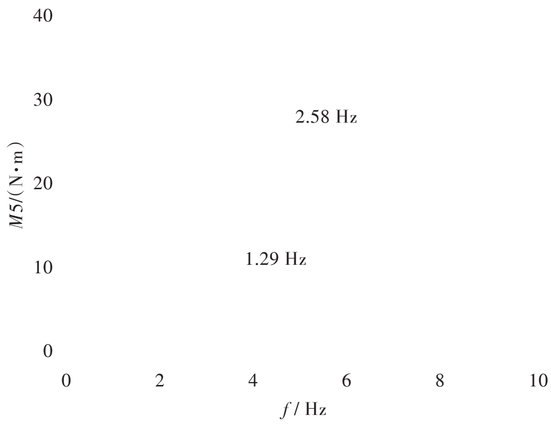
(a) Subsample of the time history curves of the midship section VBM of the original hull-girder stiffness model



(b) Frequency spectrum of the original hull-girder stiffness model



(c) Subsample of the time history curves of the midship section VBM of the small hull-girder stiffness model



(d) Frequency spectrum of the small hull-girder stiffness model

Fig.6 Subsample of the time history curves and frequency spectrums of the VBM in regular waves of the two models

sis of the seakeeping problems of various large-scale ocean floating structures. Combining the 3D seaworthiness theory and 3D structural dynamics theory, Wu[8] developed a 3D hydroelasticity theory suitable for analysis of arbitrary 3D deformable bodies in waves according to the generalized fluid-solid interface conditions proposed by him. Since then, the theory has been widely used in design researches of many kinds of ships and ocean engineering structures, such as Hirdaris et al.[9], Malenica et al.[10], Hu et al.[11] and Wang et al.[12]. In this paper, modal analy-

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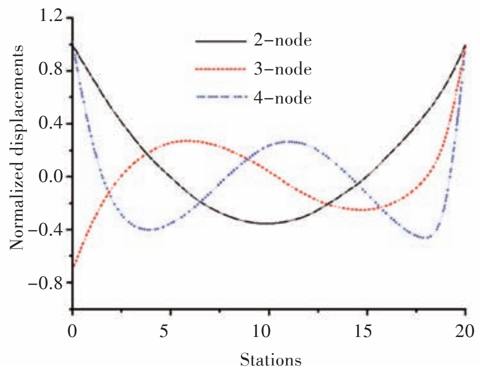
sis is firstly done on this large-scale engineering ship by using 3D hydroelasticity theory. Its responses in regular and irregular waves are predicted, and the effect of stiffness change on the springing behavior is analyzed by combining the model test results.

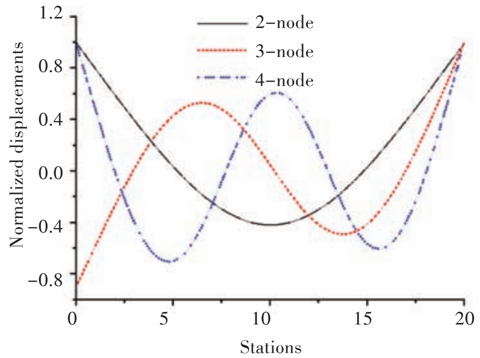
2.1 Modal analysis

The modal analysis of the large-scale engineering ship is carried out by using the dry mode and wet mode calculation method successively. The dry mode calculation method means that the hull-girder is simplified to Timoshenko beam, and then its vertical vibration mode in the vacuum is analyzed by using the finite element software directly. The wet mode calculation method is using the calculation results of dry mode (vibration mode and frequency) as the input of dry structure information, combined with the wet surface grid information of the hull, and then the vertical vibration mode of the hull-girder in the water is analyzed through the hydroelasticity software. The dry structure model of the ship can be simplified into a Timoshenko beam composed of 20 variable cross-section beams according to the weight and transverse-section moment of inertia distribution of the hull. The vertical vibration dry mode of this beam is analyzed by MSC/NASTRAN finite element software, to replace the 3D whole ship finite element analysis whose task is heavy and consuming time is huge. Dry structure data input such as Timoshenko beam form can greatly reduce the data preparation work of 3D hydroelasticity calculation in earlier stage. Without detailed hull structure information, combined with the subsequent wet mode and response calculation, it is convenient to carry out the theoretical analysis of wave load characteristics in the initial design stage of ship structures.

