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〈Original Paper〉

Beam-Like Ship Vibration Analysis in Consideration of Fluid

유체력을 고려한 보-유추 선체진동 해석

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ABSTRACT

In the beam-like ship vibration analysis, three-dimensional correction factor(J-factor) can be calculated by considering the three-dimensional effect of the two-dimensional added mass. However, existing method is time-consuming with low accuracy in respect of global vibration analyses for vessels with large breadth. In this paper, to improve the demerit of the previous method, a new method of the beam-like ship vibration analysis is introduced. In this method, the three-dimensional fluid added mass of surrounding water is calculated directly by solving the velocity potential problem using the Boundary Element Method (BEM). Then the three-dimensional added mass is evaluated as the lumped mass for each strip. Also, the beam-like ship vibration analysis for the structural beam model is performed with the lumped mass considered. It was verified that this new method is useful for the beam-like ship vibration analysis by comparing results obtained from both the existing method and the new method with experimental measurements for the open top container model.

요 약

선박의 보-유추 진동해석에 있어 2차원 부가수질량의 3차원 효과를 고려하기 위해서 3차원 수정계수(J-factor)를 계산해야 하는데 광폭선의 경우에는 J-factor의 계산이 부정확하고 번거롭다. 이 논문에서는 이를 개선하기 위해 새로운 선박의 보-유추 접수진동해석 방법을 소개하였다. 이 방법은 선박에 접수된 유체에 대해 BEM 기법을 이용하여 3차원 유체력을 직접 계산하고 이를 일정 간격으로 나눈 각 스트립에 집중질량으로 평가한 후에 선체의 보모델과 결합하여 보-유추 진동해석을 수행하는 방법이다. 오픈탑 컨테이너선의 모델에 대해 기존의 보-유추 진동해석방법과 이 논문에서 제시한 새로운 진동해석방법을 이용하여 진동해석을 수행하고 가진실험에 의한 진동계측결과와 상호 비교함으로써 새로운 방법의 유용성을 검증하였다.

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1. Introduction

The vibration problem of floating elastic bodies can be characterized as the coupling between the elastic structure and the fluid. In general, the beam-like ship vibration analysis is carried out by using the strip theory for fluid and beam theory for ship structure. The conformal mapping technique[1,2] has been adopted for the calculation of hydrodynamic force on the two-dimensional rigid body section on the basis of sink-source distribution concept. Therefore, three-dimensional correction factor [J-Factor] for three-dimensional coupling effect should be calculated subsequently. Since this method has the limitation theoretically, this approach has difficulties being applied to three-dimensional fluid coupling problems with various section ratios. For the ships with higher breath-draft and length-breath ratios than a certain value, this method should be applied with care. Since the limitation of this approach was much severer for the ship with the high ratio of breadth to draft or the high ratio of length to breadth, this approach was not appropriate for three-dimensional fluid-structure. For the J-factor proposed by Kumai, K. C. Kim, C. R. Kim[3~5], the limit of ratio L/B is 4.0~10.0 or 4.0~8.0

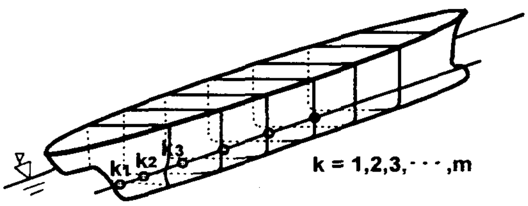


Fig. 1 Lumped mass

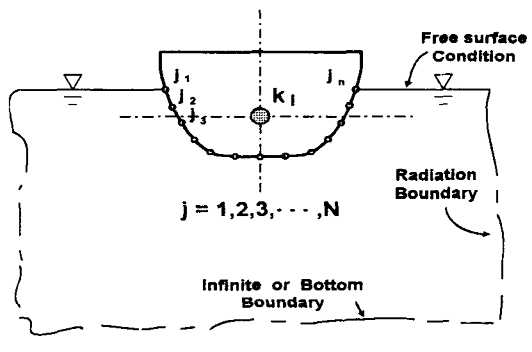


Fig. 2 Boundary condition

and that of ratio B/d is 1.0~4.0. But, in the case of very large breath vessels of which the slenderness ratio is larger than 10.0(sometimes 8.0) or B/d ratio is larger than 4.0, J-Factor can be inaccurately calculated due to the expediency trick of the extrapolation method.

