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Motion and Longitudinal Strength of a Ship in Head Sea and the Effects of Non-Linearities (4th Report)

—Experiments—

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Summary

A series of tank tests for slamming was carried out in the seakeeping basin, making use of an elastic ship model. The flexural rigidity of the model were reduced according to the laws of similitude. In this paper, foamed vinyl chloride was chosen for the material of the model. This material, which has relatively low modulus of elasticity and large damping for vibrations, is one of the best candidates for clarifying the characteristics of whipping vibrations caused by respective slams.

The experimental results are compared with the nonlinear theory proposed by the authors in the previous papers, which shows good agreements.

1. Introduction

In order to investigate responses of a ship among waves, series of model tests have been carried out in basins by numerous authors; their interest was concentrated on the ship motion in waves, and experiments were performed with the use of wooden models, which can be considered to be rigid. Recently, in relation to longitudinal strength and springing, increasing attentions have been paid to the measurement of bending moments of a ship in waves with the use of the so-called segmented model, which is made by connecting rigid-parts with elastic springs whose strains give bending moments.1~2) In these experiments, only the Froude scaling law is met, and they are sufficient for the study of slowly-varying responses of a ship induced by waves, but insufficient for investigating rapid responses due to localized impulses like slamming. For the latter purpose, experiments should be done with the use of elastic models for obtaining time histories of elastic strains, and they should follow not only the Froude scaling law but also laws of similitude for elasticity. With the use of elastic ship models, some experiments were carried out in the basin,3~4) and the models were made of brass with structural members similar to those in the actual ship. In this case, the laws of similitude for elasticity cannot be strictly satisfied.

On the other hand, a considerable number of ships' failures have been reported. Serious ones might be caused by slamming; therefore, slamming and subsequent whipping vibrations of a ship are getting more important. In this connection, the authors proposed a nonlinear theory for a ship's response to slamming among waves in the previous papers,5~6) which has been applied for the analysis of actual failure of ships. To demonstrate the validity of the theory, a series of model tests was carried out in the seakeeping basin with an elastic ship model. Foamed vinyl chloride was chosen for the material of the model. This material has relatively low modulus of elasticity and large damping for vibrations. The experimental results obtained, in the present peper, are compared with the authors' nonlinear theory, which shows good coincidence.

2. Laws of Similitude

According to the dimensional analysis, several laws of similitude can be derived for the model tests in a basin.7~9) Since the present objective is the analysis of motions and longitudinal

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strength of a ship as a girder in waves, similarity related to friction of water and lateral deformations can be disregarded. In the case of floating bodies like ships, average density of a ship is of the same order as that of water, and forces acting on the ship girder can be compared with the displacement. Therefore, the following laws will be taken into account:

1) Wave Similarity. Froude number, $U/\sqrt{gL}$, and the ratio, λ/L and H_w/L, equality.
2) Static Load Similarity. P_i number, $EI/\rho gL^5$, equality.
3) Dynamic Load Similarity. Cauchy number, $(EI)T^2/\rho L^6$, equality.

Here g is the acceleration due to gravity, ρ is the mass density of water, λ and H_w are the length and height of waves, L, U and EI are the length, speed and flexural rigidity of the ship, and T is a characteristic time duration related to external loads.

For designing a model ship, its lineal scale, α, should be chosen first. From the above laws, it follows that

$$L_m=\alpha L_s \tag{1}$$

$$\lambda_m=\alpha\lambda_s \tag{2}$$

$$(H_w)_m=\alpha(H_w)_s \tag{3}$$

$$U_m=\sqrt{\alpha}\ U_s \tag{4}$$

$$T_m=\sqrt{\alpha}\ T_s \tag{5}$$

$$(EI)_m=\alpha^5(EI)_s \tag{6}$$

where the subscripts s and m indicate the actual or model ship, respectively. Eq. (6) is a restriction for designing the model, and Eqs. (2)~(4) are for test conditions. Eq. (5) directly follows from the others if loads are governed only by the ship-wave interaction.

