Vibration Characteristics of Separated Superstructure of a Ship

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Abstract. The IMO noise code revised in 2012 is applied to newly built ships whose tonnage are equal or larger than 1600GT's. Particularly for vessels of 10,000 GT's or more, the noise regulation value of the living quarter became more severe than before. As a countermeasure to the noise code in the living quarter, it is recommended to separate accommodation area from funnel casing structure. However, as the result of the separation, natural frequencies of the superstructure is expected to decrease and possibly cause resonance with the excitation due to the engine or propeller excitation.

Therefore, in the present research we aim to elucidate the vibration characteristics of a separated superstructure of a chemical tanker with L × B × D = abt.146 m × 24 m × 13 m. We have calculated principal natural frequencies and modes of the separated superstructure by using finite element vibration analysis for 3 types of models, as 1) superstructure (S.S.) only on the rigid foundation, 2) S.S. with the aft part of the ship including the engine room considering the effect of the elastic foundation, and 3) whole ship model considering the effect of hull girder vibration including the effect of added mass of outer sea water.

Then the effect of shallow water and proximity related to added mass are investigated by using the whole ship FE model. Finally some structural modifications to increase the natural frequencies are investigated by using the numerical analysis, and the effects of reinforcement on the vibration characteristics have been discussed by comparing with those of the original structure.

Keywords: Vibration · Superstructure · Whole ship FE analysis

1 Introduction

In 2012, IMO Maritime Safety Committee adopted a draft amendment on the inboard noise code that recommends that noise generated from engine room and crew's noise exposure be kept below a certain level in order to preserving health of crews. In the new noise code [1], noise regulation values, measurement methods, measurement devices, etc., have been revised.

The revised noise code is applied to newly built ships whose tonnage are equal or larger than 1600GT's. Particularly for vessels of 10,000GT's or more, the noise regulation value of the living quarter was reduced by 5 dB.

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As a countermeasure to the noise code in the living quarter, it is recommended to separate accommodation area from funnel casing structure. However, as the result of the separation, natural frequencies of the superstructure are expected to decrease and possibly cause resonance with the excitation due to the engine or propeller excitation. Therefore, in the present research we aim to elucidate the vibration characteristics of a separated superstructure of a chemical tanker with L × B × D = abt.146 m × 24 m × 13 m.

Firstly, the effect of modeled range of the ship structure are investigated by calculating natural frequencies and modes of the separated superstructure. FE analysis has been performed for 3 types of FE models, 1) superstructure alone model on the rigid foundation, 2) S.S. with the aft part of the ship including the engine room considering the effect of the elastic foundation, and 3) a whole ship model considering the effect of hull girder vibration including the effect of added mass of sea water.

Secondly the effect of the shallow water or a quay on the natural frequencies and modes are investigated, because the excitation test is usually performed near the quay. To verify the FE analysis results, the numerical results were compared with the excitation test ones.

Thirdly the effect of structural design change to raise natural frequencies are investigated to prepare for the possibility of resonance after construction. We have performed numerical analysis for some realistic cases by structural change and discussed by comparing with those of the original structure.

2 Effect of FE Modeling Range on Superstructure Vibration

2.1 Natural Vibration Analysis Using FEM

In the present study, finite element analysis is used to derive the natural frequencies and their natural vibration mode by solving the following equation of an eigenvalue problem,

$$\left(\mathbf{K} - \omega^{2}(\mathbf{M} + \mathbf{M}^{*}\right)\mathbf{u} = \mathbf{0} \tag{1}$$

where **K**, **M**, **M***, and **u** are stiffness matrix of the structure, mass matrix, added mass matrix of sea water, and nodal displacement vector respectively. Solution of Eq. (1) are derived as natural angular frequencies, ω_{i} and mode vector, $\mathbf{u}_{\mathrm{i}}$. Mass matrix includes not only the structural mass but also all the other mass contained in the ship structure. Added mass matrix is obtained by the virtual mass method based on the potential fluid theory considering the free surface location. In the present study, only the surrounding sea water produces the added mass effect on the hull structure. Various inner liquid contained in the ship structure are replaced by equivalent nodal mass or distributed mass attached to the structural elements. All the matrices and solutions are calculated by using a commercial software, MSC Nastran.

