Vibration control of ship

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Abstract

Recently, the ship size and speed are increased but the structure of ship become more flexible because of the energy and cost efficiency by using the weight reduction. In addition, the vibration criteria become lower and lower because of request for the passenger comfort, crew habitability, durability of equipment and hull soundness of structure, so the ship vibration control is more important than ever.
The aim of this article is to explain the process of ship vibration control to avoid excessive vibration from design stage to sea trial.

1 Introduction

With the increase of ship size and speed, shipboard vibration becomes a great concern in the des ign and construction of the vessels. Excessive ship vibration is to be avoided for passenger comf ort and crew habitability. In addition to undesired effects on humans, excessive ship vibration ma y result in the fatigue failure of local structural members or malfunction of machinery and equip ment.
The procedure of ship vibration control is shown in Figure 1. For the vibration control of ship, firstly, the vibration criteria have to be set up based on the Building Specifications, class recommendation and international standards. In the initial design stage, predominant excitation sources of ship vibration are selected by using the data of experienced ships such as the number of main engine cylinders and propeller blades. In the detail design stage, global vibration and local vibration analysis are carried out by using the Finite Element Analysis to predict the vibration level and natural frequency for whole ship and local structure. Finally, global and local vibration measurements are carried out during the sea trial to assess the vibration performance of ship. At each stage, vibration levels are checked and if the vibration levels are not satisfied the criteria, appropriate methods for vibration control are applied.

2 Vibration criteria

The vibration criteria have to be set up based on the Building Specifications, class recommendation and international standards. The vibration criteria are divided into three parts as below.

- Criteria for human beings
- Criteria for structural vibration
- Criteria for equipment

With regard to vibrations on human beings, the criteria are aimed solely at ensuring comfort and well-being. The international standard ISO 6954(2000)[1] is normally used as the guidelines for the evaluation of vibration with regard to habitability on passenger and merchant ships as shown in Table 1. The upper allowable vibration limits of ISO 6954(2000) are 6 mm/s and 8mm/s for crew accommodation areas and working areas, respectively.

As for the structural vibration, the ship structures are exposure to the vibration due to the predominant excitation forces such as main engine and propeller. The criteria of structural vibration are recommended in view of the low risk of fatigue cracks as shown in Table 2 on the VIBRATION CLASS(2011) [2] published by DET NORSKE VERITAS.

To protect the machinery from the excessive vibration, the criteria for equipment vibration is recommended on the VIBRATION CLASS(2011) as shown in Table 3. The vibration criteria are applied for both the internal sources(vibration from the machinery itself) and the external sources(vibration transferred from other machinery).

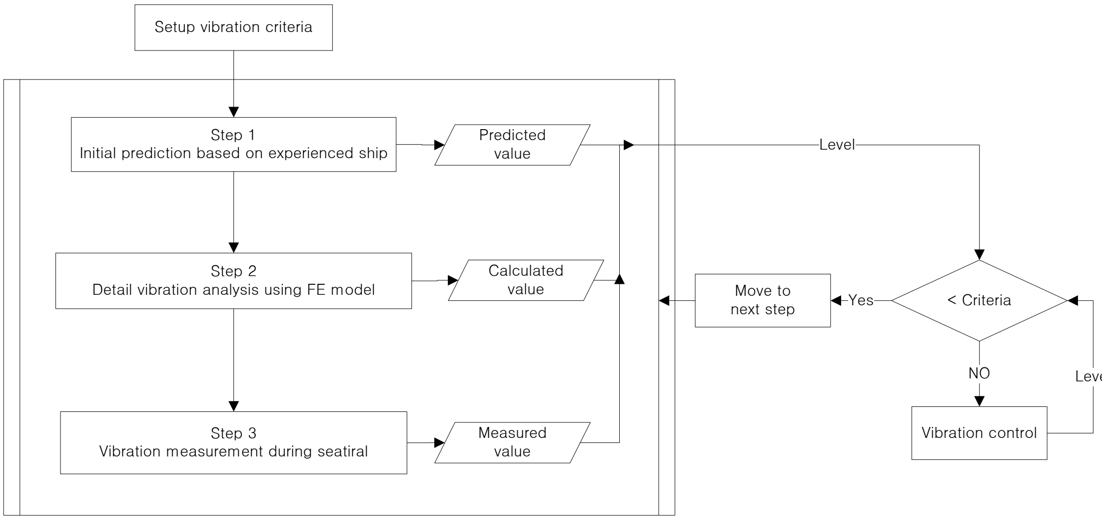


Figure 1 Flow chart of ship vibration control

Table 1 Overall frequency-weighted r.m.s. values from 1 Hz to 80 Hz given as guidelines for the habitability of different areas on a ship