3. An Elastic Ship Model

The same container ship treated in the previous report[5)] will be investigated herein, and her body plan is shown in Fig. 1, indicating large bow-flare. The main interest in the present experiments is the whipping vibrations due to slamming, which will be tested with a self-propulsive elastic ship model of 3 m in length; that is,

$$\alpha=1/58.33 \tag{7}$$

Particulars of the model are shown in Table 1, and the material is foamed vinyl chloride, whose modulus of elasticity is about 15 kgf/mm^2 ($=147\ N/\text{mm}^2$), namely,

$$E_m\simeq\frac{1}{1400}E_s \tag{8}$$

According to the laws of similitude, the flexural rigidity, $(EI)_m$, of the model must be reduced with the ratio α^5. For the present material, the following relation is derived:

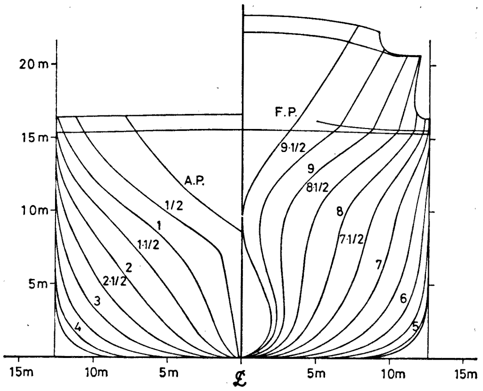


Fig. 1 Body plan of container ship

Table 1 Particulars of model

Length between Perpendiculars	(L)	3.0000 m
Breadth Moulded	(B)	0.4320 m
Depth Moulded	(D)	0.2620 m
Draft at A.P.	(d_a)	0.1704 m
Draft at Midship	(d_m)	0.1667 m
Draft at F.P.	(d_f)	0.1630 m
Displacement	(Δ)	124.6000 kg
Block Coefficient	(C_b)	0.5787
Center of Gravity from Midship	(x_G)	0.0154L
Longitudinal Gyradius	(κ_ℓ)	0.2380L
GM		0.0354B

$$I_m=24\alpha^4 I_s \tag{9}$$

which indicates that the model's shell plating is effectively 24 times that of the reduced size, and the local structures of the model are sufficiently strengthened, resulting in easy installation of the instruments. The scanting of midship section is shown in Fig. 2. The model has double bottom structures for the convenience of the installment of the measuring instruments. In the experiments, hatch covers were fitted for water tightness.

Besides the modulus of elasticity of the material, another important problem exists. In order to clarify the characteristics of whipping vibrations caused by respective slams, it is necessary that vibrations caused by previous slams damp rapidly. Foamed vinyl chloride is one of the best materials for this purpose; the logarithmic decrement of the model in still water is measured as,