The first three-order vertical bending vibration modes of the hull-girder dry structure are shown in Fig. 7, in which the abscissa is the station number and the ordinate is the normalized displacement. As can be seen from the figure, apart from the two-node vibration mode, the amplitudes of three-node and four-node vibration modes of the small hull-girder stiffness model dry structure are larger than those of the original hull-girder stiffness model. To calculate the wet mode, the wet surface grid only counts the hull wet surface molded lines below the water line. The vertical bending wet mode frequencies obtained from the theoretical calculation are shown in Tab. 2. In the hydrostatic excitation model test, due to the high-order vertical vibration frequencies of the original hull-girder stiffness model are not remarkable, only the two-node vertical bending wet mode frequencies are given here. However, the two-node, three-node and four-node wet mode frequencies are given for the small hull-girder stiffness model.



(a) Original hull-girder stiffness model



(b) Small hull-girder stiffness model

Fig.7 Vertical modes of vibration in vacuum

Table 2 Vertical bending mode frequencies in water

Node frequency	Original stiffness			Small stiffness		
	Model test value /(rad·s^{-1})	Theoretical calculation value /(rad·s^{-1})	Error /%	Model test value /(rad·s^{-1})	Theoretical calculation value /(rad·s^{-1})	Error /%
$f_{2\text{-node}}$	6.25	6.20	−0.80	2.40	2.30	−4.17
$f_{3\text{-node}}$	–	–	–	5.59	5.35	−4.29
$f_{4\text{-node}}$	–	–	–	9.26	10.00	7.99

As can be seen from the numerical comparison of the vertical bending wet mode frequencies of the two kinds of stiffness in Tab. 2, the two-node vertical vibration frequency is reduced to 37% of the original value. Deviations of the model test value and the calculated value of the vertical bending wet mode frequency ($f_{2\text{-node}}$) under the original and small stiffness are 0.8% and 4.2% respectively, which indicates the correctness of using 3D hydroelasticity theory to predict the wet mode frequency of the hull.

2.2 Response analysis in waves

In order to compare the responses of the two kinds of hull-girder stiffness models in regular waves, the

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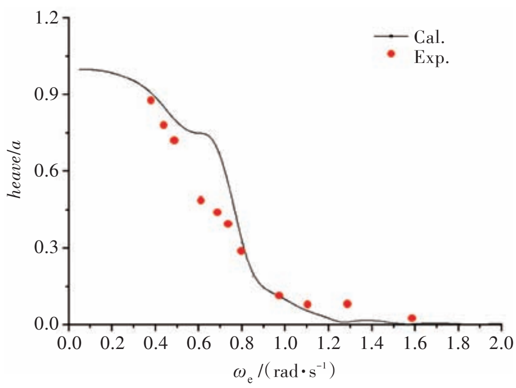
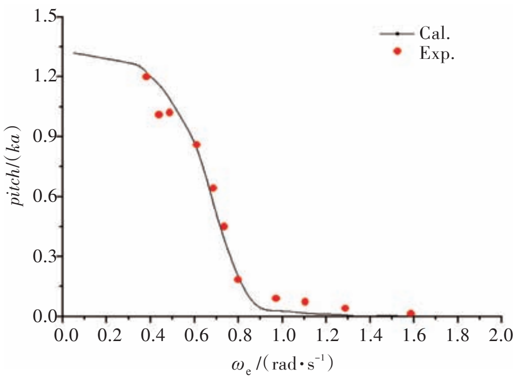
heading regular wave RAO tests are carried out on the two models under the same condition respectively, and the sailing speed is 19.5 kn. Comparison of pitch and heave RAOs is shown in Fig. 8. The dimensionless values of the heave and pitch are *heave/a* and *pitch*/(*ka*) (*a* is the wave amplitude and *k* is the wave number) respectively, and ω_e is the frequency. The model test and theoretical prediction both show that the reduction of the hull-girder stiffness does not have significant effect on the heave and pitch motions of the ship in waves.

