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A Study on Longitudinal Motions and Bending Moment of a Container Ship in Following Sea

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Summary

The vertical bending moment in following sea to be calculated by Strip Methods has an important problem as obviously shown in the results of the international joint calculation under the Seakeeping Committee of I.T.T.C.[2)]

In this paper, for the first time, the following Transient Water Wave was adopted in experiments. As the results suggested, good data was obtained effectively, and the fact that Transient Water Wave is useful even in following sea conditions was proved. Next, a practical method of calculation taking into account three-dimensional correction is presented. By applying this method, experimental values of vertical bending moment in following waves at near -zero encounter frequency can be explained satisfactorily.

1. Introduction

In recent years, comparisons of calculations on ship motions in waves as well as wave loads by Strip Methods have been carried out internationally under the Seakeeping Committee of I.T.T.C.[1),2)] Part of the reports were presented at the 15th I.T.T.C 1978, while the rest are left to be presented at the 16th I.T.T.C. scheduled for 1981. From these reports, it has been understood that calculated results on ship motions done by various institutions did not appear to differ significantly and these results also showed good agreement with results of model experiments. Hence, the fact that the Strip Method has become a practical calculation method on ship motions has been confirmed. On the other hand, the calculated results on wave loads such as bending moment, shearing force, etc., which are regarded to be more important practically, showed considerable differences. And the results of model experiments did not agree with calculations as well as that on the ship motions.

Among these, an interesting note is the estimation of vertical bending moment while the encounter frequency approaches zero in following sea condition. In this case, the value of vertical bending moment, V.B.M., tends to be infinite if the widely used Strip Method is applied. This fact is also very clearly shown by the graph of comparison of calculated values by I.T.T.C.[2)] Moreover, as medium and small high-speed displacement ships do come across this state of following sea in service, and the values of bending moment appear not to be so small, it can not be ignored in practice.

In this paper, results of model experiments on vertical bending moment in following sea condition, which mostly has not been presented due to difficulties in carrying out these experiments, are presented. In order to obtain good results effectively, Transient Water Wave (T.W.W.) was employed. However, running in following sea with T.W.W., considerable effort is necessary, taking into account the interaction between the ship speed and the encounter frequency. Therefore, a number of precautions are to be taken for carrying out experiments of this kind and these precautions will also be stated.

The fact that V.B.M. tends to be infinite, as shown by the results of conventional calculation, was not found in the experimental result of V.B.M.. So as not to let the wave loads increase to infinity while the encounter frequency becomes zero, improvement on the method of calculation was made by taking into account three-dimentional correction. This calculated results of vertical bending moment is able to explain the experimental results well.

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2. Experiment

2.1 Encounter wave phenomena in Following Sea

A certain understanding on the encounter wave phenomena is necessary before introducing the procedure of the experiment.

In the moving reference frame of a ship, the incident waves arrived with the encounter frequency.

$$\omega_e = |\omega - VK\cos\chi| \qquad (1)$$

where

ω: circular frequency of wave
$K=\omega^2/g$: wave number
χ: encounter angle
V: forward speed of ship

This equation introduces a Doppler effect between the wave frequency ω and the frequency of encounter ω_e. The variation of ω_e with ω, when it is defined in this way, is as shown in Fig. 2.

Usually ω axis can be divided into the following three ranges:[3)]

Range I

$$\omega < \frac{g}{2V\cos\chi} \quad \text{so that} \quad V\cos\chi < C/2 = C_g$$

Range II

$$\frac{g}{2V\cos\chi} < \omega < \frac{g}{V\cos\chi}$$

$$\text{so that} \quad C_g = C/2 < V\cos\chi$$

Range III

$$\frac{g}{V\cos\chi} < \omega < \infty \quad \text{so that} \quad C < V\cos\chi < \infty$$

In deep water waves, the phase velocity of wave C is defined as follows.

$$C = \omega/K = g/\omega$$

And the group velocity C_g has the following relation.

$$C_g = C/2$$

In following waves, $\chi=0°$ and $V\cos\chi=V$. Non-dimensional wave frequency ω is defined as

$$\bar{\omega} = \omega\sqrt{L/g} \qquad L\text{: ship length}$$

Then, there is the non-dimensional relation such as.

$$\bar{\omega} = 1/Fn\cos\chi \quad \text{corresponds to} \quad \omega = g/V\cos\chi$$

where

$$Fn = V/\sqrt{Lg}\text{: Froude Number}$$

As shown in Fig. 2, in the range of $0 \leq \omega_e \leq g/4V\cos\chi$ or $0 < \bar{\omega}_e < 1/4Fn\cos\chi$, there are three different values of ω for one value of ω_e.

2.2 Model Condition and Instrumentation

A S-175 container ship model was used in the towing tank of Yokohama National University ($L\times B\times d = 100\times 8\times 3.5$ m). And the experimental conditions were fitted to the designation in the I.T.T.C. comparative study (see Table 1).