2.2 FE Modellings for Superstructure Vibration Analysis

The target ship to investigate is a chemical tanker. The principal particular is L × B × D = abt.146 m × 24 m × 13 m. Figure 1 shows a separated superstructure's FE model above the upper deck level where accommodation area is separated from funnel-casing structure above upper deck. Deck plates, hull skins and side walls of the superstructures are reproduced with equivalent shell elements with 4 nodes, and stiffeners and pillars are created with beam elements. The mesh size of each element is 0.700 m or less which is the frame space of the present ship. Details of the method to derive the equivalent property is explained in Ref. [2]. For FE analysis, a commercial finite element analysis software, MSC Nastran was used.

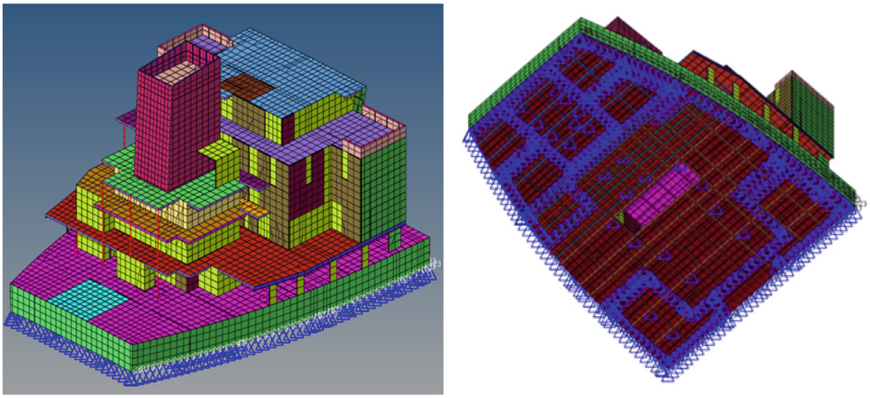

Fig. 1. A FE model and constrained nodes of a separated superstructure alone model above the upper deck (Blue triangle markers are the restrained points)

Superstructure Alone Model

The simplest FE model for the superstructure is a ‘superstructure alone model’ shown in Fig. 1. In this case, the range of the model is limited above the upper deck. In this analysis, comparatively rigid edges connected with the wall of the lower structure are constrained as the geometrical boundary condition as shown in the Fig. 1. Therefore, the elastic foundation effect of the lower structure is neglected in this model.

Stern Structure Model of Superstructure with Engine Room

The second FE model is the superstructure with the aft part of the ship including the engine room as shown in Fig. 2. For the vibration analysis, this FE model is constrained at the fore transverse bulkhead and the bottom narrow part. Added mass effect of sea water contacting the hull surface is considered. This FE model can take the elastic foundation effect for the superstructure into consideration, but the interaction with the hull girder vibration cannot be incorporated enough.

Whole Ship FE Model

The third FE model is a whole ship FE model shown in Fig. 3. There is no constraint all through the structure as kinematic boundary condition. Added mass effect of sea water contacting the hull surface is considered. Number of shell elements are 15,295 for the superstructure and 10,939 for hull girder where the maximum size of the shell