In this paper, the new method is proposed to calculate a three-dimensional hydrodynamic force directly by solving potential problem with the boundary element method technique for the three-dimensional fluid model. The fully coupled three-dimensional added mass calculated at each node is also evaluated with the lumped mass in each strip divided by regular intervals, which was added to the structural constant mass for the beam-like ship vibration analysis. The ideal model is shown in Fig. 1 and 2. The newly proposed method has the merit that three-dimensional hydrodynamic force can be calculated more accurately with no concern for the sectional shape of each strip of vessel. The beam-like vibration analysis of ship can be performed conveniently as the lumped added mass is applied to the analysis. To verify the usefulness of the proposed method, the vibration analyses by both the existing method and new method and the experimental measurement using exciter were carried out for the open top container ship model as shown in Fig. 5. The results of calculations and measurement were also compared with each other. Through the tests, the efficiency of the improved method was confirmed.

2. Theory

2.1 Boundary Problem

(1) Governing Equation

The surrounding water of ship is assumed as ideal fluid in the fluid-structure interaction problem and ship vibration problem. The velocity potential $\Phi(x;t)$ is expressed in the following separated variable form.

$$\Phi(x;t) = RE\{\phi(x)e^{i\omega t}\} \tag{1}$$

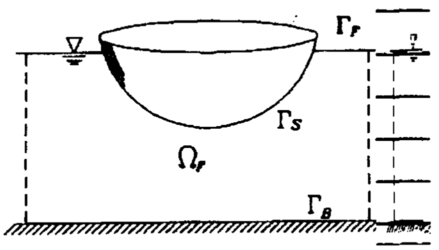


Fig. 3 The definition of fluid domain and boundary condition

where ω means frequency of fluid motion and velocity potential $\phi(x)$ is the function of space coordinate x. If the ship is oscillating in fluid domain, the governing and boundary conditions are expressed as follows :

Fluid Governing Equation :

$$\nabla^2 \phi = 0 \qquad on \qquad \Omega_F \tag{2}$$

Boundary Condition :

$$\frac{\partial \phi}{\partial n} = 0 \quad : \text{ on bottom} \tag{3}$$

$$\frac{\partial \phi}{\partial n} - \frac{\omega^2}{g}\phi = 0 \quad : \text{ on free surface} \tag{4}$$

$$\frac{\partial \phi}{\partial n} - ik\phi = 0 \quad : \text{ on radiation boundary} \tag{5}$$

$$\frac{\partial \phi}{\partial n} = \dot{W}(x,t) \cdot n(x) : \text{ on wetted surface} \tag{6}$$

where $n(x)$, g, k and $\dot{W}$ indicate normal vector at point x, acceleration of gravitation, wave number and velocity of structure, respectively. Equation (6) means non-homogeneous kinematic boundary condition and also compatibility condition of structure coupled with fluid in hydroelasticity. In Fig. 3, the definition of fluid domain and boundary conditions are shown.

2.2 The Boundary Element Method

(1) Boundary Integral

To solve the governing Eq. (2), the following weighted residual integral is obtained by introducing the weighting function ϕ^* and the boundary conditions Eqs. (3)~(6) to Eq. (2) :

$$\int_{\Omega_F} \nabla^2 \phi\, \phi^* d\Omega = \int_{\Gamma_S} \left(\frac{\partial \phi}{\partial n} - \dot{W} \cdot n\right)\phi^* d\Gamma + \int_{\Gamma_R+\Gamma_F} \phi\phi^* d\Gamma + \int_{\Gamma_B} \frac{\partial \phi}{\partial n}\phi^* d\Gamma \tag{7}$$

where Ω_F, Γ_S, Γ_B, Γ_R, and Γ_F indicate fluid domain, wetted surface of structure, bottom boundary, radiation boundary and free surface, respectively. To apply the partial integral technique to Eq. (7), the inverse formulation is obtained as follows :

$$\int_{\Omega_F} \nabla^2 \phi^* \phi d\Omega = - \int_{\Gamma_F+\Gamma_R} \nabla^2 \phi\phi^* d\Omega + \int_{\Gamma_S+\Gamma_B} \frac{\partial \phi^*}{\partial n}\phi\, d\Gamma - \int_{\Gamma_S} G^T\, \dot{W}\, \phi^* d\Gamma + \int_{\Gamma_R+\Gamma_F} \phi\phi^* d\Gamma \tag{8}$$