Experiments were carried out at $Fn=0.0$ and $Fn=0.275$ in head as well as following waves, and $Fn=0.40$ only in following sea. However, in this paper only following sea is treated.

Arrangement of instruments used is shown in Fig. 1.

Heaving and Pitching were free and Surging was fixed. Vertical bending moment at midship was measured through strain gauge by detecting the bending of the horizontally set flat steel bars connecting the fore and the aft bodies divided at midship.

Table 1 Principal dimensions and experimental conditions of the used model

ITEMS		Ship	Model
Length (p.p.)		175.00 m	2.000 m
Breadth		25.40 m	0.290 m
Depth		15.40 m	0.176 m
Draft		9.50 m	0.1088 m
Displacement		24742 ton	36.14 Kg
Block Coefficient		0.5716	0.5716
C.G. from Keel		9.50 m	0.1088 m
C.G. from Midship		-2.48 m	-0.0028 m
Longi. Gyradius		42.00m (0.24Lpp)	0.48 m (0.24Lpp)
Trim		0	0
Scale		1	1/87.5
Nat. Period in Water	Heave	7.52 sec	0.803 sec
	Pitch	7.86 sec	0.842 sec

Separated Parts of Model

	Weight	C.G from (fore +)	Longi. Cyradius
fore	17.38 Kg	0.3872 m	0.262 m (0.131 Lpp)
aft	18.76 Kg	-0.4128 m	0.271 m (0.136 Lpp)

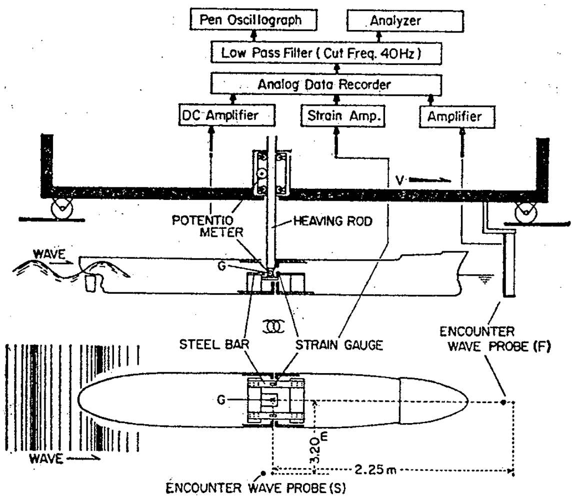

Fig. 1 Block diagram of the experiment

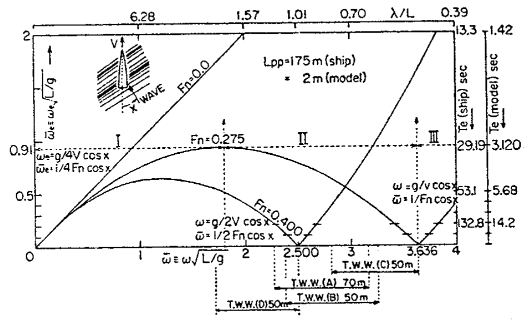

Fig. 2 Relation between encounter frequency and wave frequency and ranges of T.W.W. used in experiment

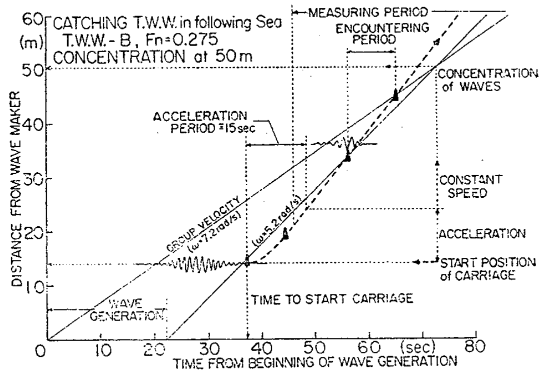

Fig. 3 Procedure of the experiments in following Transient Water Waves

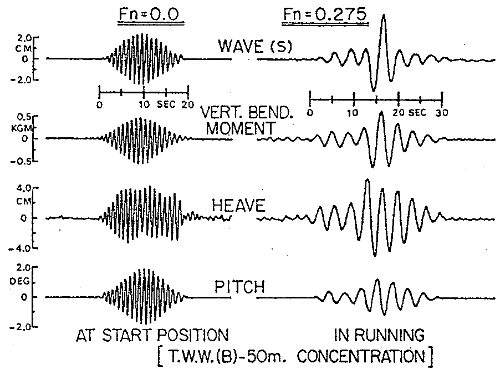

Fig. 4 A sample of time history in a folloing Transient Water Wave

The wave probe fixed to the carriage was located at one side of the ship at a distance of 3.2 m (position S) from the center of gravity (C.G) in order to avoid the influence of the disturbance by the ship hull. Another wave probe was set in front of the stem at a distance of 2.25 m (position F) from C.G. Wave probe F was used for checking on the height of wave which was to pass the ship.

