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A Study of Wave-Induced Vibrations (2nd report)

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Summary

As a continuation of the previous work[10], the study on wave-induced vibrations (springing) has been presented in this report. Model experiments in irregular waves have been carried out. Full scale experiments of springing on board large tanker have been performed. Using these results, characteristics of springing have been examined. Expressions for combined stress are shown. Short-term and long-term distributions of springing stress are also presented. It is shown that the combined stress is less than the sum of wave bending and springing stresses. The extreme value for 20 years of springing stress of 237 000 dwt tanker is estimated about 4 kg/mm².

1. Introduction

Springing has been investigated by many researchers both theoretically and experimentally[1)~16)]. A prediction of springing response of full scale ships, however, is difficult since there are still some difficulties and uncertainties in estimating the wave-exciting forces, wave spectrum, damping of vibration etc. quantitatively by theoretical procedures and model experiments. The authors studied springing by theoretical calculations and model experiments in the preceding paper[10]. In this paper, results of data analysis of model in irregular waves and those of full scale experiments are shown.

2. Results of Model Experiments in Irregular Waves

In the previous report[10] the model experiments were described which were mainly carried out in regular waves. The results in irregular waves are shown hereafter. The model is the same as was used in regular waves[10], which consists of 7 segments connected by flexible bending springs so as increase the bending flexibility of hull girders. The model is 7 metres long and other particulars are shown in the previous report[10]. The model is towed in the see-keeping tank of Nagasaki Technical Institute, Mitsubishi Heavy Industries, Ltd. Four different wave spectra have been provided in the experiment, i.e., the spectra I, II, III and IV as shown in Fig. 1. Mean wave periods ($\tilde{T}$) and significant wave heights ($H_{1/3}$) of the spectra are shown in Figs. 2 and 4.