	Area classification					
	A Passenger cabins		B Crew accommodation		C Working areas	
	Acceleration (mm/s^2)	Velocity (mm/s)	Acceleration (mm/s^2)	Velocity (mm/s)	Acceleration (mm/s^2)	Velocity (mm/s)
Values above which adverse comments are probable	143	4	214	6	286	8
Values below which adverse comments are not probable	71.5	2	107	3	143	4
NOTE : The zone between upper and lower values reflects the shipboard vibration environment commonly experienced and accepted.						

Table 2 Criteria for the structural vibration r.m.s. values from 4 Hz to 200 Hz

Table B1 Steel
Velocity
4 – 200 Hz
45 mm/s

Table B2 Aluminium
Velocity
4 – 200 Hz
15 mm/s

Table 3 Criteria for the machinery vibration

Table C1 Shaft line bearings
Velocity
1 – 200 Hz
5 mm/s
To be measured horizontally or vertically with the shaft centre. Shaft line vibration is specified in Pt.4 Ch.4 Sec.1. Frequency spectra to be presented to identify low frequency components.

Table C2 Diesel engines < 200 rpm		
	1 – 200 Hz	
	Displacement	*Velocity*
Vertical	1 mm	10 mm/s
Longitudinal	1 mm	10 mm/s
Transverse	1.5 mm	25 mm/s
To be measured at the top of the A – frame at engine ends. Frequency spectra to be presented to identify low frequency components.		

Table C3 Diesel engines > 200 rpm	
Velocity	
4 – 200 Hz	
Firmly mounted	Resiliently mounted
15 mm/s	25 mm/s
To be measured on the engine block top and bottom. 20% overshoot of the above criteria allowed for non continuous running in the operating speed range.	

Table C4 Turbochargers		
4 – 200 Hz		
Total combined power from cylinder group serving one turbocharger	*Velocity*	*Acceleration*
Below 5 MW	45 mm/s	2.5 g
5 - 10 MW	50 mm/s	2.0 g
Above 10 MW	55 mm/s	1.5 g
To be measured at the top of compressor casing. 20% overshoot of the above criteria allowed for non continuous running in the operating speed range.		

Table C5 Diesel driven generators and electrical motors on thrusters
Velocity
4 – 200 Hz
18 mm/s
To be measured in any direction on the bearings. Applies to both fixed and resilient mounted. 1st order vibration above 7 mm/s should be investigated.

Table C6 Turbines
Velocity
4 – 1000 Hz
7 mm/s
To be measured in any direction on the bearings. Applies to both fixed and resilient mounted.

Table C7 Turbine driven generators
Velocity
4 – 1000 Hz
7 mm/s
To be measured in any direction on the bearings. Applies to both fixed and resilient mounted.

Table C8 Gears
Velocity
4 – 1000 Hz
7 mm/s
To be measured in any direction on the foundation and on the input shaft bearing

Table C9 Electric motors, separators, motor driven hydraulic pumps, fans not installed on reciprocating engines	
	Velocity
	4.0 – 200 Hz 1)
Internal excited	7 mm/s 2)
External excited	12 mm/s
To be measured in any direction on the bearings. 1) The upper frequency limit shall be at least 200 Hz and above 2 x rpm 2) For vertically mounted motors the vibration level may be increased by 50% for the top of the motor.	

Table C10 Compressors (screw or centrifugal)	
	Velocity
	4 – 200 Hz 1)
Elastically mounted	10 mm/s
Fixed mounted	7 mm/s
To be measured in any direction on the bearings. 1) The upper frequency limit shall be at least 200 Hz and above 2x rpm	

Table C11 Reciprocating compressors
Velocity
4 – 200 Hz
30 mm/s
To be measured in any direction on the bearings. Applies for both resilient and fixed mounted.

Table C12 Boilers
Velocity
4 – 200 Hz
45 mm/s
To be measured on stiff parts, e.g. lugs, flanges etc.