Furthermore the analysis of data in T.W.W. was carried out by using a mini-computer based on F.F.T. (Fast Fourier Transformation) algorithm.

To measure the wave exciting pitch moment, the method was identical to that of the vertical bending moment except that either one of fore or aft body was fixed.

2.3 Procedure of Experiment

Regular waves and T.W.W. were used to obtain the transfer functions. As previously mentioned, there are some problems with experiments in following T.W.W.

Therefore, these experiments had to be carefully planned (refer to Figs. 2, 3, 4).

It has been confirmed earlier that the T.W.W. advances fundamentally with group velocity.[5] Two types of experiments could be considered. In the first case where the ship velocity is greater than the group velocity of waves (Range II and III of Fig. 2), the carriage was started after the total passage of the waves (see Fig. 3). Only this case was carried out in this experiment. For the second case where the ship velocity is less than the group velocity of waves (Range I), the carriage had to be started before the arrival of waves. However, since waves in this range possess long wave length, which is not within the important range and experiments are difficult without a very long towing tank, experiments were not conducted for this case.

To decide the timing of starting the carriage, the wave generation time had to be taken into consideration, for the encounter had to occur before the concentration of the T.W.W. in order to maintain its property. In addition, the total of the measured record had to take place when the speed of carriage was constant and same zero-base was necessary before and after the encounter in order to achieve good precision of data analysis to be carried out later (see Figs. 3, 4.). As the result, time-histories of waves as well as responses during the passage of waves before the starting of carriage (i.e. at $Fn=0.0$) and that during the encounter after the starting of carriage are shown in Fig. 4. This can be better understood by refering to Fig. 3. Attention is to be given to the difference in measuring period for the two kinds of time-histories shown in Fig. 4. An advantage of this experiment is that two curves of transfer function can be obtained in one run.

To set up the signal of T.W.W. for following waves, additional considerations were necessary besides those mentioned in references 4), 5), 6), 14) in order to achieve good experimental results. As there are three wave frequencies corresponding to each encounter frequency, as shown in Fig. 2, it is necessary to divide the wave frequency into three ranges so as to obtain just one wave frequency corresponding to one encounter frequency in each range.

In this particular case, if $Fn=0.275$, the $\bar{\omega}$ base was divided into three ranges such that Range I be $\bar{\omega}=0\sim1.81$, Range II be $\bar{\omega}=1.81\sim3.636$ and Range III be $\omega=3.636\sim\infty$ (see Fig. 2). The approximate value of the sweep time of wave generating signal is given by the formula[5]

$$T=2x(\omega_H-\omega_L)/g \tag{2}$$

where

- T: sweep time or duration of wave generation
- x: concentrating position from wave maker
- ω_H: virtual high frequency of T.W.W.
- ω_L: virtual low frequency of T.W.W.

A limitation of frequency range in each range was necessary in order to achieve appropriate sweep time.

Eventually, the frequency range of T.W.W. used for experiment is indicated in Fig. 2, where T.W.W. (A), (B), and (C) were used for $Fn=0.275$ and T.W.W. (C) and (D) were used for $Fn=0.40$.

Another advantage of the use of T.W.W. is that experiment of small ω_e($\omega_e\to0$, i.e. T_e tends to be very large, see Fig. 2) which is very difficult in regular waves was made possible.

In the case when the wave phase velocity is larger than the ship's velocity (Range III), there was no problem in obtaining the encounter. On the other hand the difficulty with the high frequency component waves is that these waves either become nonlinear or break as it passes the model.

Consequently, necessary data was obtained within the important frequency range (near $\omega_e=0$) in our experiments.

3. Analysis and Considerations

3.1 N.S.M. and O.S.M.

On the theoretical calculation of ship motions and wave loads, Strip Methods such as Ordinary Strip Method (O.S.M.)[17] New Strip Method (N.S.M.),[15] Salveson, Tuck and Faltinsen's Method (S.T.F.)[16] etc., have been proved practical and are widely used in spite of some difference in the way of treating. Calculation of ship motions by these methods present good agreement with experimental ones.

In this paper, only vertical bending moment formulae is dealt with, and equation of motions, on which many reference and literature[22),23)] have been published, are excluded.

Vertical bending moment at x' is given by the Strip Methods as follows.

$$M_V(x')=\int_{l_a}^{x'}\left\{\frac{dF_{z0}}{dx}+\frac{dF_{dz}}{dx}+\frac{dF_{FK}}{dx}+\frac{dF_{Iz}}{dx}\right\}\cdot(x-x')dx \tag{3}$$

where

- dF_{z0}/dx: the vertical component of the radiation and restoring force on the strip dx
- dF_{dz}/dx: the vertical component of the diffraction force on the strip dx
- dF_{FK}/dx: the vertical component of the Froude-Kriloff force on the strip dx
- dF_{Iz}/dx: the vertical component of the inertia force on the strip dx

respectively. The last two forces dF_{FK}/dx and dF_{Iz}/dx are identical in both N.S.M. and O.S.M.