If weighting function ϕ^* is adopted as the Green's function to satisfy the governing Eq. (2), the boundary integral equation can be obtained. In this case, the weighting function ϕ^* satisfies the following equation :

$$\nabla^2 \phi^*(\xi;x) = \delta(\xi - x) \tag{9}$$

where ξ means space coordinate or potential source point. The inverse formula Eq. (7) is solved by substituting Eqs. (2) and (9) into Eq. (7) as follows :

$$c(x)\phi(x) - \int_{\Gamma_F+\Gamma_R} \phi\phi^* d\Gamma + \int_{\Gamma_S+\Gamma_B} \frac{\partial \phi^*}{\partial n}\phi d\Gamma + \int_{\Gamma_R+\Gamma_F} \phi\phi^* d\Gamma = \int_{\Gamma_S} (\dot{W} \cdot n)\phi^* d\Gamma \tag{10}$$

where $c(x)$ is the form factor depending on the configuration of the structural wetted surface. The fundamental solutions of Eq. (9) for three-dimensional body(3-D) and two-dimensional body(2-D) are as follows :

$$\phi^*(\xi;x) = \frac{1}{4\pi r(\xi;x)} \quad \text{for 3-D} \tag{11}$$

$$\phi^*(\xi;x) = \frac{1}{2\pi}\ln\frac{1}{r(\xi;x)} \quad \text{for2-D} \tag{12}$$

where the distance from source point to observation point is written as $r(\xi;x) = |\xi - x|$. The velocity potential at the observation point

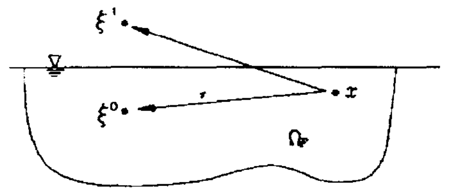


Fig. 4 The image source due to the virtual effect

x can be calculated by substituting suitable boundary conditions Eqs. (3) and (4) into Eq. (10).

(2) Free Surface Effect

The free surface boundary condition is expressed as Green's function $\phi^*=0$ when ω is converging to the limit of infinite, and by the image-function method, it can be described as follows :

$$\phi^*(\xi;x)=\phi^*(\xi^0;x)-\phi^*(\xi^1;x) \quad (13)$$

where $\xi^0=\xi$ and $\xi^1=-\xi$. The image source due to the virtual effect is shown in Fig. 4.

(3) Discrete process

The Boundary Element Method can be applied to the discrete numerical model with the following assumed shape function by introducing the free surface condition due to virtual effect Eq. (13) and the fundamental solutions Eqs. (11), (12) of Green's function to the fundamental boundary integration Eq. (10).

$$\phi^*=\sum_l N_l\phi_l^* \quad (14)$$

$$\frac{\partial\phi^*}{\partial n}=\sum_l N_l\left(\frac{\partial\phi^*}{\partial n}\right)_l \quad (15)$$

$$\dot{W}\cdot n=\sum_l N_l(\dot{W}\cdot n)_l \quad (16)$$

where l = 1, 2, ⋯, NOPe . NOPe denotes the number of nodes in a fluid element, and $N_l=N_l(x)$ means isoparametric shape function. H and G matrices can be defined as follows :

$$H_{ji}=\int_\Gamma\frac{\partial\phi^*}{\partial n}\,d\Gamma=\left[\int_{e_i}\left\{\sum_l N_l\left(\frac{\partial\phi^*_e}{\partial n}\right)_l\right\}d\Gamma_i\right]_j \quad (17)$$

$$G_{ji}=\int_\Gamma\phi^*d\Gamma=\left[\int_{e_i}\left\{\sum_l N_l(\phi^*_e)_l\right\}d\Gamma_i\right]_j \quad (18)$$

Therefore, the boundary element integration Eq. (10) is described in matrix form as follows :

$$H\phi-Gq=\{(\dot{W}\cdot n)\} \quad (19)$$

where the flux $q=\frac{\partial\phi}{\partial n}$ and Eq. (19) is the formulation in matrix form of boundary element method.