Table C13 Pipes
Velocity
4 – 200 Hz
45 mm/s

Table C14 Electronic instruments and equipment	
	Velocity
	4 – 200 Hz
Mounted on bulkheads	12 mm/s
Mounted on masts	20 mm/s
Mounted on machinery	25 mm/s
To be measured on the foundation of the actual equipment	

3 Initial prediction

For the vibration control at the initial design stage, the natural frequencies in cycles per minute (CPM) of hull girder vertical mode are predicted from the data of the experience ship or an empirical formula as shown in Equation (1) suggested by Jung[3] which are originally developed by Todd etc. If there is the possibility of resonance between the predicted hull girder natural frequency and 2nd order moment of main engine, the moment compensator is considered to reduce vibration. The optimal control force for 2nd order moment compensator could be calculated considering the hull girder mode suggested by KS Kim[4] as shown in Figure 2 and Figure 3. It showed an example which is a VLCC with a fixed 4 bladed propeller powered by a diesel engine with 7 cylinder (7G80ME). The compensation force is determined by Equation (3) by using the balance of moments. In Figure 3, the maximum vibration level in the longitudinal direction at the deckhouse is compared for the case with/without moment compensator and the desirable compensation force calculated by Equation(3) is produced at 50 % load of moment compensator for our experienced ship(VLCC tanker, 7G80ME). The velocities for each case are compared at the wheel house deckhouse in longitudinal direction because the deckhouse is the area which most severe vibration criteria applied and the vibration due to 2nd order moment of main engine excite the hull girder vertical vibration and it cause the deckhouse longitudinal vibration. As shown in Figure 2, we expect maximum vibration level is 90% reduced if we use moment compensator with 50% load at 2.2Hz and the other frequencies are below the vibration limit.

$$N_{2v} = 11.38 \times 10^4 \sqrt{\frac{BD^3}{\Delta_1 L^3}} - 0.8 \quad \text{(cpm)} \qquad (1)$$

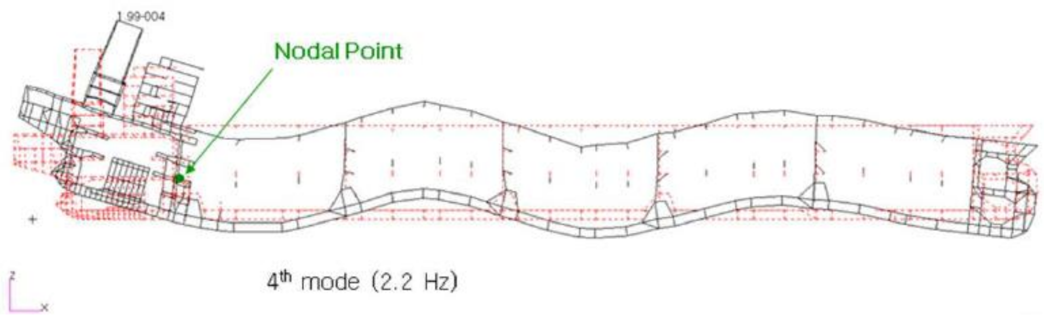
Where N_{2v}, L, B and D are the natural frequency of vertical 2 node, length(m), breadth(m) and depth(m) of ship,

$$\Delta_1 = \Delta(1.2 + \frac{1}{3} \cdot \frac{B}{d}) \quad \text{(ton)} \qquad (2)$$

Δ_1, d and Δ are adjusted displacement for Eq.(1), draft (m) and displacement of ship (ton)

$$F_m = \frac{(L_a - L_f)}{L_a} F_a = \frac{L}{L_a} F_a = \frac{M}{L_a} \qquad (3)$$

Where,
Fm : compensation force
Fa : Aft force due to 2nd order moment of main engine
M : 2nd order moment of main engine
La : distance between main engine aft and nodal point
Lf : distance between main engine forward and nodal point
L : length of main engine