At the Kobayashi's N.S.M.[15] used in our computer program[7] the radiation component is given by

$$\int_{l_a}^{x'}\frac{dF_{z0}}{dx}(x-x')dx=\theta_A[(C'_{\theta\theta}-A'_{\theta\theta}\omega_e^2)-B'_{\theta\theta}\omega_e]+z_A[(C'_{\theta z}-A'_{\theta z}\omega_e^2)-B'_{\theta z}\omega_e] \tag{4}$$

where

$$A'_{\theta\theta}=\frac{V}{\omega_e^2}\int_{l_a}^{x'}N_H(x-x')dx+\int_{l_a}^{x'}x(x-x')M_Hdx$$

$$\begin{aligned}B'_{\theta\theta}=&\int_{l_a}^{x'}x(x-x')N_Hdx\\&-V\int_{l_a}^{x'}(x-x')M_Hdx+V\int_{l_a}^{x'}xM_Hdx\\&+\frac{V}{\omega_e^2}\int_{l_a}^{x'}N_Hdx-V[x(x-x')M_H]_{l_a}^{x'}\\&-\frac{V^2}{\omega_e^2}[(x-x')N_H]_{l_a}^{x'}\end{aligned}$$

$$\begin{aligned}C'_{\theta\theta}=&2\rho g\int_{l_a}^{x'}x(x-x')b(x)dx+V\int_{l_a}^{x'}xN_Hdx\\&-V^2\int_{l_a}^{x'}M_Hdx-V^2[M_H(x-x')]_{l_a}^{x'}\\&-V\int_{l_a}^{x'}N_H(x-x')dx+V[x(x-x')N_H]_{l_a}^{x'}\end{aligned}$$

$$A'_{\theta z}=-\int_{l_a}^{x'}(x-x')M_Hdx$$

$$B'_{\theta z}=-\int_{l_a}^{x'}(x-x')N_Hdx-V\int_{l_a}^{x'}M_Hdx+V[M_H(x-x')]_{l_a}^{x'}$$

$$C'_{\theta z}=-2\rho g\int_{l_a}^{x'}b(x)(x-x')dx-V\int_{l_a}^{x'}N_Hdx+V[N_H(x-x')]_{l_a}^{x'}$$

where ⌊___⌋ terms are not included in the modified O.S.M.[23] which is used in this paper, and moreover $\sim\sim\sim$ terms are not included in original O.S.M.[17),18] and ⌊.....⌋ terms disappear in N.S.M.

The diffraction component is given by

$$
\begin{aligned}
\int_{l_a}^{x}\frac{dF_{dz}}{dx}(x-x')dx
&=\mp\zeta_a\omega\omega_e\int_{l_a}^{x'}M_H(x-x')e^{-KT_m}\begin{pmatrix}\cos\\ \sin\end{pmatrix}(k^*x)\,dx\\
&\mp\zeta_a\omega\int_{l_a}^{x'}N_H(x-x')e^{-KT_m}\begin{pmatrix}\cos\\ \sin\end{pmatrix}(k^*x)\,dx\\
&\mp\zeta_a\omega V\int_{l_a}^{x'}M_H(x-x')e^{-KT_m}\begin{pmatrix}\cos\\ \sin\end{pmatrix}(k^*x)\,dx\\
&\underline{\pm\zeta_a\frac{\omega}{\omega_e}V\int_{l_a}^{x'}N_H e^{-KT_m}\begin{pmatrix}\cos\\ \sin\end{pmatrix}(k^*x)\,dx}\\
&\underline{\pm\zeta_a Vw\left[M_H(x-x')\begin{pmatrix}\cos\\ \sin\end{pmatrix}(k^*x)\right]_{l_a}^{x'}}\\
&\underline{\mp\zeta_a V\frac{\omega}{\omega_e}\left[N_H(x-x')\begin{pmatrix}\cos\\ \sin\end{pmatrix}(k^*x)\right]_{l_a}^{x'}}
\end{aligned}
\tag{5}
$$

M_H: sectional added mass
N_H: sectional damping coefficient
ζ_a: wave amplitude
ω: circular frequency of wave
ω_e: encounter circular frequency
k^*: $K\cos\chi$
K: $=\omega^2/g$ (wave number)
ρ: density of water
g: gravitation acceleration
V: forward speed of ship
T_m: mean draft of section
$b(x)$: water plane half beam at x
l_a: aft end length
θ_A: pitch amplitude
z_A: heave amplitude

For comparison with experimental results, longitudinal motions as well as vertical bending moment were calculated by both O.S.M. and N.S.M. In both calculations, damping coefficient and added mass was directly calculated by the Ursell–Tasai Method[19] at each frequency. Moreover, end effect was taken into consideration as shown in equations(4), (5).