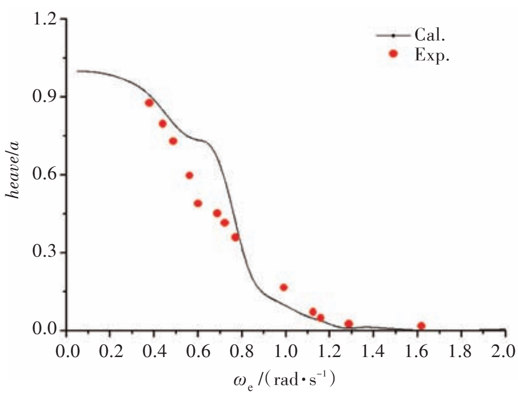
To compare the effect of hull-girder stiffness change on the vertical bending loads of regular waves, comparison of test and experimental values of the VBM RAO for two kinds of hull-girder stiffness is given in Fig. 9. Limited by the wave generation ability of the present laboratory tank and the model scale, the model test value can only be limited to the



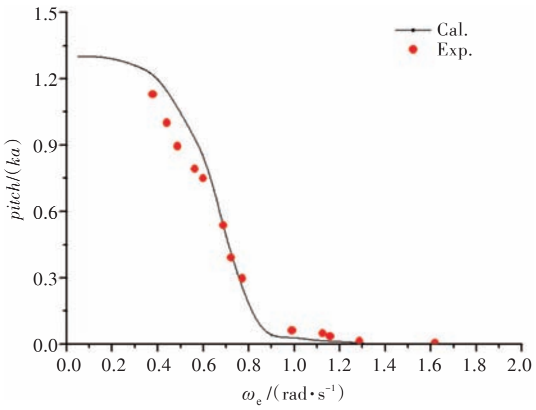
(a) Heave RAO of the original hull-girder stiffness model



(b) Pitch RAO of the original hull-girder stiffness model



(c) Heave RAO of the small hull-girder stiffness model

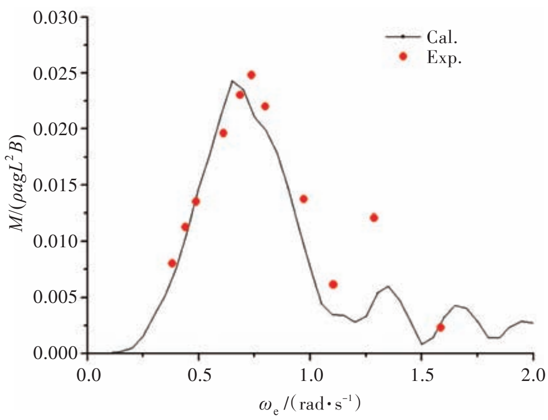


(d) Pitch RAO of the small hull-girder stiffness model

Fig.8 Comparison of heave and pitch RAOs between theoretical and experimental results

frequency range less than 2.0 rad/s, which is less than the two-node vertical bending wet mode frequencies of the two hull-girder stiffness. Therefore, in order to realize RAOs comparison of two-node vertical bending wet mode frequencies, even higher order frequencies, it is necessary to use the tank with stronger wave generation ability to carry out large-scale model test. However, though in the frequency range less than 2.0 rad/s, the differences between model test value and theoretical calculation value are also large at some frequencies. The experimental values show that there is a small peak at 1.25 rad/s, in addition to the peak near the frequency of 0.75 rad/s. The peak (although the peak position is slightly deviated) is also reflected in the theoretical prediction results, but its amplitude is only about half of the model test value. This is because the theoretical prediction cannot fully reflect some of the springing effects subjected by the hull in the model test. It can be seen from the comparison of theoretical prediction results that the peak values of the RAOs of the small hull-girder stiffness are all greater at the frequency range of 1.25 to 2.0 rad/s.