(4) Fluid Added Masses

The potential obtained in the wetted structural surface is transformed as follows to satisfy the compatibility condition :

$$Re\{\Phi(x,t)\}=A_M(x)\{\dot{W}(x,t)\cdot n(x)\} \quad (20)$$

where $A_M(x)$ is the coefficient matrix in proportion to structural velocity. And it is the potential refracted from structural surface. The diffraction pressure is defined as follows :

$$P_I(x,t)=\rho A_m(x)\{\dot{W}\cdot n(x)\} \quad (21)$$

The inertia force $F_I(x,t)$ is calculated by the integration of diffraction pressure on the whole of structure surface.

$$F_I(x,t)=-M_F\{\ddot{W}\cdot n(x)\} \quad (22)$$

$$M_F(x)=\rho\left\{\int_{\Gamma_s}n(s)N(s)\,d\Gamma(s)\right\}A_m(x) \quad (23)$$

where $N(s)$ means the shape function for approximation of the structural surface, $n(s)$ means an unit normal vector to the structural surface, and $M_F(x)$ means the three- dimensional added mass matrix which is coupled with the ship structure. The added mass in the form of the lumped mass at each structural node is obtained by summing up all coupling mass effects at all source points multiplied by the directional cosines of the coupling added mass terms.

$$(M_{F_i})_j=\left[\sum_i\{n_p\cdot(M_{F_i})_{pq}\cdot n_q\}_i\right]_j \quad (24)$$

The solution of Eq. (24), $(M_{F_i})_j$, means the added mass with all the coupled effects considered, and it is the lumped mass at the observation node point j. The lumped added mass of each strip divided by regular stations is evaluated by summing up the added masses at the corresponding nodes of each strip.

$$[M_{F_L}(x_1,x_2,x_3)]_k = \sum_{j=l}^{l+e_i} [M_{F_L}(x_1,x_2,x_3)]_j \quad (25)$$

where k means the divided station number, e_i the number of the nodes in each strip and subscript F_L implies that the mass matrix is composed of the lumped fluid masses.

2.3 Analysis of the Fluid-Structural Coupled Problem

In the fluid-structural coupled problem, the equation of motion for the whole system is as follows :

$$M_S \ddot{W} + C_S \dot{W} + K_S W = F_E + F_I \quad (26)$$

where F_E indicates the external force due to wave and F_I means the inertia force corresponding to hydrodynamic force which is calculated at each station by using Eq. (22) and Eq. (25). After a ship is divided by 20 or more stations and fields, the equation of motion is modified for the free vibration analysis of the ship by using Eq. (26) and the free vibration condition $F_E=0$ in water as follows :

$$(M_S+M_{F_L})_k \ddot{W}_k + (C_S)_k \dot{W}_k + (K_S)_k W_k = 0 \quad (27)$$

To apply the analysis method of the beam-like ship vibration, the ship is assumed as Timoshenko beam. And then, the equations of motion and boundary conditions are as follows :

Equation of motion

$$(\rho A + m_{F_L})\frac{\partial^2 y}{\partial t^2} - \frac{\partial}{\partial x}\left[KAG\left(\frac{\partial y}{\partial x} - \psi\right)\right] = 0 \quad (28)$$

$$\rho I\frac{\partial^2 \psi}{\partial t^2} - \frac{\partial}{\partial x}\left(EI\frac{\partial \psi}{\partial x}\right) - KAG\left(\frac{\partial y}{\partial x} - \psi\right) = 0 \quad (29)$$

Boundary condition

$$\left[KAG\left(\frac{\partial y}{\partial x} - \psi\right)\right]_{x=0,L} = 0 \quad (30)$$

$$\left[EI\frac{\partial \psi}{\partial x}\right]_{x=0,L} = 0 \quad (31)$$

where x is the spatial coordinate in the length direction of ship, y horizontal displacement, ψ slop of bending deflection curve, ρA structural weight per unit length, m_{F_L} lumped fluid added mass per unit length, KAG shear rigidity, EI bending rigidity, ρI rotational moment of inertia of bending, and t time variable. And vertical vibration of ship was analyzed by using the transfer matrix method proposed by Myklestad and Prohl[6,7].