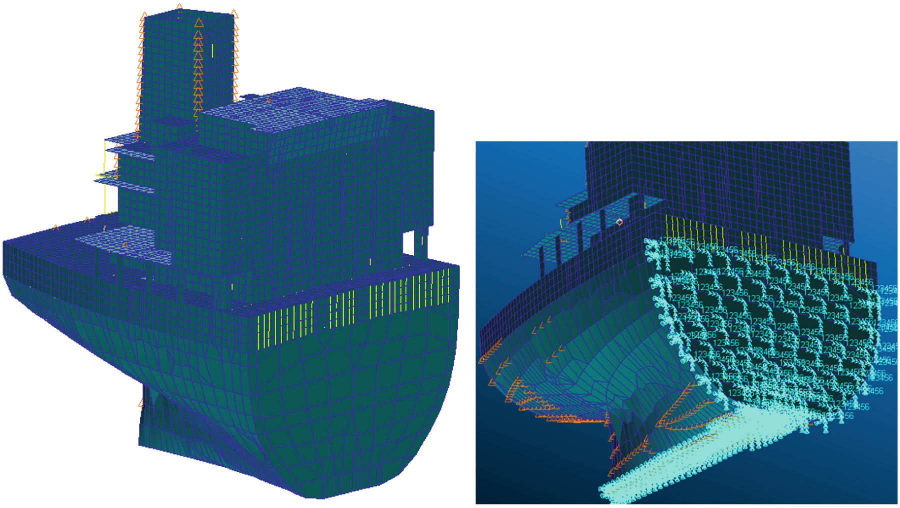

Fig. 2. Stern structure FE model and constrained points (Light blue markers indicate constraints)

element in the hull girder is the same as one transverse frame space. Corrugate bulkhead in the tank holds are replaced by the equivalent orthotropic shell element referring to [3]. Number of shell elements in contact with outer seawater is about 2500. Numerical calculations are conducted for the loading conditions corresponding to empty, ballast, and full load conditions respectively. The empty condition is a special light weight condition where the ship is floating in the shallow water near a quay. Impact hammering test was conducted to investigate the vibration characteristics by using the technique of experimental modal analysis. Hull surface area contacting with seawater is dependent on the loading conditions. Loading conditions we considered are shown in Table 1.

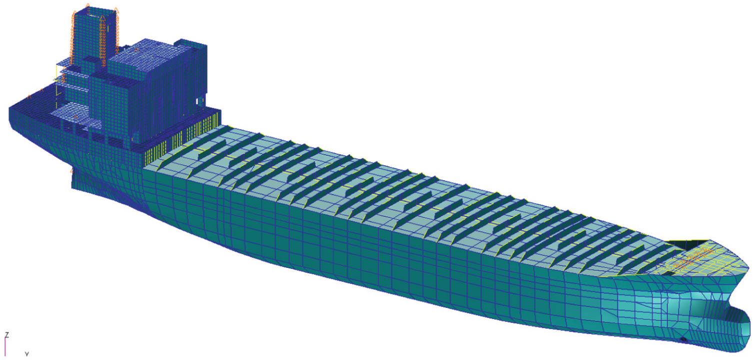

Fig. 3. Whole ship FE model

Table 1. Loading conditions and draft

Loading condition	Total weight of whole ship model (ton)	Aft draft da (m)	Front draft df (m)
Empty	abt. 5,000	4.7	0.3
Ballast	abt. 11,500	5.9	4.1
Full load	abt. 25,000	10.0	9.4

2.3 Numerical Results of the Effect of Modelling Range

We focus on the fore-aft vibration of separated superstructure in the present study. Representative fore-aft vibration modes of the present chemical tanker in full load condition by solving Eq. 1 for a whole ship FE model are shown in Figs. 4 and 5. Two modes in Fig. 4 are strongly affected by the hull girder vibration where the motion of superstructure is dependent on the global hull girder vibration with 6 nodes and 7 nodes respectively.

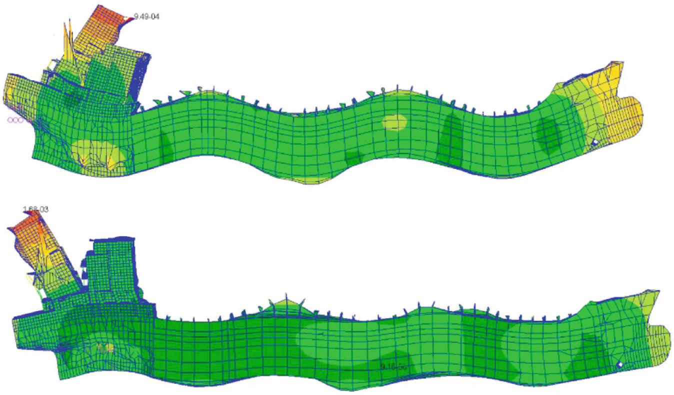

Fig. 4. Hull girder dominant modes (upper: 422 cpm (7.03 Hz), lower: 505 cpm (8.42 Hz))