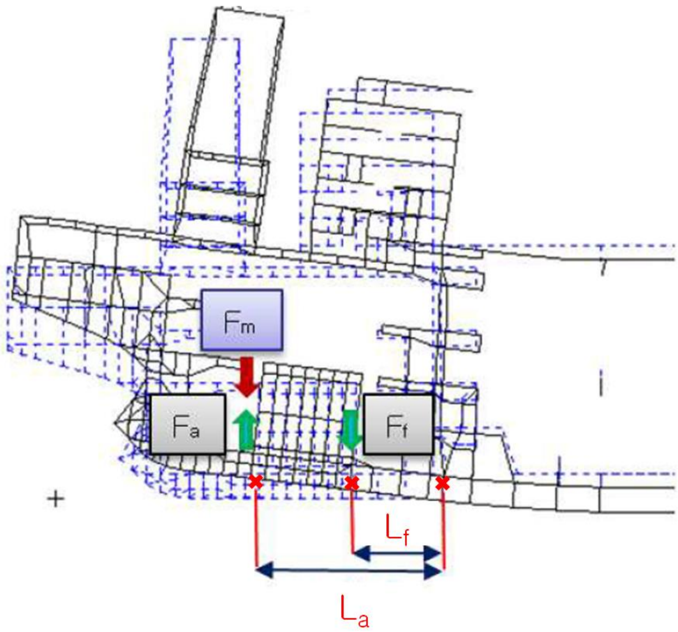


Figure 2 Mode shape and compensation force

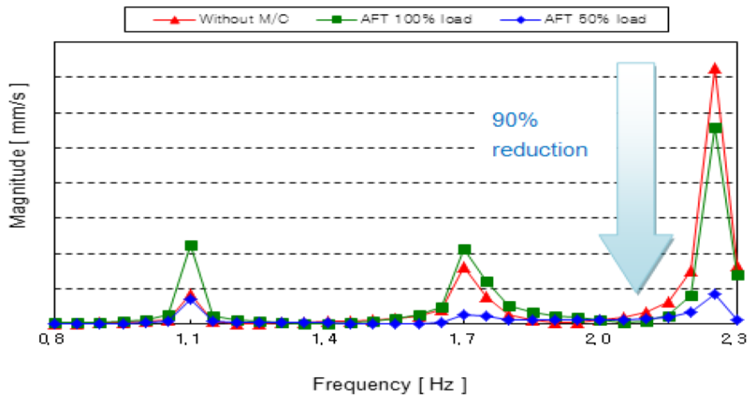


Figure 3 Vibration reduction by using the 2nd order moment compensator - calculated vibration level at wheel house top (Stb'd)

4 Vibration Analysis

At the detail design stage, the vibration analysis is carried out by using the Finite Element Analysis. The vibration analysis is divided into global vibration analysis and local vibration analysis. For the global vibration analysis, the vibration level and mode shape of whole ship are estimated due to predominate excitation forces such as main engine and propeller. The main object of global vibration analysis is to evaluate whether the calculated vibration levels are satisfied the vibration criteria or not. The criteria of vibration level at the deckhouse are much lower than other areas because of the viewpoint of habitability of human being, so the global vibration analysis is focused on the deckhouse.

For the local vibration, the local structures are evaluated by the viewpoint of resonance avoidance for all area in the vicinity of the excitation forces.

4.1 Global vibration analysis

The aim of global vibration analysis is to investigate the overall vibration characteristics of whole ship including following tasks.

- Free vibration analysis of hull girder including deckhouse, aft body and engine room
- Forced vibration analysis to calculate the vibration responses of selected points representing overall vibration behaviors

For the vibration analysis, the whole ship has been idealized to a complete finite element model as shown in Figure 4. The forced vibration responses in deckhouse caused by main engine and propeller have been evaluated. The excitation forces of main engine are supplied by engine manufacturer and propeller excitation due to the fluctuating pressure for each blade passing frequencies is estimated considering fluid dynamics of propeller in the wake field of the ship. The calculated vibration responses for each excitation force and typical mode shapes from global vibration analysis are shown in Figure 5 and 6. The calculated vibration levels in accommodation area are evaluated by comparing with the vibration criteria. In case the vibration level is higher than the criteria, the vibration reduction methods are investigated such as structural modification or vibration control measure by using the moment compensator or top bracing based on the mode shape and mode participation factor.