Table 1 Principle data of model ship

· L.O.A.	2.75 [m]
· Breadth	0.31 [m]
· Depth	0.16 [m]
· Draft	0.1014 [m] (Estimated) 0.10 [m] (Measured)
· Hold length	0.25 [m]
· No. of hold	8
· E(Young's modules)	1.96E+11 [N/m2]
· ν (Poisson's ratio)	0.3
· ρ (Mass density)	7850.0 [kg/m3]
· Plate thickness	3.20 [mm]
· Weight	68.94 [kg] (Estimated) 67.5 [kg] (Measured)

3. Model of Ship

In this paper, a model ship was constructed to verify the new method of vibration analysis. The model ship is devised by considering an open top container ship built recently as the prototype ship. The principal data are as follows :

The drawing for construction of the model ship is shown in Fig. 5.

It has a larger breadth and slenderness ratio than normal ship, such as $B/d=3.1$ and $L/B=8.87$. For this model ship, the vertical vibration analyses of wetted structure were performed by using both the existing method with considering two-dimension added mass and three-dimension correction factor[J-Factor] and the new method proposed in this paper. Through the experimental measurement by the exciter test in a laboratory basin, the natural frequencies of model ship were

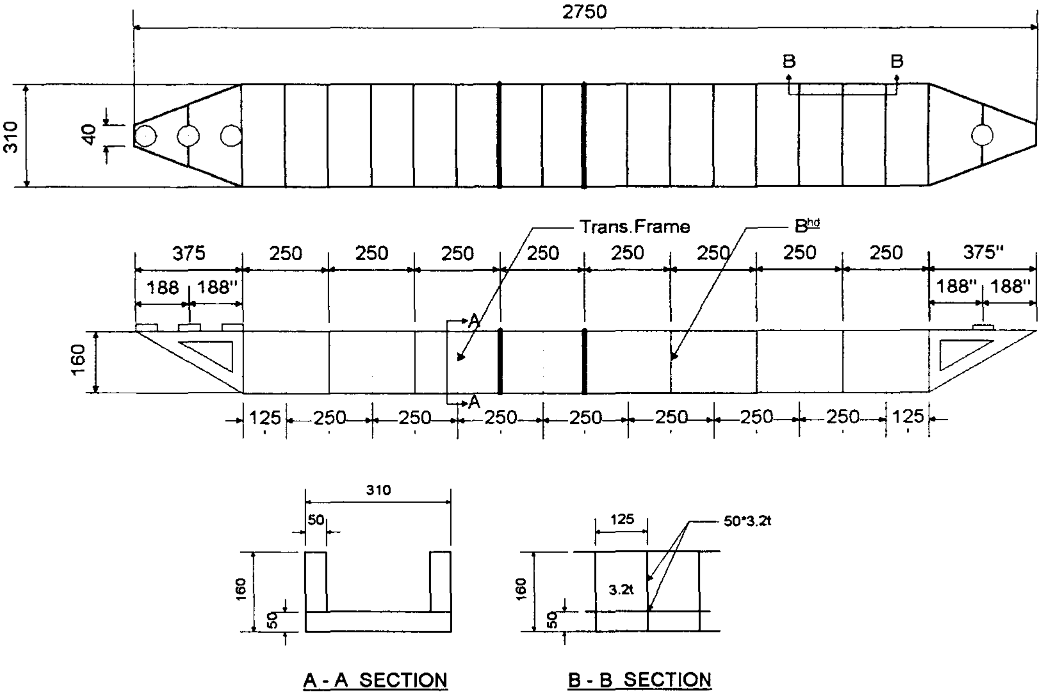


Fig. 5 Cross-sectional view of model ship

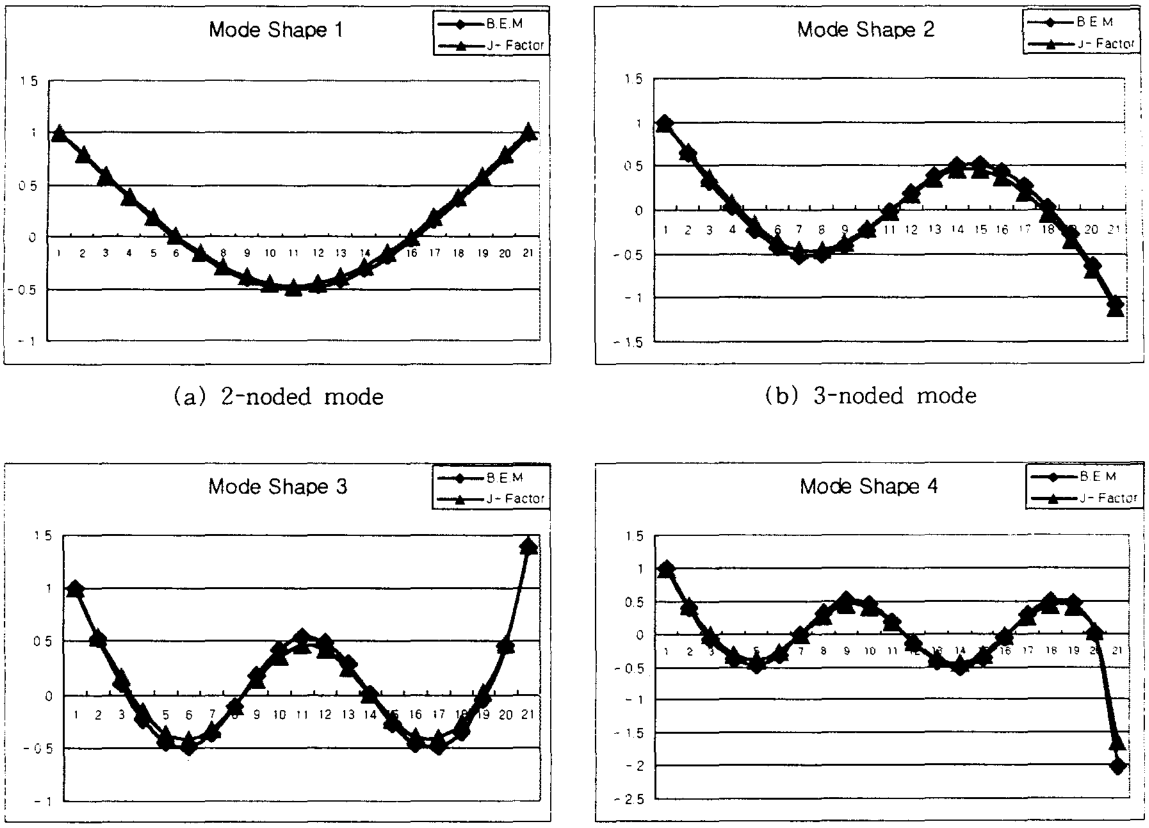
Table 2 Comparison of analysis results with measurement results [Hz]

Mode	On air		In contact with water			
	Experimental measurement	Calculated	Experimental measurement	Calculated		
				2-D		
		2-D		2-D J-Factor	3-D BEM	3-D
1	108.8	103.1	78.6	77.4	75.9	77.9
2	268.8	260.9	194.0	192.8	189.6	194.9
3	463.1	451.8	325.5	334.1	324.7	327.0
4	645.1	641.8	430.6	482.2	448.2	430.7

detected. The results obtained from the analysis by the two above- mentioned methods and the measurement results were compared with each other.

4. Results of Analysis and Discussion