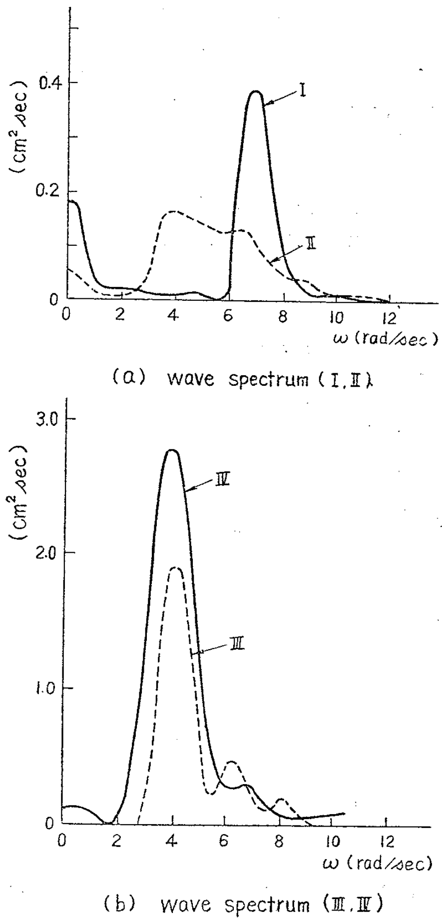

Fig. 1 Wave spectra of model experiment in irregular waves

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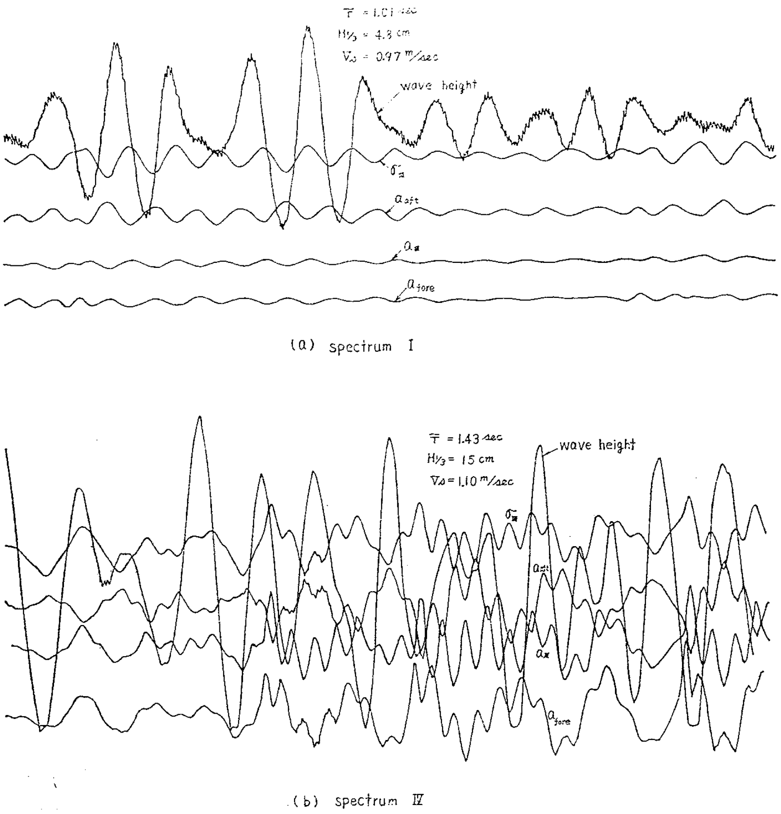


Fig. 2 Time history of springing response of model

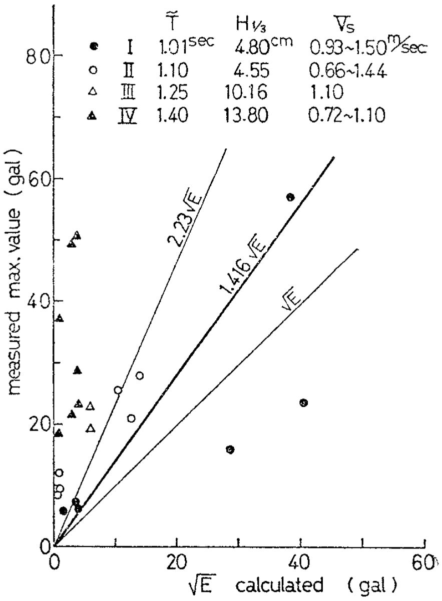


Fig. 4 Comparison between measured and calculated springing acceleration of model in irregular waves

Fig. 3 shows the relation among various stochastic values of measured springing stress amidships. The abscissa is taken as $\sqrt{E}$ values. E is a mean value of squared amplitudes of springing. All the data well coincide with the straight line representing the Rayleigh distribution.

Calculation of the springing acceleration in four wave spectra mentioned above has been carried out by means of the ordinary linear random vibration theory—such as used by Goodman—where the frequency response characteristics of springing obtained by the experiments in regular waves[10] are used. Fig. 4 shows the relation between calculated and measured springing response in various wave spectra. The abscissa is taken as $\sqrt{E}$ values of springing acceleration amidships calculated by the method mentioned above, and the ordinate is taken as the measured maximum acceleration. As mentioned in Fig. 3, the data should be on the straight lines—i.e., the measured maximum stress should be proportional to calculated $\sqrt{E}$- stress— if the random vibration theory well applies to the springing phenomenon. The proportionality is not so well as is in Fig. 3. On the whole, however, the data show the tendency of proportionality, excepting the data in wave spectrum IV which represents very rough sea. The reason of deviation for the case of spectrum IV is supposed to be the appearance of whipping. As shown in Fig. 2, the time history of springing acceleration shows sharp pulses in spectrum IV, whereas there is no pulse in spectrum I which represents milder sea states.