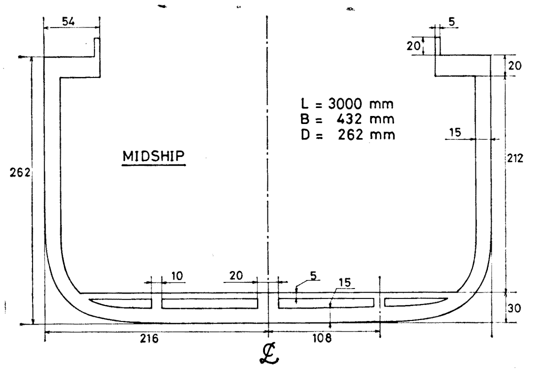


Fig. 2 Scantling of midship section of model

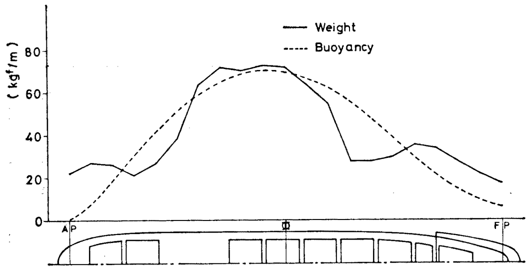


Fig. 3 Weight and buoyancy distributions of model

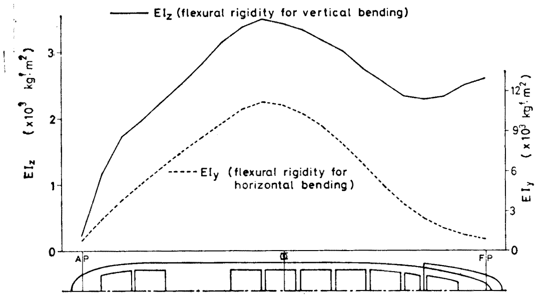


Fig. 4 Distributions of flexural rigidity of model

$$\delta=0.142 \tag{10}$$

which was used for structural damping.

In the case of container ships, serious slamming occurs in fully loaded condition, and model tests were carried out for this condition. The weight and buoyancy, and flexural rigidity distributions are shown in Figs. 3 and 4; weight and flexural rigidity distributions of the actual ship may not be similar to those of the model. Moreover, the damping of the vibrations of the model differs from that of the actual ship as mentioned before, and therefore, it is noted that the time histories of whipping vibrations obtained by this model are not the same as the actual ship. This difficulties can be eliminated by comparing test results with theoretical calculations.

4. Experiments and Calculations

A series of tank tests was conducted in the Seakeeping and Maneuvering Basin at the University of Tokyo. The following data were recorded; wave, pitch, roll, yaw, vertical bow acceleration, pressure at bow-flare, and deck-strains. The locations of the gauges are shown in Fig. 5. The tests were conducted in regular waves of various conditions: Direction, χ, length, λ, and height, H_w, of waves were such that

$$\chi=180°,\ 157.5°,\ 135°,\ 90°,\ 45°,\ 0°$$

$$\lambda/L=0.8,\ 1.0,\ 1.2,\ 1.5$$

$$L/H_w=30,\ 20,\ 15$$

Here $\chi=180°$ means right head sea, and $\chi=0°$ right follow sea. The numbers of revolutions of the propeller shaft were adjusted so that the Froude number in still water, Fn, was 0.15, 0.24, or 0.33; in reality, significant speed loss was observed in waves.

Calculations for the longitudinal motions are performed according to the previous papers,[5~6] which will be referred as *nonlinear calculation*, while those by the conventional strip theory as *linear calculation*. In oblique waves, transverse motions are generated, and the fluid forces for heave, pitch, and vertical vibration modes should be determined by considering the rotated configurations of the ship's sections.[5] As for sway-yaw-roll couplling motions, only rigid-body motions are considered in the present paper, and are calculated by the linear strip theory.

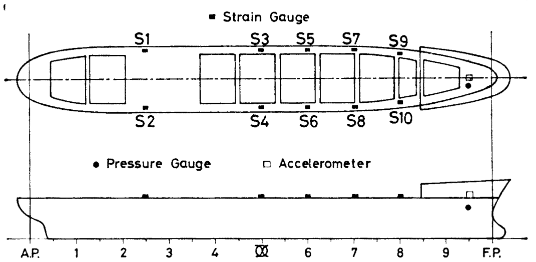


Fig. 5 Locations of gauges etc.

5. Results and Considerations

In Head Sea In the case of the constant revolutions of the propeller shaft in the self-propulsive tests, ship speed decreases in waves. In Fig. 6, ship speed loss in head sea is shown with respect to wave length. Speed loss increases, in general, with the wave height, and becomes maximum at $\lambda/L\simeq1.0$, for each wave height $H_w/L\geqq1/20$, attaining to 90% of the speed in still water.