The results of the free vibration analysis and the measurement were summarized in Table 2. In Table 2 , "2-D" in the column labeled as On Air" means the two-dimensional beam-like vibration analysis. The 2-D J-Factor" and "3-D BEM" labeled as "In Contact with Water" indicate the existing method and the proposed method respectively. The "3-D" in the last right-hand-sided column shows the fully modeled three-dimensional analysis in consideration of the fully coupled three-dimensional fluid added mass. From Table 2, the natural frequencies of the lower mode vibrations of two-noded and three-noded modes obtained by the existing method were more accurate than those by the new method. But it revealed the trend that the higher the vibration mode, the more accurate the result obtained by the new method. The adopted model in this paper has the almost rectangular shape of box girder structure. It is not surprising that the results by the existing method had more accuracy in lower mode vibrations, but it is noticeable that the



(a) 2-noded mode (b) 3-noded mode

(c) 4-noded mode (d) 5-noded mode

Fig. 6 Mode shapes of result

results in higher modes were not satisfying. On the contrary, the new method has very remarkable accuracy as the modes are getting higher. If the new method is applied to real ships, it is obvious that the phenomenon can be confirmed. In Fig. 6, the vibration mode shapes of beam-like model by both 2-D methods are shown.

5. Conclusion

In the case of the vibration analysis for the very large vessel even at the concept design stage, it can be expected that the proposed method will give more accurate results for higher beam modes. Furthermore, in the respect of computation time, the new method can be implemented more than five times faster than the three-dimensional full model analysis. So if anyone use the new method in vibration analysis for the real ship, payments and calculating time should be economized, what is more, accuracy will be increased at highermodes.

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