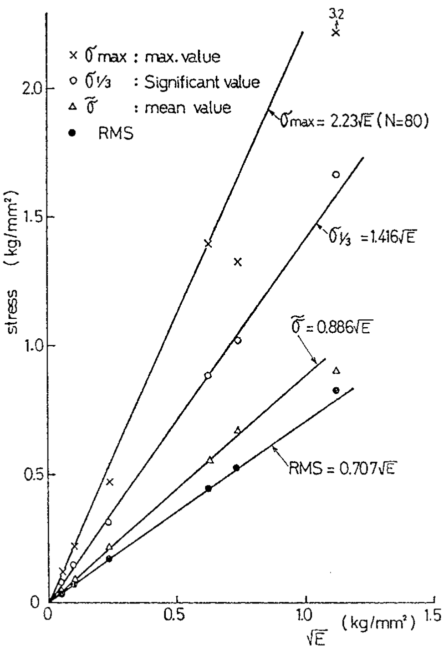


Fig. 3 Relation among measured statistical values of springing stress of model

In the irregular waves, the wave bending stress is induced in addition to springing stress, and the combined stress of both of them is important from the point of view of longitudinal strength. Table 1 shows the relation among these three types of stresses in the model experiment. It is seen from this table that the rms of combined stress, $RMS_{(C)}$, is less than the sum of rms's of wave bending stress, $RMS_{(W)}$, and springing stress, $RMS_{(S)}$, and

Table 1 Measured stress of model in irregular waves

wave		I		II		III	IV	
V_s (m/sec)		0.93	1.48	0.70	1.40	1.10	1.10	
a	$\mathrm{RMS}_{(S)}$	0.040	0.523	0.073	0.171	0.448	0.824	
b	$\mathrm{RMS}_{(W)}$	0.026	0.064	0.076	0.110	0.576	1.377	(kg/mm²)
c	$\mathrm{RMS}_{(C)}$	0.047	0.527	0.105	0.204	0.730	1.605	
d	$a+b$	0.066	0.587	0.149	0.281	1.024	2.201	
e	$\sqrt{a^2+b^2}$	0.048	0.527	0.105	0.203	0.730	1.605	mean
ratio	c/d	0.71	0.90	0.70	0.73	0.71	0.73	0.75
ratio	c/e	0.98	1.0	1.0	1.01	1.0	1.0	1.0
A	$\sigma_{\max(S)}$	0.130	1.326	0.221	0.467	1.404	3.227	
B	$\sigma_{\max(W)}$	0.115	0.351	0.271	0.478	1.373	3.428	(kg/mm²)
C	$\sigma_{\max(C)}$	0.171	1.308	0.401	0.646	2.241	5.651	
D	$A+B$	0.245	1.677	0.492	0.945	2.777	6.655	
E	$\sqrt{A^2+B^2}$	0.174	1.372	0.350	0.668	1.964	4.708	mean
ratio	C/D	0.70	0.78	0.82	0.68	0.81	0.85	0.77
ratio	C/E	0.98	0.95	1.15	0.97	1.14	1.20	1.07

equal to the root of sum of square of these two, i.e., $\mathrm{RMS}_{(C)}=\sqrt{\mathrm{RMS}_{(W)}^2+\mathrm{RMS}_{(S)}^2}$. It is also seen that the maximum combined stress, $\sigma_{\max(C)}$, is less than the sum of maximum wave bending stress, $\sigma_{\max(W)}$, and maximum springing stress, $\sigma_{\max(S)}$. Therefore the following expressions are derived from Table 1.

$$\mathrm{RMS}_{(C)}=0.75\{\mathrm{RMS}_{(S)}+\mathrm{RMS}_{(W)}\} \tag{1}$$

$$\mathrm{RMS}_{(C)}=\{\mathrm{RMS}_{(S)}^2+\mathrm{RMS}_{(W)}^2\}^{1/2} \tag{2}$$

$$\sigma_{\max(C)}=0.77\{\sigma_{\max(S)}+\sigma_{\max(W)}\} \tag{3}$$

$$\sigma_{\max(C)}=1.07\{\sigma_{\max(S)}^2+\sigma_{\max(W)}^2\}^{1/2} \tag{4}$$

3. Full Scale Experiment

Springing response has been measured on a full scale ship during the service voyage for half a year. The ship, Ship A, is a 237 000 dwt tanker whose particulars are shown in Table 2. Her route is usually between Japan and the Persian Gulf, occasionally between the Persian Gulf and Europe. The measurements have been carried out by means of an automatic data acquisition and processing system controlled by a mini-computer. The details of the system and the measurement have been reported[19] and omitted from the present report. Fig. 5 shows an example of the record of the processed data. This shows the time history, the power spectral density and the histogram of the measured springing stress. The system can auto-