On the other hand, two modes in Fig. 5 are not affected by global hull girder deformation. In this superstructure dominant modes, natural frequency of reverse mode is lower than that of in-phase mode. In the reverse mode, rocking motion of the structure of living quarter occurs because the front wall of the structure is rigidly supported by the transverse bulkhead while the aft wall of the structure is not supported generally due to the existence of the engine room. As for the in-phase mode, the superstructure of both living quarter and funnel casing structure moves in the same direction but the stern part above propeller moves vertically in reverse.

Comparison of Natural Frequencies of Superstructure

The superstructure dominant modes are observed both superstructure alone model and stern structure modes. Natural frequencies of fore-aft vibration modes of superstructure for empty, ballast, and full load condition have been calculated as shown in Fig. 6.

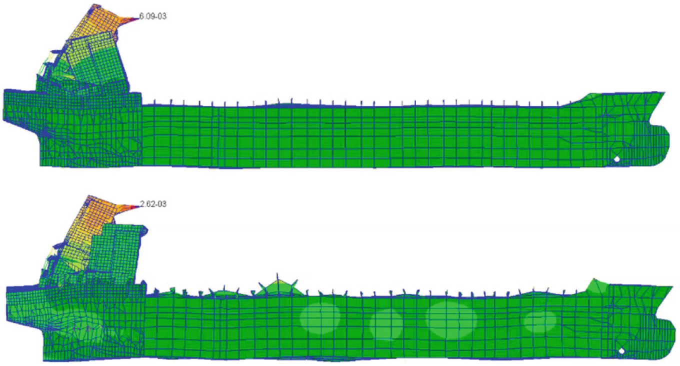

Fig. 5. Superstructure dominant mode (upper: opposite phase mode, 568 cpm (8.47 Hz), lower: in-phase mode, 644 cpm (10.73 Hz))

In reverse phase mode, it is largely influenced by the elastic foundation effect below the upper deck level and natural frequency is reduced for stern structure model and whole ship model while the influence of the loading condition is small.

In in-phase mode, natural frequency is largely influenced by the loading condition because this mode is coupled by the stern part. Loading condition changes the added mass of sea water largely on the stern part.

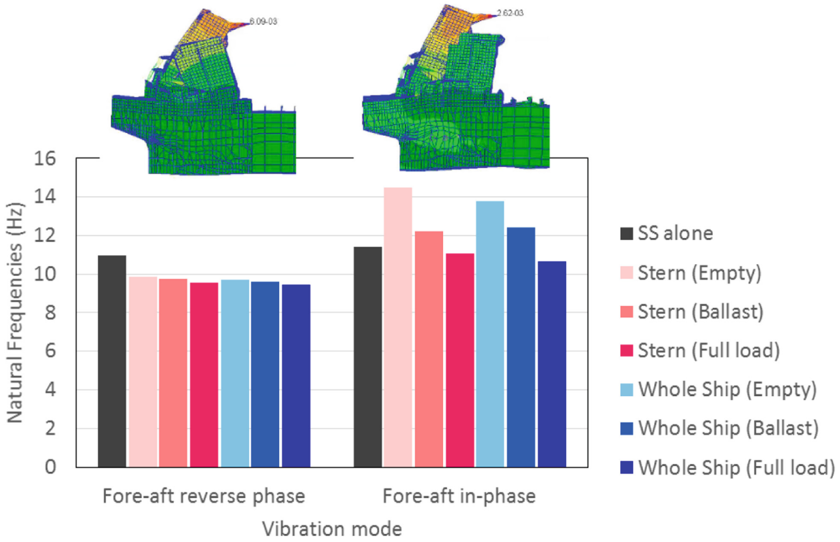

Fig. 6. Numerical results of natural frequencies of fore-aft vibration of superstructure in empty, ballast, and full load conditions (SS alone: Super structure alone model, Stern model with superstructure, Whole Ship: whole ship FE model)