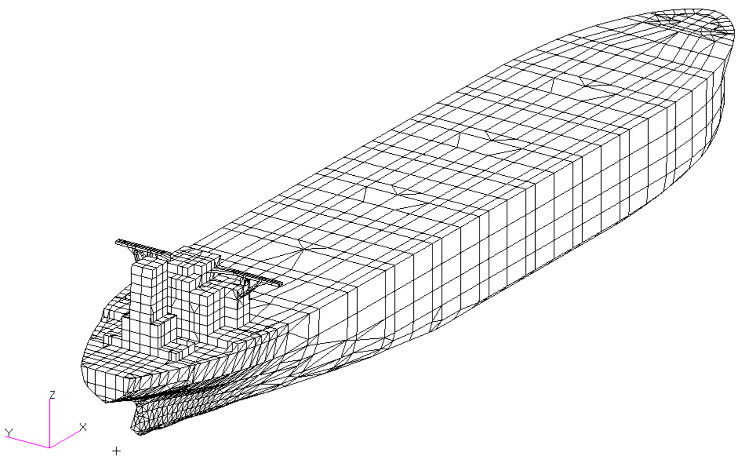


Figure 4 Three dimensional finite element model

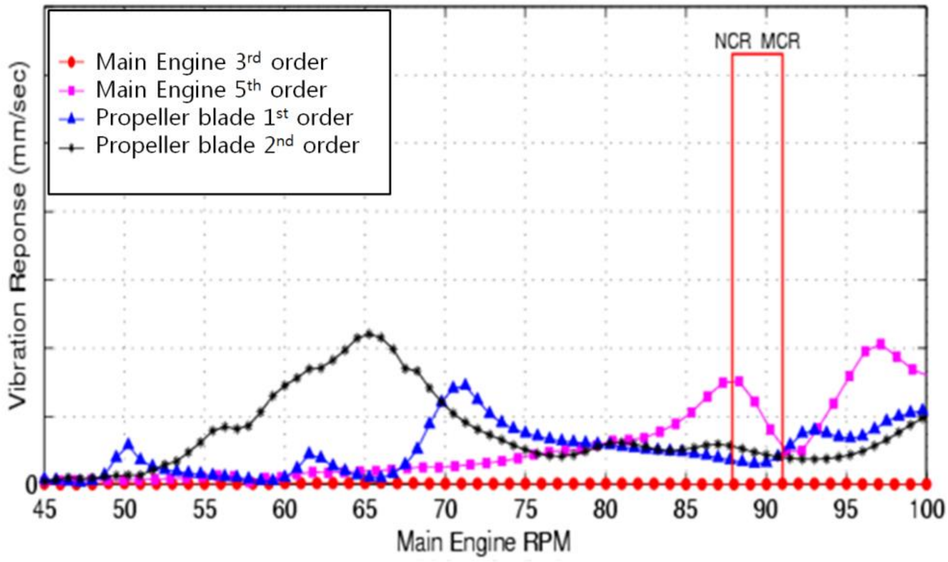


Figure 5 Calculated vibration response at deck house top in longitudinal direction

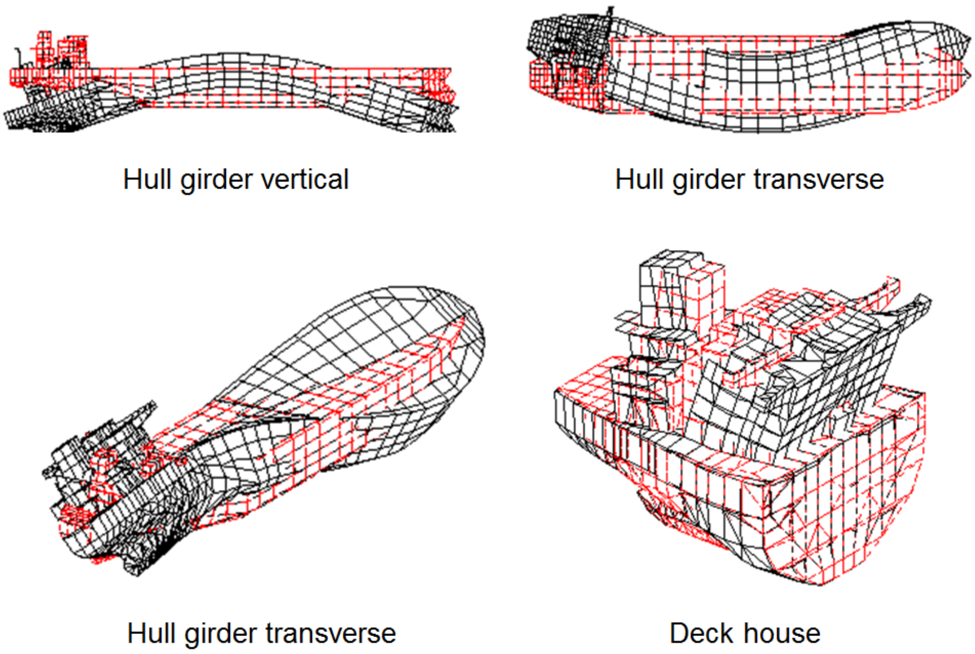


Figure 6 Typical mode shapes of a ship

4.2 Local vibration analysis

The local vibration analysis are performed for local structures in aft body, engine room and deck house areas to prevent the hull structures from the excessive vibration, by means of avoiding the resonance between natural frequencies of local structures and relevant excitation frequencies. The local vibration study has been performed for typical local structures in each concerned area by using F.E analysis.