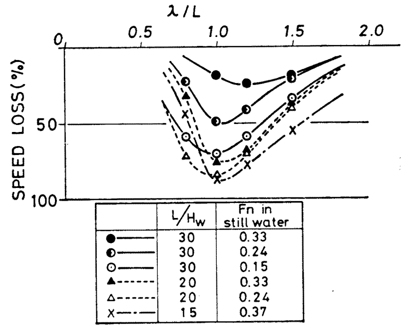


Fig. 6 Speed loss in head sea

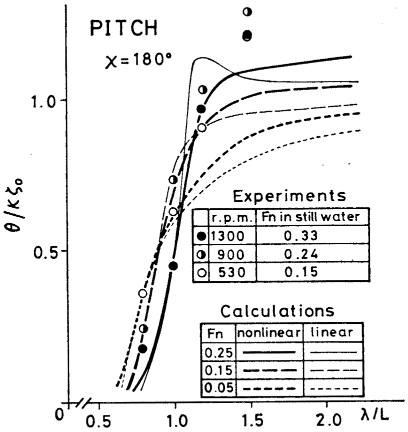


Fig. 7 Pitching amplitudes ($\chi=180°$, $L/H_w=30$)

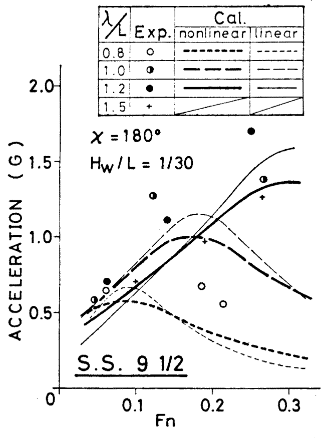


Fig. 8 Acceleration amplitudes at S.S. 9 1/2 ($\chi=180°$, $L/H_w=30$)

Pitching amplitudes in head sea are shown in Fig. 7. Linear and nonlinear calculations are performed for $Fn=0.25$, 0.15, and 0.05. Experimental results show good agreements with calculations around $\lambda/L=1.0$, *where heavy slamming may occur.*

Vertical bow acceleration amplitudes at S.S. 9 1/2 are shown in Fig. 8. The amplitudes have some difference between calculations and experiments. It is considered that the whipping components of the acceleration obtained are larger than those of theoretical one.

Theoretical and experimental time histories of deck-strains are shown in Figs. 9 and 10 for three kinds of ship speed. With the increase of the ship speed, slams become heavier, which is observed in both experiments and calculations. The absolute values of deck-strain amplitudes obtained by the nonlinear calculation show good agreements with experiments. The difference between calculations and experiments at $Fn=0.250$, as shown in Fig. 9, is related to the phase lag between bottom and bow-flare impacts; that is, the dynamic swell-up of water is disregarded in the calculations.

Peak-to-peak amplitudes of the deck-strain are shown in Fig. 11, calculations show good agreements with experiments; that is, the strain amplitudes increase with the ship speed.

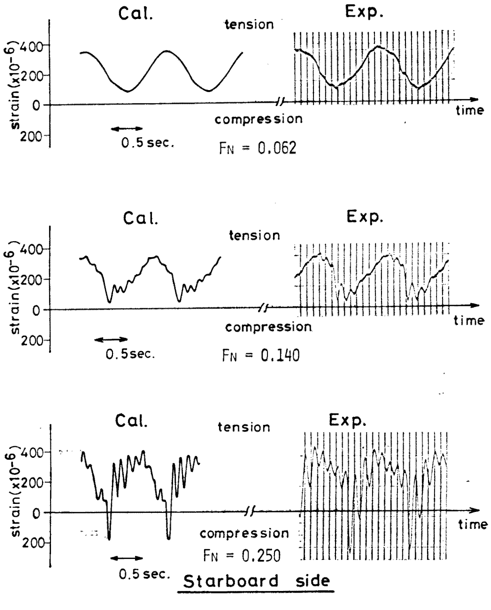


Fig. 9 Time histories of deck-strain at midship ($\chi=180°$, $\lambda/L=1.2$, $L/H_w=30$)