Time history curves of VBMs from theoretical calculations with different wave periods in two kinds of hull-girder stiffness are shown in Fig. 10. As can be



(a) RAO of VBM of the original hull-girder stiffness model

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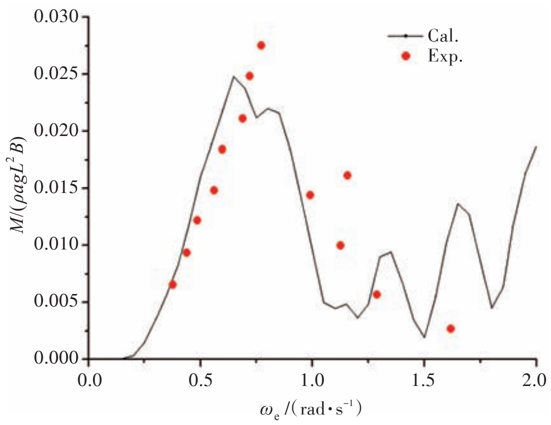
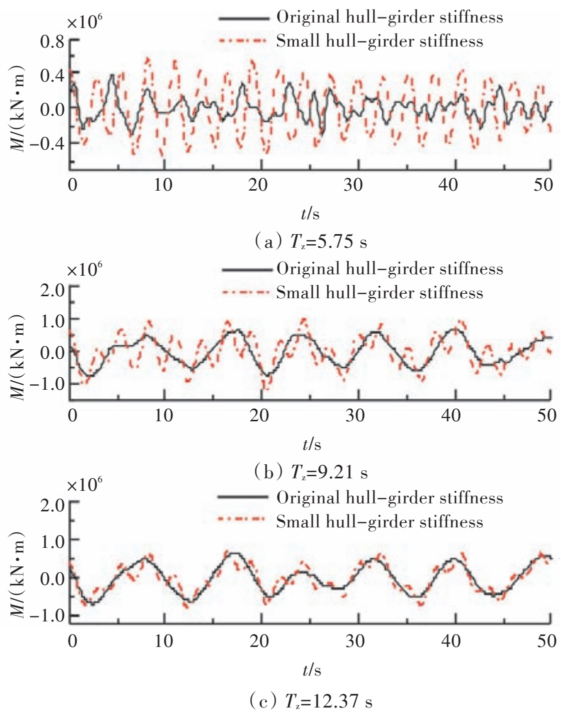


(b) RAO of VBM of the small hull-girder stiffness model

Fig.9 RAOs' comparison of VBMs

seen from the figure, the springing phenomenon can be fully reflected in the time history curves of VBMs from theoretical calculations with small hull-girder stiffness. It becomes more remarkable with the wave period decreasing. However, the time history curves under the original hull-girder stiffness only present a slight springing phenomenon even in the minimum wave period in the figure.

Fig. 11 presents the histograms of VBMs from theoretical calculations with different wave periods in two kinds of hull-girder stiffness corresponding to Fig. 10. As shown in the figure, in the original hull-girder stiffness, the *WM* and *HM* of theoretical calculation results are all in well accordance with test values; wave frequency components are close to synthetic components in different wave periods. They indicates that the contribution of high-order



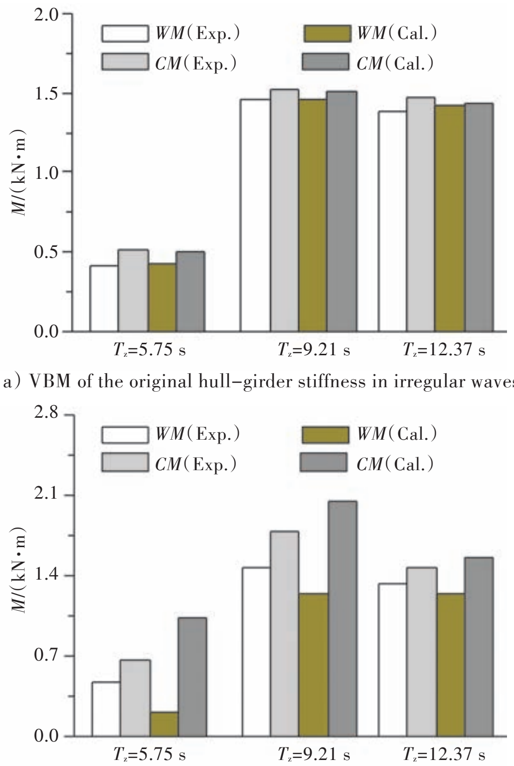
(a) T_z=5.75 s

(b) T_z=9.21 s

(c) T_z=12.37 s

Fig.10 Time history curves of VBMs from theoretical calculations with different wave periods in two kinds of hull-girder stiffness