Because local ship structures have higher natural frequency than those of hull girder, FE models must be built in detail considering the additional mass such as fluid in a tank and distributed mass on a deck. The areas for local vibration analysis include the deckhouse, engine room, stern, as shown in Figure 7.

The design criteria are different depending on the location of the concerned local structures since the affecting excitation sources are different. The desired frequencies on the natural frequency for local structure applied to each region of the subject vessel are as below.

- Desired frequency is 10% higher than a excitation frequency considering once or twice the propeller blade frequency or main engine ignition frequency in the ship's aftbody, engine room and deckhouse area

For a subcritical design, the assumption of simply supported edges is conservative, because each constraining effect increases the safety margin between natural frequency and excitation frequency. In case that the natural frequencies of local structure do not satisfy the design criteria, some modification works are discussed with structure design team such as increase of a plate thickness, stiffener size and or girder size based on a concerned mode shape.

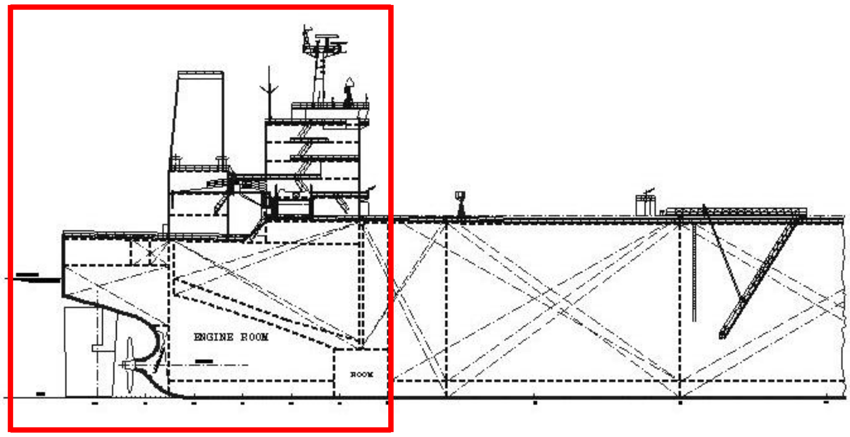


Figure 7 The areas for local vibration evaluation

5 Vibration measurement

To confirm accordance with the criteria stipulated in Building Specification, global and local vibration measurements are carried out. The global vibration measurements are carried out to find out global vibration behaviors of the deckhouse and the aft body of the ship in viewpoint of habitability and structural fatigue.

The local vibration measurements are performed to estimate vibration levels of local structures, machinerys and outfittings in the deckhouse, engine room and aft body in viewpoint of machinery and structure failure.

Normally, vibration measurements are performed on the first ship of a series to show that it does not suffer from vibration deficiencies.

For the measurement condition, the water depth shall be more than 5 times the ship draught. This loading condition (test condition) during sea trial of the ship should preferably be a normal operating condition and the vessel should run ahead as straight as possible. The rudder angle should be restricted within 2 degrees port and starboard.

Figure 8 shows the typical measurement position for the global vibration recommended by ISO 20283-2:2008[5]. The typical measured vibration levels are shown in Figure 9 and the peak frequency and dominant excitation forces are distinguished by using the order and rotating speed of excitations. As shown in Figure 9 a), waterfall plot is used to find out the natural frequency of hull structure because the vibration level is distinguishably high at around the natural frequency. The slice of waterfall along the each excitation force is pick plot ant it is used for the vibration level due to each excitation source with regard to the RPM as shown in Figure 9 b).

The measurement locations for the local vibration at deckhouse shall be selected on the decks of occupied spaces in sufficient quantity in order to characterize satisfactorily the vibration of the ship with respect to habitability. In addition, for equipment vibration, vertical, transverse and longitudinal measurements are to be taken at some positions on the machinery which show a representative behavior.

In case of high vibration, some appropriate control measures are applied to reduce the vibration.