Table 2 Main particulars of Ship A

kind	oil tanker	class	NK
L_{pp}	304.0 m	D/W	237 000 t
B	52.4 m	Δ_{full}	278 300 t
D	25.7 m	d_{full}	19.8 m

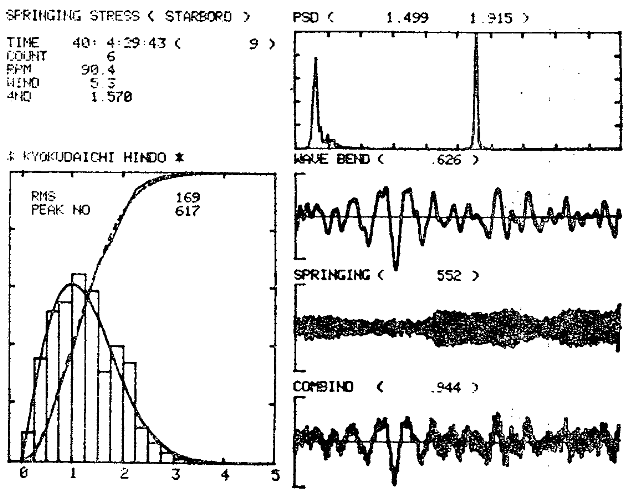


Fig. 5 Hard copy of CRT display unit obtained by full scale experiment on Ship A

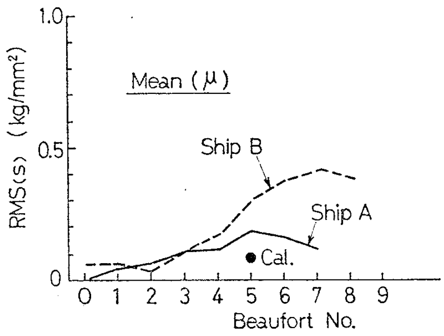
matically begin measurement, data processing and recording such as shown in Fig. 5.

4. Results of Full Scale Experiment

Table 3 shows the frequency of occurance of springing stress amidships (rms) versus Beaufort number (B_n) measured on Ship A during half a year voyage in ballast condition. Though there are few data in higher Beaufort numbers, as is expected, there is a tendency that the springing stress increases for higher Beaufort number. From these data the mean value (μ) and the standard deviation (s) have been computed for each Beaufort number and shown in Fig. 6. In this figure the dark spot indicates the calculated springing stress for the sister ship of Ship A. In the upper part of Fig. 6, the calculation has been carried out by means of the linear random vibration theory mentioned in the model experiment. In this calculation the wave spectrum is assumed to be ISSC-spectrum, and the frequency response function of springing is taken as shown in the previous report[10]. It is seen that this calculation underestimates the springing stress. Another type of calculation has been carried out and compared with measurement in the lower part of Fig. 6. In this calculation the irregular sea has been replaced by equivalent regular waves and the springing stress in resonant condition has been calculated. The detail of this approximate calculation is shown in the previous report[10]. There is no logical justification that the stress calculated in this manner can be equivalent to $\mu+3s$ of stochastic stress but it is plotted in the lower part of Fig. 6 only for reference. It is seen that neither method

Table 3 Frequency of springing stress (rms) obtained by full scale experiment on Ship A

sum		0	1.36	13.01	23.11	32.62	13.59	8.54	7.57	0.19	0	100	(%)
sum		0	7	67	119	168	70	44	39	1	0	515	100
Springing stress (rms kg/mm²)													
	0.9												
	0.8								1			1	0.19
												0	0
	0.7								1			1	0.19
												0	0
	0.6								1			1	0.19
												0	0
	0.5							1	1			2	0.39
						1		1				2	0.39
	0.4						1	2				3	0.58
					1	3	2	4				10	1.94
	0.3					2	7	3				12	2.33
					6	7	9	1				23	4.47
	0.2			3	8	20	13	4				48	9.32
				5	17	25	13	1				61	11.84
	0.1			4	15	35	8	2	1			65	12.62
			2	9	27	16	8	7	8			77	14.95
			5	46	45	59	9	18	26	1		209	40.58
B_n		0	1	2	3	4	5	6	7	8	9	sum	