components of the load components is small. When the stiffness becomes smaller, the wave frequency and high-frequency components of theoretical calculation results have a certain difference from model test values. The smaller the wave cycle is, the more significant the difference is. As can be seen from the comparison analysis of model test results and theoretical calculation results in the two kinds of hull-girder stiffness, the characteristics of springing behavior in the small wave period are more remarkable, and springing behavior is more prone to happen with small hull-girder stiffness.



(a) VBM of the original hull-girder stiffness in irregular waves

(b) VBM of the small hull-girder stiffness in irregular waves

Fig.11 Comparison of histograms of VBMs from theoretical calculations with different wave periods in two kinds of hull-girder stiffness

3 Conclusions

The large scale development trend and the demand of lightweight design of ship structures make the hull-girder become relatively more flexible, therefore, springing behavior is prone to happen with large-scale ships in small and middle-sized waves when the ship is sailing in waves. The springing behavior usually does not cause structure strength problems, however, it can increase the number of stress cycles of hull structures sharply and result in the fatigue damage problems of hull structures. In this paper, aimed at the hull transverse-section characteristic parameter such as the stiffness, the influences of the stiffness change on the springing behavior are studied synthetically from the two aspects of model test and theoretical prediction. The following conclu-

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sions are drawn:

1) Although the reduction of the hull-girder stiffness has little effect on the rigid body motion (such as heave and pitch) of the ship in waves, the elasticity of the hull-girder is relatively increased, resulting in the decrease of the vertical vibration frequency and the increase of load response corresponding to the frequency multiplication. The model test can fully reflect the springing phenomenon. Among the contributions to the total load components, *WM* and *HM* (namely springing) are developing towards two directions of smaller and larger respectively.

2) Under the influence of any or the combination of the two factors which are smaller wave periods and lower hull-girder stiffness, the two-node vertical vibration frequencies of the hull-girder will gradually be close to those of the encountered waves, overlapping or even less than the latter. It is bound to propose new development needs of wave load characteristic analysis methods after the large-scale development of ships.

3) Frequent springing behaviors may lead to the serious fatigue damage of ship structures, therefore, when doing the optimization design of ship structures, it is necessary to consider the relative decrease problem of the transverse-section stiffness caused by the use of materials such as high strength steel. Although the small hull-girder stiffness will not appear in the real ship, it is a meaningful exploratory study for the development super-large marine structure design in the future.

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船体梁刚度对波激振动影响的比较研究

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摘　要：船舶大型化发展的趋势使得其尺度越来越大，而结构轻量化设计的需求则使高强度钢被大量应用于其结构设计之中，相对于传统的小尺度船舶，相对刚度的下降使得船体梁变得越来越“软”，这将导致大型船舶在波浪中航行时船体结构波激振动特性发生变化。采用模型试验和理论预报的方法，研究某大型工程船在不同船体梁刚度下的低频和高频垂向波浪载荷响应。分段试验模型采用2种横剖面惯性矩的钢质梁，用以分别模拟船舶横剖面原始的和变化后的刚度。采用三维水弹性理论对该船在波浪中的响应进行预报，并与模型试验结果进行比较。结果显示：小刚度的船体梁更易在波浪中发生波激振动；频繁的波激振动将导致结构发生严重的疲劳损伤问题。这种刚度变化对船体梁波激振动的影响规律表明，有必要将刚度作为大型船舶结构优化设计的重要参数之一。

关键词：船体梁；刚度；波激振动；模型试验；三维水弹性理论

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