3 Effect of Shallow Water and Proximity of Quay

3.1 Modeling of Sea Bottom and Quay and Numerical Convergence

Impact hammering test or exciter test is often conducted near quay because of the convenience of loading and unloading of the test machine. But it is located in shallow water and close to the quay wall. Generally the added mass effect may increase when the fluid motion is restricted. Also the loading condition is different from normal operating condition. Therefore it is difficult to predict the natural frequency or vibration response from the experimental test in quay area. In case of hull girder dominant vibration of superstructure, there might be the large effect of the shallowness and proximity on the natural frequencies.

Therefore, a whole ship vibration analysis considering the effect of shallow water and quay wall has been performed. Those effect is realized by the function of MFLUID in MSC NASTRAN arranging the rigid large plate to restrict fluid motion around the whole ship FE model as shown in the right of Fig. 7. As the results of investigation of the numerical convergence, the length and breadth of the rigid plate is decided to be three times large as the ship length and 7 times large as the ship width respectively, and the mesh size of the square plate element is selected to be 2.8 m.

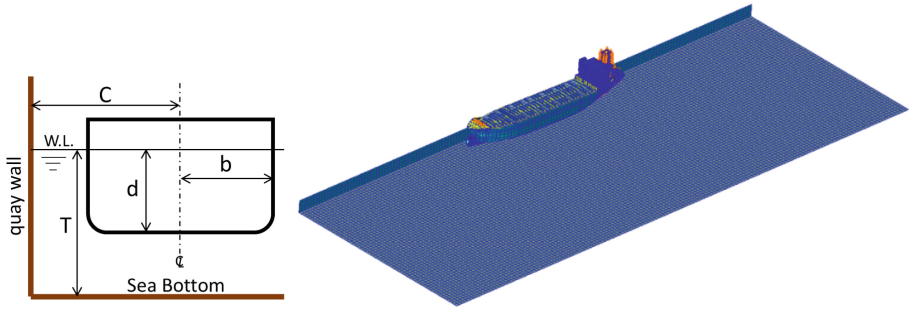

Fig. 7. Configuration of a ship, sea bottom, and quay and FE to restrict the fluid motion

3.2 Added Mass Effect of Shallow Water and Quay on the Natural Frequencies

The effect of shallow water and the effect of proximity of quay wall on the natural frequencies of vertical hull girder vibrations are shown in Fig. 8 and Fig. 9 respectively. The parameters of shallowness to water depth and proximity to quay wall are defined respectively T/d and C/b referring to the left figure in Fig. 7.

The effect of shallow water is negligible for $T/d > 5$, but cannot be negligible for $T/d < 2$. This result is consistent with refs. [4] and [5]. The effect of proximity of quay wall is negligible for $C/b > 2$, and much smaller for vertical hull girder vibration compared with the effect of shallowness.

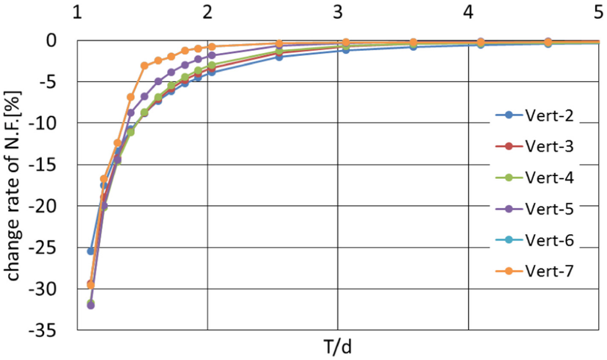

Fig. 8. Effect of shallow water on the natural frequencies of vertical hull girder vibration