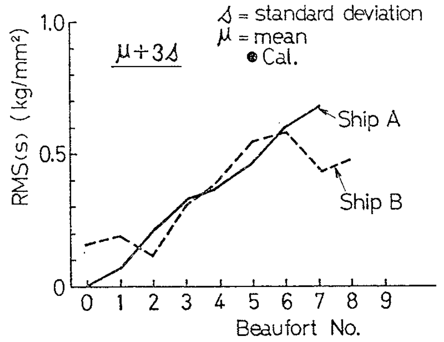


Fig. 6 Relation between Beaufort no. and measured springing stress of full scale ship (rms)

can estimate the springing stress accurately. A part of this discrepancy is attributed to the inaccuracy of the frequency response function of the springing in actual ships. Another, and probably greater, reason would be the inaccuracy of the wave spectrum in the region of very short wave length. Therefore the refinement of these item is recommended in the future study.

The data of springing stress in the service voyage of Ship B[21], a 153 000 dwt tanker, are also shown in Fig. 6 for comparison. Mean value of rms springing stress of Ship B is larger than that of Ship A, in spite of nearly the same value of $\mu+3s$ for both ships. The difference is considered to be in the difference of ship's headings relative to the wave direction. Ship B was nearly in head seas throughout all the voyages whereas Ship A encountered various heading angles.

In the previous report[10] the authors proposed the simplified relation that the springing stress per unit wave height is proportional to the parametre P defined as follows (formula (7) in the report).

$$P=\frac{D}{L}\cdot\frac{B/d}{C_b\left(1.2+\dfrac{B}{3d}\right)}\cdot\left(\frac{L_w}{L}\right)^n\cdot\exp\left(-\frac{\pi^2}{2}\cdot\frac{d}{L_w}\right) \tag{5}$$

where n : 6

L_w: wave length of encountered wave resonant with 2-noded vibration,

L, B, D, d and C_b: length between perpendiculars, breadth moulded, depth moulded, draft and block coefficient of the ship.

Therefore the springing stress amidships σ is given as follows*).

$$\sigma=kP\frac{H_w}{L_w} \tag{6}$$

where k: empirical constant, H_w: wave height.

This relation means that, under the same sea condition, the springing stress for the different ship is equal if the parametre P is equal. In Table 4 the parametre P for Ship A and B is shown together with their $\mu+3s$ value of springing stress, which is regarded as the practical upper limit of springing stress. It is seen from this table that the parametre P can be used as an index for springing response.

Results of combined stress measured on Ship A are shown in Figs. 7 to 9. Relations between wave bending and springing stresses in combination and combined stress are presented in Fig. 7 as for the root mean square and in Fig. 8 as for the maximum value. From the figures, following expressions have been derived, as expected by the model experiment and partially expected by the results of the Great

*) Formula (7) in the previous report has not the same expression as formulae (5) and (6) in this report but has the same meaning. If L_w is replaced by natural frequency of 2-noded vibration and ship speed and exponential function is approximated by algebraic function, formulae (5) and (6) tend to formula (7) of the previous report, when $n=4$. n is increased by 2 corresponding to the model test in regular waves of the previous report.

Table 4 Comparison of springing stress of Ship A and Ship B

ship	L_{pp}(m)×B(m)×D(m)	d (m)	V_s (knot)	N_2 (cpm)	P	RMS(S)*)		
						4	5	6**)
A	304×52.4×25.7	9.75	16.5	33.3	1.56×10^{-8}	0.39	0.47	0.60
B	268×53.6×20.0	8.70	16.0	36.0	1.52×10^{-8}	0.40	0.55	0.58
A/B					1.03	0.98	0.85	1.03

*) kg/mm²　　**) Beaufort no.