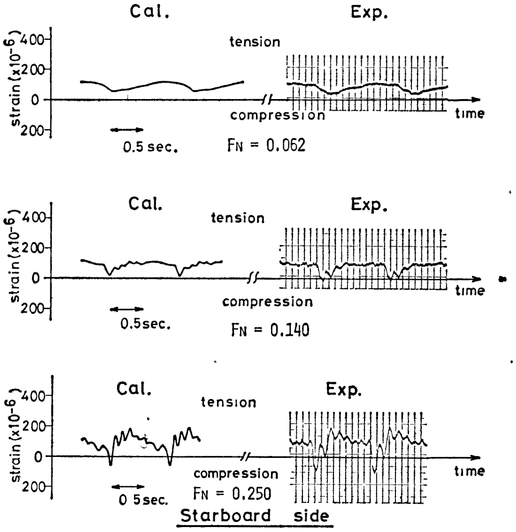


Fig. 10 Time histories of deck-strain at S.S. 8 ($\chi=180°$, $\lambda/L=1.2$, $L/H_w=30$)

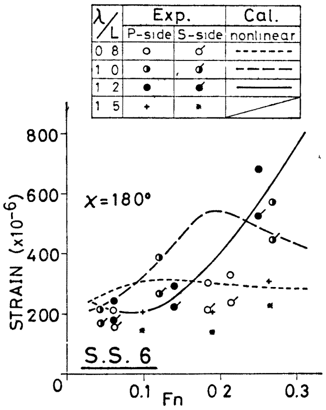


Fig. 11 Deck-strain amplitudes at S.S. 6 ($\chi=180°$, $L/H_w=30$)

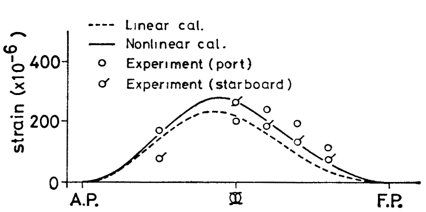


Fig. 12 Longitudinal distribution of deck-strain amplitudes ($Fn=0.062$, $\chi=180°$, $\lambda/L=1.2$, $L/H_w=30$)

In Figs. 12~14, longitudinal distributions of peak-to-peak amplitudes of deck-strain are shown. At high speed ($Fn=0.140$, 0.250), they

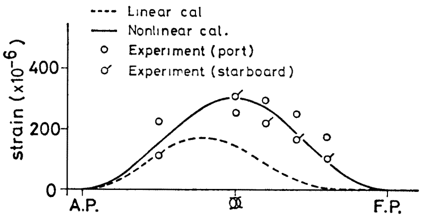


Fig. 13 Longitudinal distribution of deck-strain amplitudes ($Fn=0.140$, $\chi=180°$, $\lambda/L=1.2$, $L/H_w=30$)

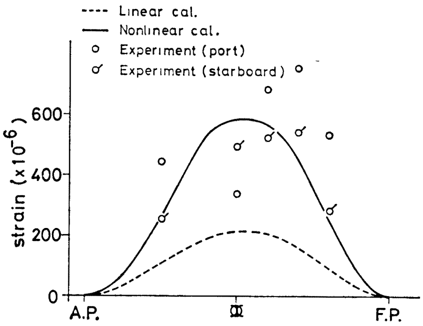


Fig. 14 Longitudinal distribution of deck-strain amplitudes ($Fn=0.250$, $\chi=180°$, $\lambda/L=1.2$, $L/H_w=30$)

are in excess of two times of those obtained by the linear calculation in the fore body, and are in conformity with the nonlinear calculation. On the other hand, at low speed, both linear and nonlinear calculations show good agreements with experiments.