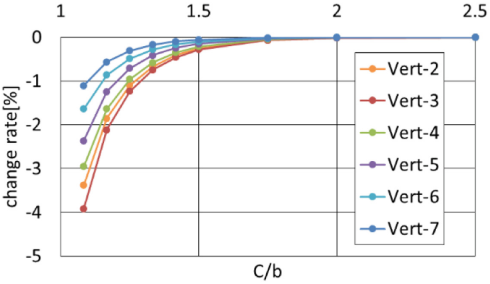

Fig. 9. Effect of proximity of quay on the natural frequencies of vertical hull girder vibration

3.3 Comparison of Natural Frequencies Between Experimental Results and Whole Ship FE Analysis

In Fig. 10, natural frequencies obtained by hammering test close to a quay is compared with those obtained by whole ship FE vibration analysis with and without considering the effect of shallow water and quay wall explained in the Sect. 3.2. Hammering test means the impact excitation method based on the experimental modal analysis. The impact excitation was performed using large hammering equipment fixed on the stern deck. And the structural responses are derived simultaneously from multiple accelerometers placed on the ship structure. Natural frequencies and corresponding vibration modes are identified from experimental modal analysis with FFT of the obtained data. In the FE analysis, water depth T = 7 m are used.

Judging from the results in Fig. 10, shallow water effect can be observed. But some of the analysis results are too reduced by the effect compared with experimental ones. It may come from the difference of the flatness and inclination of the sea bottom between the numerical model and real experimental condition.

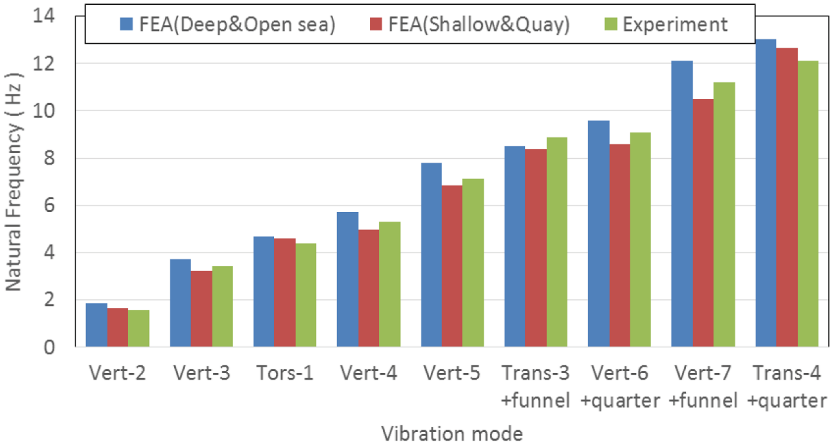

Fig. 10 Comparison of natural frequencies between whole ship FEA and experimental test (Vert2: vertical hull girder vibration with 2 nodes, Tors-1: torsional hull girder vibration with 1 node, Trans-3: transverse hull girder vibration mode with 3 nodes, funnel: funnel casing structure, quarter: living quarter structure)

4 Effect of Design Modification on Natural Frequencies and Modes

4.1 Design Modification to Raise the Natural Frequencies

Separated superstructure has lower natural frequencies than conventional integrated superstructure. Therefore possibility of resonance against the excitation source may be higher. It is important to know the ways to increase the natural frequencies of the superstructure effectively by structural modification to avoid resonance to excitation forces.

The effect of three kinds of stiffening approach are considered and investigated by numerical analysis using whole ship FE model.

1. Large connecting structural members are added between the superstructure and hull girder. Large girder type or box girder support type are considered as shown in Fig. 11. The latter is introduced in this paper (Box girder support type).
2. Plate thickness of side walls of living quarter structure is increased to raise the vertical in-plane shear stiffness (Wall thickness increased type) as shown in Fig. 12 Breadth and depth of the cross section are 1.500 m and thickness is 10 mm.
3. Partial connections between living quarter and funnel-casing structures are built to avoid the settling with rocking motion (Partial bridge type) as shown in Fig. 13. Three girders are built on each floor of C deck and D-deck respectively. The cross section size of the girder is 600 mm × 300 mm each.