3.2 Three Dimensional Correction in Strip Method

Usually in the Strip Method, three dimensional effect is not taken into consideration. If the wave length is sufficiently short, hydrodynamic coefficients obtained from the Ursell–Tasai Method is quite similar to that from three dimensional theoretical results.[9),11]

Nevertheless, as wave period increases the difference between the two becomes larger. Especially when ω_e tends to zero, it is not seen that the added mass coefficient increases to infinity in three dimensional theoretical calculation,[11] whereas it appears in the result of the Strip Method.

Recently, Maruo–Tokura[24] introduced a numerical calculation method of sectional hydrodynamic coefficients using Maruo's[8] improved slender body theory. The base of this method is to introduce the slender ship[12),21] theory at very low frequency, so that at high frequency, the derived results from this method coincides with that of the results of the Strip Theory. This calculation finally becomes such that as if three dimensional correction is added to the Ursell–Tasai Method at low frequency.

Similar work exists in Newman's unified theory[13] but here only Maruo's formulation was adopted.

From this theory, the hydrodynamic force $f(x)$ acting on each section is

$$f(x)=+(M_H+M_H')\omega^2 z_A-(N_H+N_H')i\omega z_A \tag{6}$$

where

M_H and N_H are sectional heave added mass and damping coefficient obtained from Ursell–Tasai Method respectively. And here M_H' and N_H' are considered as three dimensional correction in heave sectional hydrodynamic coefficients.

Similarly we can obtain coupling coefficient of pitch with three dimensional correction

$$f(x)=-(M_{Hx}+M_H'')\omega^2\theta_A-(N_{Hx}+N_H'')i\omega\theta_A \tag{7}$$

where M_H'' and N_H'' are considered as three dimensional correction in coupling hydrodynamic coefficients of pitch. More details are shown in reference 24).

In this paper, we define

—M_H' and M_H'' as three dimensional correction in sectional added mass.

—N_H' and N_H'' as three dimensional correction in sectional damping coefficients.

3.3 Comparison between Experiments and Calculations

All the calculation conditions as well as model conditions (see Table 1) were in accordance with the I.T.T.C. designation.

Combining three dimensional correction with N.S.M. and O.S.M., the following six cases of calculations were carried out in this study. Therefore, six curves are found in Fig. 5 ~ Fig. 15 as calculated results. In some cases where there are no differences among calculated results such as Fig. 10, the number of curves seems to be less. Here, we define the calculation methods as follows

1. N(O): original N.S.M. calculation based on Eq. 3), 4), 5) for vertical bending moment without three dimensional correction.
2. N(A): N(O) with three dimensional correction of sectional added mass M_H' and M_H'' only
3. N(A.D): N(O) with three dimensional correction of sectional added mass M_H' and M_H'', and damping coefficient N_H' and N_H''
4. O(O): original O.S.M. calculation based on Eq. 3), 4), 5) except ____ terms for vertical bending moment without three dimensional correction
5. O(A): O(O) with three dimensional correction of M_H', M_H'' only
6. O(A.D): O(O) with three dimensional correction of M_H', M_H'', and N_H', N_H''

It was found out that for longitudinal motions in following sea, the calculated values nearly coincided with experimental ones in regular waves. All the calculated results of pitch and heave by both O.S.M. and N.S.M. (for N(O), N(A), N(A.D), O(O), O(A), O(A.D)) appeared to be quite identical to one another and with measured motions (see Figs. 5, 6, 13, 14).

Experimental results obtained in T.W.W. were also very close to that in regular waves. Thus, it can be said that the effectiveness of measurement in T.W.W. in following sea was equally well as that in head sea.

In spite of the difference in sectional hydrodynamic coefficients between the calculations with three dimensional correction and original Strip Method, good results can be obtained from the original Strip Methods for the estimation of motions.

Although the sectional added mass tends to infinity as ω_e tends to zero, it is of little importance for prediction of ship motions. This is because it is the $\omega_e^2 a$ (a is the mass term) and $\omega_e b$ (b is the damping term) which occur in the equations of motion. Since the Strip Theory correctly predicts the hydrostatic effects which are dominant as ω_e tends to zero, the resulting equations of motion are also correct for the case where ω_e tends to zero.[10]

Next, concerning the vertical bending moment (Fn=0.275) shown in Fig. 7, unlike the values from N(O) calculation, no singular phenomena

Table. 2 Representation of calculation methods in Fig. 5~Fig. 15

CAL. METHOD	N.S.M.	O.S.M.
without 3D-COR.	N(O) ———	O(O) ———
with 3D-COR. on MH only	N(A) -------	O(A) -------
with 3D-COR. on MH & NH	N(A·D)— — —	O(A·D)— — —