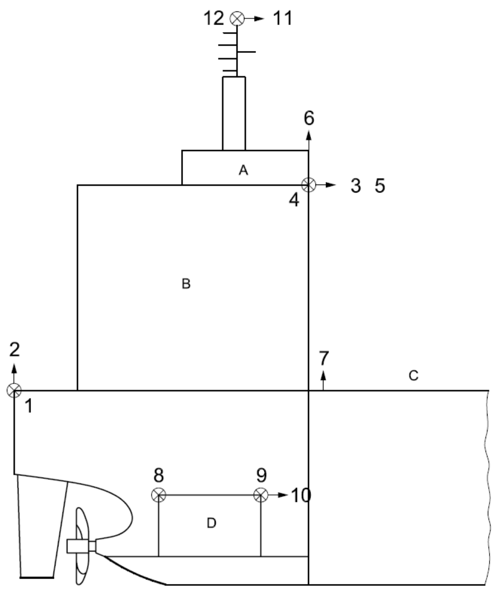
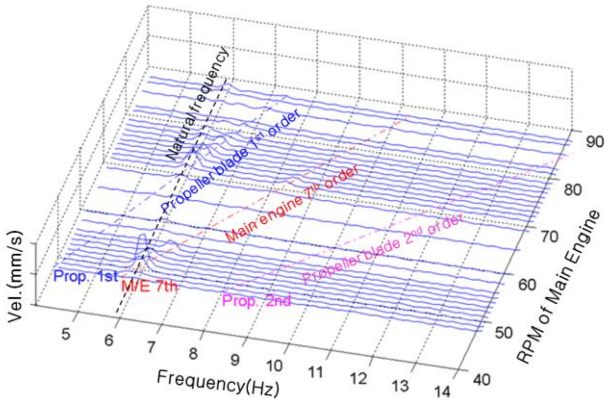
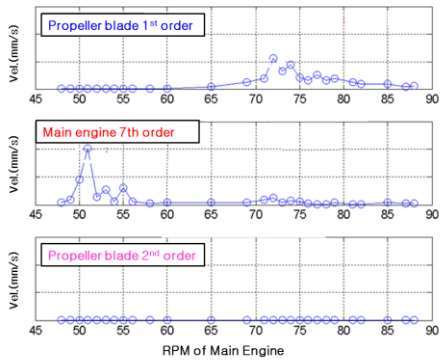


Figure 8 Typical measurement positions of global vibration



a) Waterfall plot



b) Peak plot

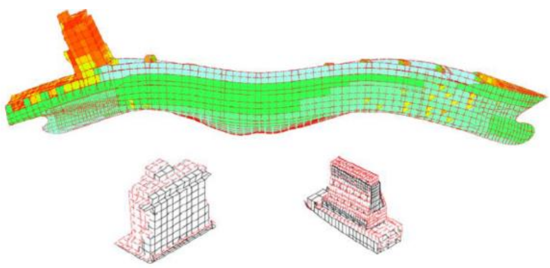
Figure 9 Vibration spectrum

6 Ship vibration control

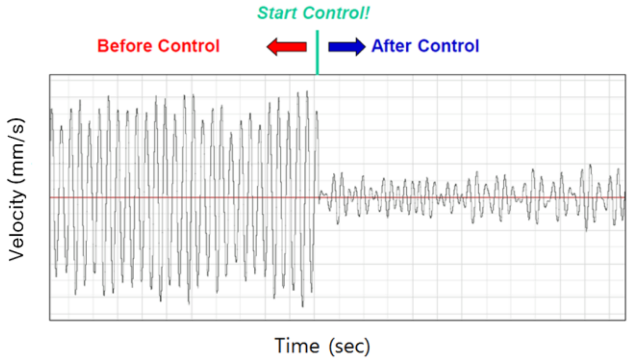
In case of high vibration, there are many control measures to reduce the vibration. Normally, the control measures are divided as source, path or receive control in viewpoint of the control position. For the ship vibration control, the source and receive control of vibration are generally used.