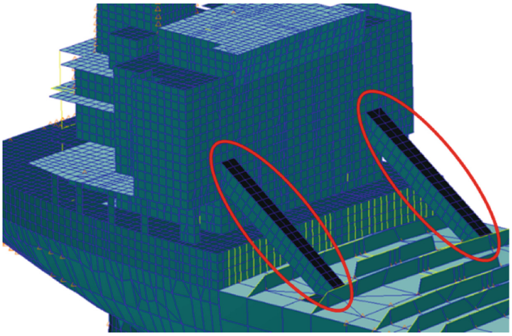

Fig. 11. Box girder support

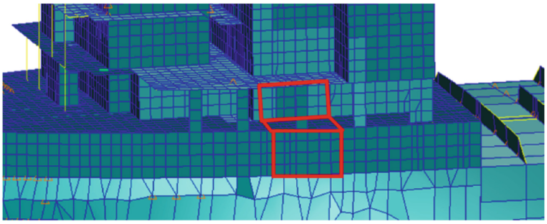

Fig. 12. Wall thickness increased to enhance the shear stiffness

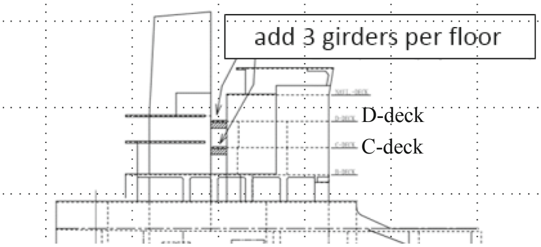

Fig. 13. Partial connection by 6 girder between superstructures

Increase of the natural frequency to the original structure is shown in Table 1. In case of box girder support type as shown in Fig. 11, natural frequencies of superstructure are remarkably increased for both reverse and in-phase modes. Especially this support is effective to in-phase mode in superstructure. But it should be noted that hull girder vibration modes are strongly influenced and natural frequencies are decreased as shown in Table 1. In case of increasing side wall thickness, effect is smaller than any other type though it is observed a small improvement in reverse mode of superstructure. In case of the partial bridge connection type, it is effective to both reverse and in-plane modes. This is especially effective to the reverse mode (Table 2).

Table 2. Increasing rates of natural frequencies by structural modification (unit: %)

Vibration Mode	Box girder support	Side wall thickness increased	Partial bridge connection
Vert-2	−10.3	−0.1	−0.0
Vert-3	−14.2	−0.0	−0.0
Vert-4	−16.5	0.0	−0.0
Vert-5	−12.2	0.1	−0.0
Vert-6	−6.0	0.1	0.0
Vert-7	4.7	0.1	0.1
SS-reverse	4.8	0.6	9.2
SS-in-phase	18.4	0.1	0.9

5 Conclusion

Natural frequencies of separated superstructure are calculated for superstructure only model, superstructure with stern structure model, and whole ship mode. As the results, it is proved that the elastic foundation effect is large for reverse mode and that loading condition affects the in-phase mode related to the interaction with stern part vibration in contact with seawater. Superstructure dominant modes can approximately be derived by stern structure model.

Shallow water effect and proximity effect to quay wall have been investigated. Hull girder dominant mode are strongly affected by the effect while superstructure dominant modes are hardly affected.

Comparison between natural frequencies obtained from hammering test and those of whole ship FE model. It proved the reduction of natural frequencies due to the effect of shallow water and proximity of quay wall.

The effects of some structural modifications are investigated using whole ship model to raise natural frequencies related to superstructure. As the results, connection between superstructure and hull girder with large support members may raise the natural frequencies effectively, but may largely reduce the natural frequencies of hull girder vibration. The method to increase the thickness of sidewall of the superstructure increases the natural frequency a little. Connection between the accommodation structure and funnel casing structure is very effective to reverse mode.

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