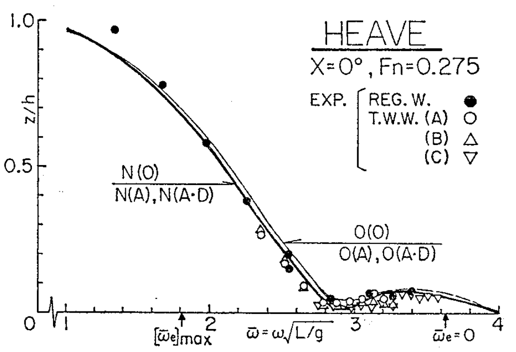

Fig. 5 Heave transfer function in following waves Fn=0.275

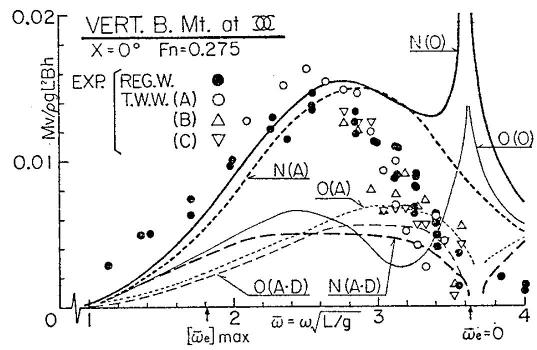

Fig. 7 Vertical bending moment at midship in following waves Fn=0.275

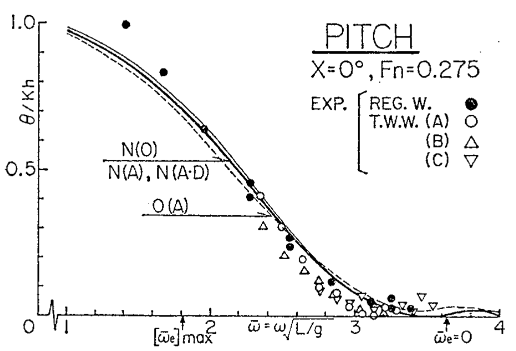

Fig. 6 Pitch transfer function in following waves Fn=0.275

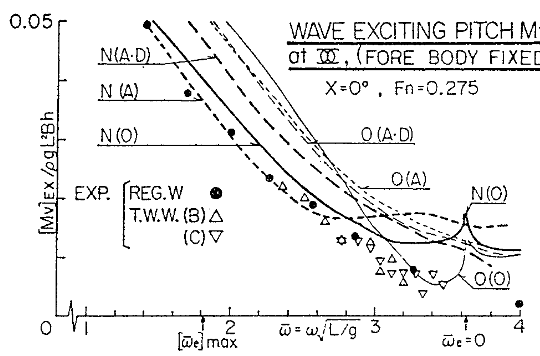

Fig. 8 Wave exciting pitch moment at midship in following waves Fn=0.275

was seen in experimental results in the region near $\omega_e=0$. Results from O(O) showed that similar singular phenomena occurred at around $\omega_e=0$, but it was generally quite lower than the experimental results. The reason for the difference in the results between O(O) and N(O) where ω_e is very low, is regarded as that terms divided by ω_e^2 in radiation force and by ω_e in diffraction force do not appear in O(O) (see Eqs. (4), (5)).

Furthermore, as shown in Fig. 15 singular phenomena appeared to be wider at $Fn=0.40$ than the former ones for both N(O) and O(O) in the region near $\omega_e=0$. Once again, results of calculation by O(O) generally appeared to be lower than the experimental ones.

The same singularity in vertical bending moment shown in Figs. 7, 15 was obtained from the widely used O.S.M. and N.S.M.

However, experimental results have proved the invalidity of the existence of such singularity. This singularity is due to the increase of added mass towards infinity obtained by Ursell–Tasai Method at very low frequency.

In order to make up for such a defect in the traditional Strip Methods, it was attempted to bring in Maruo's three dimensional correction. When Maruo's method was first applied on three dimensional correction for M_H and N_H, good results could not be obtained as shown by the curves of N(A.D) in Fig. 7 and Fig. 15. Since the influence of N_H in the region where ω_e is small, which is regarded as the main issue here, appears to be insignificant, three dimensional correction for only M_H was applied for N(O). Consequently, as shown by the curves of N(A) in Fig. 7 and Fig. 15, a characteristic capable of explaining the experimental results was obtained. As a conclusion, the authors would like to present this as a new practical method of calculation.

On the other hand, to investigate the consequence of three dimensional correction in O.S.M., the same correction was applied in O(O), which means that six kinds of method of calculation were carried out in total.