In Oblique Waves Slamming was observed only in bow waves, and the major interests in the present paper are slamming and whipping vibrations; therefore, only the results in bow waves are shown herein. General characteristics of pitch motion, vertical bow acceleration and deck-strain are the same as those in head sea.

In oblique waves, significant yaw and roll motions occurred, and their amplitudes are shown in Figs. 15 and 16 with the results of the linear calculation. Estimates by the linear strip theory agree with experiments for roll motion, but fail for yaw motion, which shows that yaw motion is influenced to a great extent by slamming impact in lateral direction. In bow wave conditions, rolling is very small, and it can be disregarded for considering the longitudinal strength.

In oblique waves longitudinal horizontal

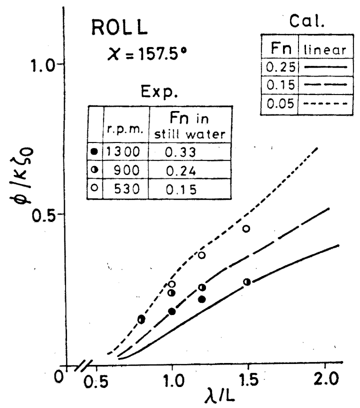


Fig. 15 Rolling amplitudes ($\chi=157.5°$, $L/H_w=30$)

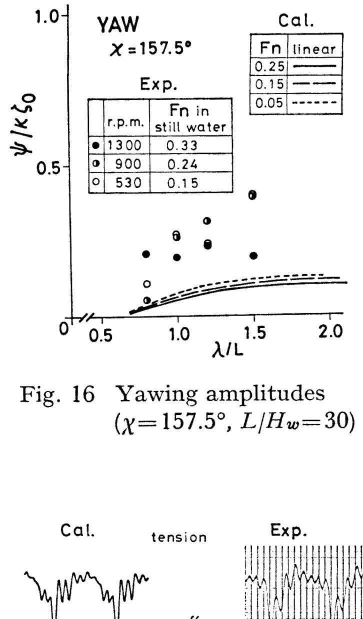
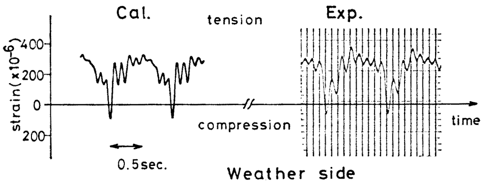
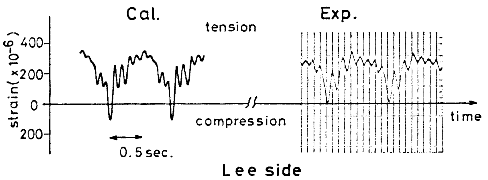


Fig. 16 Yawing amplitudes ($\chi=157.5°$, $L/H_w=30$)



Weather side



Lee side

Fig. 17 Time histories of deck-strain at midship ($Fn=0.232$, $\chi=157.5°$, $\lambda/L=1.2$, $L/H_w=30$)

bending moment occurred, and time histories of the deck-strain under the influence of linear horizontal bending moment are shown in Fig. 17 which shows that the deck-strains in bow waves are influenced only slightly by the horizontal bending moment.

6. Conclusions

A series of tank tests for slamming was conducted using an elastic model for a container ship, and whipping vibrations were observed. The results were compared with the nonlinear theory proposed by the authors in the previous papers.[5~6] The following conclusions were obtained:

1) The validity of the nonlinear theory proposed by the authors,[5~6] is confirmed by the experiments, and the theory is effective to clarify the responses of a ship due to slamming.
2) Although the ship speed loss in head sea is significant in case of high wave height, heavy slams occur for high number of revolutions of the propeller shaft, resulting in significant whipping stresses.
3) As for the material of the elastic model in the slamming tests, foamed vinyl chloride is recommended from the viewpoints of modulus of elasticity, damping characteristics, and easiness of fabrication and handling.

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