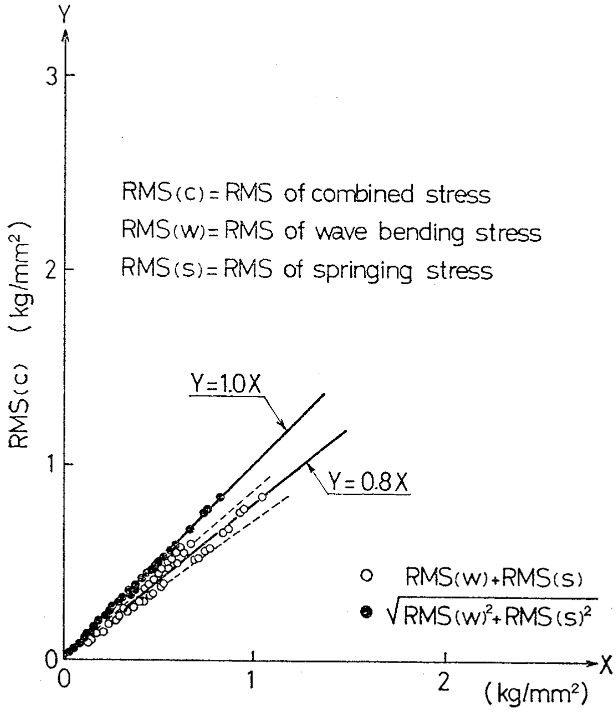


Fig. 7 Relation between measured combined stress and two components of stress (rms)

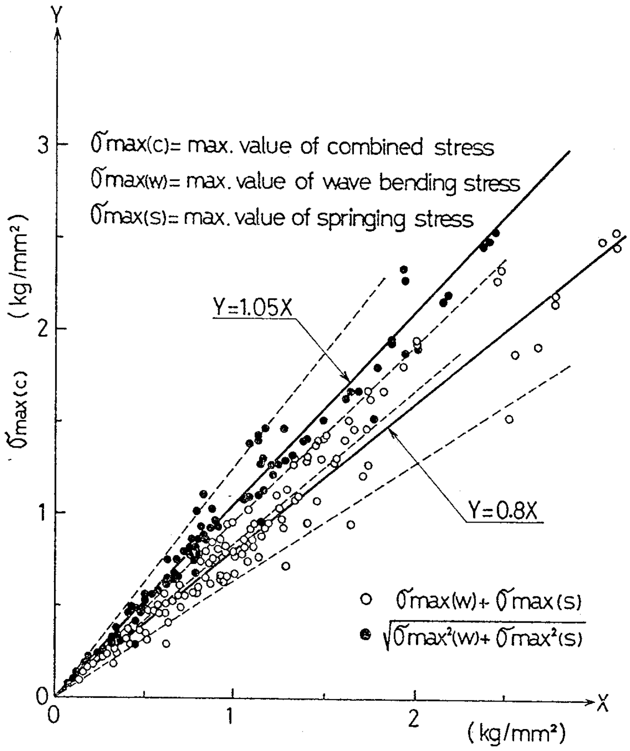


Fig. 8 Relation between measured maximum values of combined stress and two components of stress

Laker[16].

$$\mathrm{RMS}_{(C)}=0.8\{\mathrm{RMS}_{(S)}+\mathrm{RMS}_{(W)}\} \tag{7}$$

$$\mathrm{RMS}_{(C)}=\{\mathrm{RMS}_{(S)}{}^2+\mathrm{RMS}_{(W)}{}^2\}^{1/2} \tag{8}$$

$$\sigma_{\max(C)}=0.8\{\sigma_{\max(S)}+\sigma_{\max(W)}\} \tag{9}$$

$$\sigma_{\max(C)}=1.05\{\sigma_{\max(S)}{}^2+\sigma_{\max(W)}{}^2\}^{1/2} \tag{10}$$

Equations (7) to (10) for the full scale ship and equations (1) to (4) for the model ship coincide each other. Maximum values of combined stress measured on Ship A have been rearranged in the following expressions[17].

$$\sigma_{\max(C)}{}^2=\sigma_{\max(S)}{}^2+2\gamma\sigma_{\max(S)}\sigma_{\max(W)}+\sigma_{\max(W)}{}^2 \tag{11}$$

for $\gamma=1$ $\quad \sigma_{\max(C)}=\sigma_{\max(S)}+\sigma_{\max(W)}$ (12)

for $\gamma=0$ $\quad \sigma_{\max(C)}=\{\sigma_{\max(S)}{}^2+\sigma_{\max(W)}{}^2\}^{1/2}$ (13)