- **Moment compensator**

The most effective way to reduce the vibration is to reduce the excitation force regardless of cost effect. Excitation force can be compensated by the control force having same magnitude and opposite phase to the existing force. If the excitation forces are reduced, it affects to the vibration level of all of the area in a whole ship. In the ship vibration, the moment compensator is a sort of the source control which is installed on a main engine to reduce the excitation force form it. Nowadays, vibration compensator[6] is also installed on the deckhouse or aft body to reduce the global vibration of deckhouse considering the excitation source as shown in Figure 10.



a) Vibration mode shape of ship

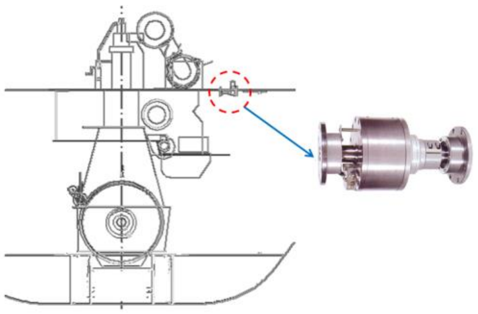


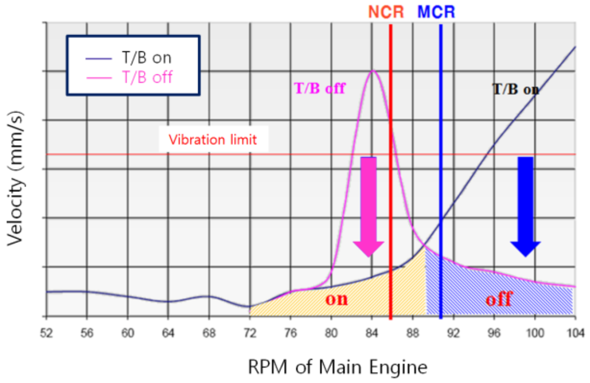
b) Compensator c) Vibration control .

Figure 10 Compensator for vibration control

- **Top Bracing**

The main purpose of top bracing for main engine is to reduce engine vibration. The top bracing is installed on the side of engine. However, the top bracing is another path to transfer a vibration form main engine to the deckhouse. In this case, the vibration can be controlled by using the on-off control of hydraulic top bracing as shown in Figure 11. The vibration level of deckhouse can be keep under the limit by controlling top bracing active(on) below 89 rpm(blue line) and top bracing inactive(off) above 89 rpm(blue line).



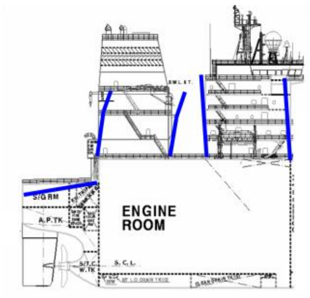


a) Top bracing b) Vibration reduction by using on-off control at deckhouse

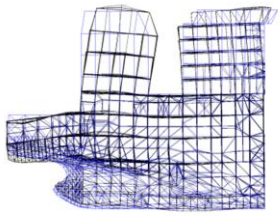
Figure 11 On-off control of top bracing

- **Modification of structure**

The simplest and most common way to reduce a vibration is a structural modification such as increasing the stiffness or supporting the structure. Before modification, firstly, the vibration behavior of hull structure shall be figured out by measuring vibration considering the phase of each position. Based on the measurement results, modification methods and their effectiveness are examined by using F.E analysis as shown in Figure 12. To reduce the longitudinal vibration of engine casing, top bridge was used between deckhouse and engine casing.

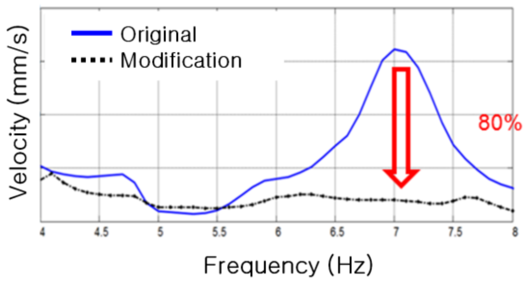


a) Deformed shape



b) Mode shape

c) Modification



d) Vibration reduction of engine casing in longitudinal direction

Figure 12 On-off control of top bracing

7 Conclusion

In this paper, the process of ship vibration control is explained to avoid excessive vibration from design stage to sea trial.

In summary, for the vibration control of ship, firstly, the vibration criteria have to be set up based on the Building Specifications. In the initial design stage, predominant excitation sources of ship vibration are selected by using the data of experienced ships such as numbers of main engine cylinders and propeller blades. In the detail design stage, global vibration and local vibration analysis are carried out by using the Finite Element Analysis. Finally, global and local vibration measurements are carried out during the sea trial to assess the vibration performance of ship. For each stage, the vibration characteristics are checked and if they are not satisfied the criteria, appropriate methods for vibration control are applied.

Reference

[1] ISO 6954-2000, ‘Mechanical vibration –Guidelines for the measurements, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships’, 2000

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