To show how small ω_e could be in following wave Fig. 9 was put in. Running with high speed in following wave, the value of ω_e could take a figure down one place than running in head wave. Moreover, added mass obtained from traditional methods in this zone appears to increase quite sharply. However, it is easily understood that this can never occur in the actual case. In addition, it is also understood that the value of added mass appears to be limited and not quite large if the Maruo's three dimensional correction is applied. Furthermore, the fact that the quantitative amount involved in three dimensional correction at low frequency zone, regarded as the main object here, appears to be considerable is also understood.

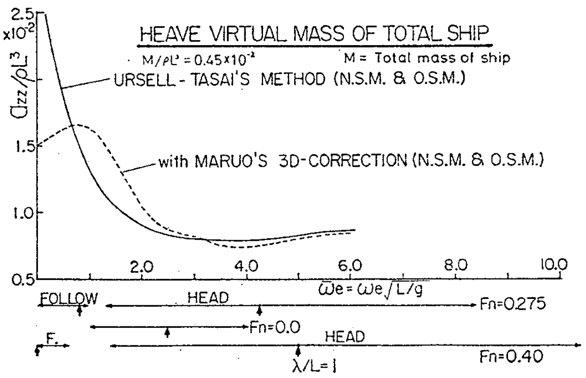

Fig. 9 Heave virtual mass coefficient of total hull

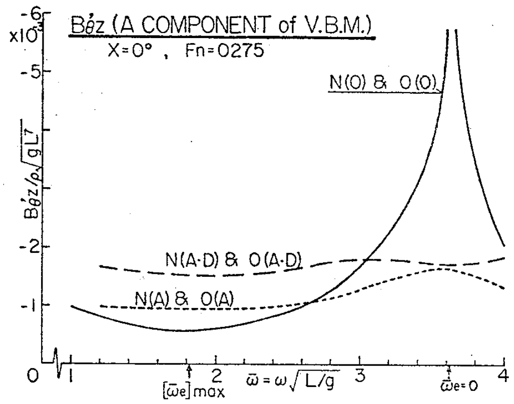

Fig. 10 A component of radiation force for vertical bending moment

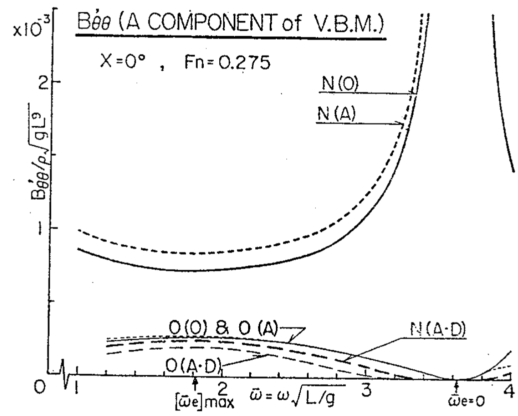

Fig. 11 A component of radiation force for vertical bending moment

Fig. 10 indicates the term in the radiation component largely affected by three dimensional correction. Moreover, it is to be noted that all coefficients consisting of M_H are affected since three dimensional correction for all M_H in Eqs. 4), 5) of N(A) is included. Fig. 11 shows the term in the radiation component which differs greatly in N(O) and O(O). Furthermore, the effect of three dimensional correction on this term is almost negligible in N(A).

The value of vertical bending moment is greatly influenced by wave exciting pitch moment, as shown in Fig. 8. As this term tends to infinity while ω_e tends to zero in N(O) and O(O), vertical bending moment does vary similarly (Fig. 7). In N(A), as the tendency towards infinity vanishes, vertical bending moment does not tend to infinity. As a result, N(A) provides the most satisfactory results compared with others. However, the zone containing a difference between N(A) and experimental results in Fig. 8 is quite similar to the zone containing a difference between N(A) and experimental results of vertical bending moment in Fig. 7. Hence, it can be considered as such that if the precision of prediction of wave exciting pitch moment is improved, the predicted value of vertical bending moment will also improved.

For O(A) calculation, although the singular phenomena disappeared, the value of vertical bending moment appeared to be considerably low compared with experiment for $Fn=0.275$ and for $Fn=0.40$ and the dislocation of peak value occured.

In the case N(A.D) (Figs. 7, 15) although the singular phenomena does not appear any longer, since the sectional damping coefficients become lower than that by the Ursell-Tasai Method, the value of vertical bending moment become lower than experimental results.

The difference between O(A) and O(A.D) is insignificant (see Figs. 7, 15), but they differ considerably with experimental results.

Results in quarter following sea of $\chi=30°$ at $Fn=0.275$ are shown in Fig. 12. The difference between N(O) and N(A) and experimental results from Sumitomo Heavy Industry square basin becomes larger in the wave range as ω_e tends to zero. On the other hand, it is clear that N(A) does not bring about any bad effects. N(A.D) calculation appeared to be considerably low and it is understood that N(A.D) is also not useful in this case.