Fig. 9 shows the correlation of combined stress

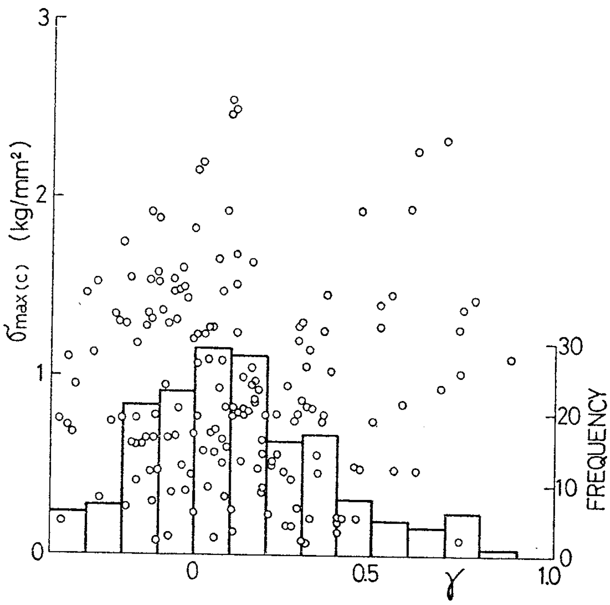


Fig. 9 Parameter derived from measured maximum value of combined stress and its histogram

and parameter and its histogram. It is concluded that γ is less than 1.0 and its mode is 0.0 to 0.1, and consequently the maximum combined stress is less than the sum of the maximum values of wave bending and springing stress. Fig. 10 shows the relation among the measured statistical values of springing stress of the full scale ship, which indicates the good agreements with the theoretical Rayleigh distribution similarly to the result of the model experiment. These results give a temporary expedient for the prediction of the long-term distribution of springing stress.

Fig. 11 shows the calculated long-term distribution of springing stress for which the short-term distribution of springing has been tentatively assumed as Rayleigh distribution[15] and the following procedures have been adopted.

$$Q=\sum_i \exp(-\sigma^2/Ei)q_i \tag{14}$$

where Q: probability of exceeding

σ: springing stress amidships

Ei: mean value of squared amplitude for i

E: $2\,\mathrm{RMS}_{(S)}{}^2$

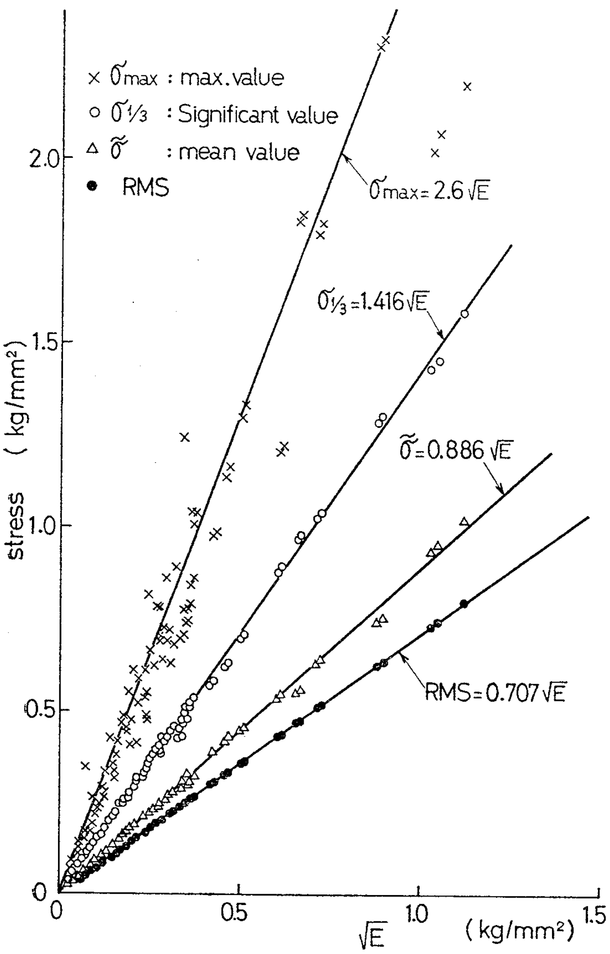


Fig. 10 Relation among measured statistical values of springing stress

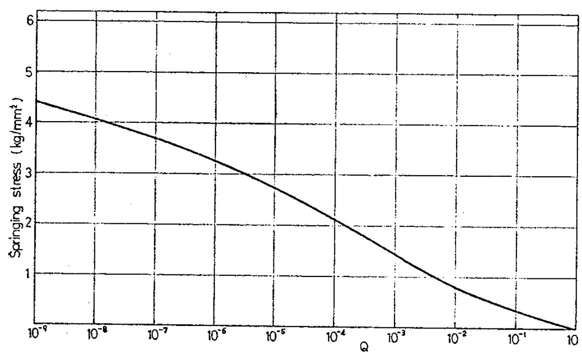


Fig. 11 Long term distribution of springing stress of Ship A

i: suffix refering to stress level

q_i: frequency of stress level i

The stress level and its frequency for the calculation mentioned above have been evaluated by Table 3. Table 3 also shows the frequency of each Beaufort no. experienced on Ship A, which is nearly the same as those of log records for about three years of other ship engaged in Japan-Persian Gulf route except the higher Beaufort no. than 8. The long term distribution shown in Fig. 11, therefore, could be compared to that of ships on Japan-PG route. The expected maximum springing stress for 20 years could be evaluated about 4 kg/mm² corresponding to Q of 6×10^{-9} provided that the half of voyages are in ballast condition. For the long term distribution of all vibratory response of the ship, however, it would be necessary to have to take into account of the higher Beaufort no. (severe sea state) and the effect of whipping.

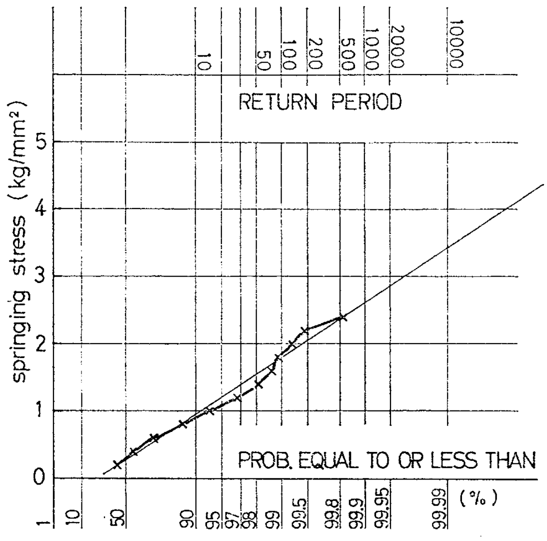


Fig. 12 Extreme value of springing stress of Ship A

Fig. 12 shows the extreme value estimation of stress by Gumbel's method using maximum values of springing stress measured on Ship A for about half a year. A return period of Fig. 12 means number of measurements. It ~~is~~ concluded that the predicted maximum value of springing stress for 20 years could be near 4 kg/mm². It should be noted, however, that there are few data of springing and no confirmation of the regular springing response in rough sea where springing would be rather replaced by whipping. Then for the prediction of long term distribution and the extreme value, further investigations are necessary.

5. Conclusive Remarks

The results of full scale experiments and model experiments show that the combined stress could be evaluated from the wave bending and springing stresses by the present procedures and that the combined stress is less than the sum of the two components. Statistical values of springing stress seem to have characteristics similar to those of theoretical Rayleigh distribution in practical use. The expected maximum value of springing stress of the ship is estimated to be about 4 kg/mm². Though the linear theory and the present procedures might be applicable for the rough estimation of springing response, further investigations are needed to complete the theoretical procedure for the precise estimation. Non-linearity of wave exciting forces and the effect of whipping should be taken into account to cover the all vibratory response of the ship in waves. In severe sea state, whipping stress is considered to be more important for the strength of ships by comparison of the present results with the stochastic prediction of whipping stress[20]. Long term distribution of springing stress presented here, however, might be used to estimate the influence of springing on the fatigue strength of ships.

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