Three dimensional effect for only added mass is included, though the singularity of vertical bending moment by original Strip Methods in following sea vanishes, the difference between calculated results by O.S.M. and by N.S.M. appear to be significant. Calculated results by N.S.M. have proved to approach better to experimental results than that by O.S.M. and this method gives a much better estimation of vertical bending moment in following sea than that obtained from the traditional Strip Methods.

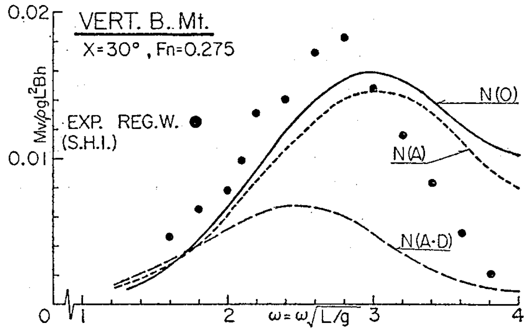

Fig. 12 Vertical bending moment at midship in quarter following waves Fn=0.4

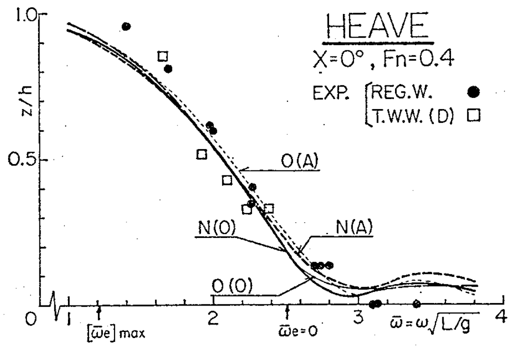

Fig. 13 Heave transfer function in following waves Fn=0.4

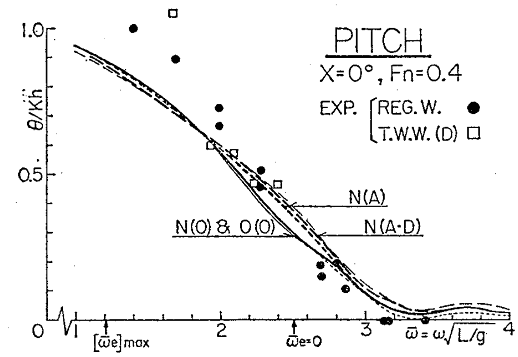

Fig. 14 Pitch transfer function in following waves Fn=0.4

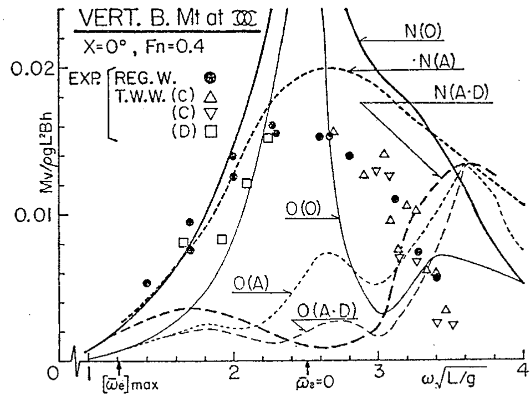

Fig. 15 Vertical bending moment at midship in following waves Fn=0.4

4. Conclusions

Summarizing this study, the following conclusions can be drawn.

1) It has been understood that in spite of experiments in following sea, good data can be obtained effectively by applying T.W.W. However efforts in limiting the frequency range for the wave components in T.W.W. as well as in making them corresponding to encounter frequency on one-to-one basis are necessary. In addition, it is also essential to predict the relations with the period of generating waves, the start position of the carriage and the measuring period in planning such experiments.

2) The actually obtained transfer functions of heave and pitch in following sea show good agreement with the Strip Method calculations such as O.S.M. and N.S.M.

3) According to Strip Methods such as O.S.M., N.S.M. etc., vertical bending moment in following sea tends to be infinite while the encounter frequency is equal to zero. Nevertheless, it is obvious from the experimental results that such a tendency does not exist.

4) In order to correct such defects in widely used Strip Methods, attempts were made in trying out many kinds of calculation method. Consequently N.S.M. modified with the Maruo's three dimensional correction for the sectional added mass coefficient, explained well the tendency of experimental results. This method was proposed as a practical method of calculation for the vertical bending moment when the encounter frequency tends to zero.

5) From the comparison of calculated results in I.T.T.C., considerable differences can be seen in calculated values of vertical bending moment in following sea although the same formation of calculation method, say O.S.M. or N.S.M., was adopted, due to the difference in detail of calculation programs. Taking this into consideration, the actually obtained characteristic of vertical bending moment in following sea, is explained better by N.S.M. than by O.S.M.

In spite of the Method of correction presented in this paper, some difference with experimental results can be seen quantitatively. The authors intend to carry out further research on calculation method as well as experiments.

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