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ON THE RESPONSE FUNCTION FOR THE ROLLING MOTION OF A FISHING BOAT ON OCEAN WAVES

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1. Introduction

It is usual that fishing boats or research ships are drifting on ocean waves by stopping their engines during their engagement in fishing or oceanographic work. It would be valuable to investigate the rolling response of the vessel to ocean waves for the purpose of safe operations while stopping on the sea. Generally, it is very difficult to determine the response characteristics of ship motion on an actual sea by means of artificial waves in an experimental tank. On the other hand, the characteristics of the ship response to the wave can be given by measuring ocean waves and ship motions, which are respectively considered as the input and output of a dynamical system. This would be the most useful method for studying the ship motions in a seaway.

We calculated the power spectrum and distribution of ship rolling angles from experiments on a ship in a seaway. In addition, we made model ship experiments in an experimental tank in which irregular waves as in the seaway were produced by a wave generator. The response characteristics for the ship rolling motion were deduced by statistical analysis from the results of observations. To describe about this is the purpose of the present paper.

2. Formation of the equation of motion for the ship rolling on waves and the actual ship rolling characteristics in a seaway

2–1 *The linear equation of motion for the ship rolling*: Studies of the problem of ship rolling motion in a seaway have been developed to the present stage under the assumptions given by W. Froude and A. N. Krilov. The oscillation system has been explained as shown in Fig. 1. A wave train produces a periodic change in the inclination of the sea surface and, in turn, causes oscillation of the ship. By the above mentioned assumptions, this oscillation is described by rolling angles of the ship due to the wave slope. The linear differential equation of the ship rolling motion with respect to the absolute coordinate system is given as follows:

$$\ddot{\theta}+2\nu\dot{\theta}+n^2\theta=n^2\Theta(t) \qquad (1)$$

where, $2\nu = 2N/A'$, $n^2 = D \cdot GM/A'$.

D : weight of the ship.
GM: transverse metacentric height.
A' : moment of inertia for the transverse axis of the ship, including the moment of inertia of the virtual mass of the ship.
θ : angle of rolling.
$2N$: linearized damping coefficient for the rolling motion.
$\Theta(t)$: wave slope which represent the input forces to the system of motion.

2-2 *Rolling motion of an actual ship in a seaway*: The ship principal dimensions and other data which were used in our experiment are given in Table 1, in which the natural period of rolling motion was given by the rolling test of the ship. The power spectrum and distribution of the amplitude of rolling angles are shown in Figs. 2 and 3, respectively. They were calculated from the record of ship rolling angles which were measured when the ship was drifting and engaging in oceanic observations in the seaway.

The chi-square test was applied to ascertaining the distribution function of the amplitude of rolling angles to be a Gaussian distribution. It is also shown in Fig. 3.

3. The model ship experiment

3-1 *Model ship*: The model ship used was of the scale 1 to 27.5 in length and the natural period of rolling was 1 to 5.24 of the actual ship's. Data obtained from the experiment using this model ship are shown in Table 1.

Table 1

The actual ship and model ship
Principal dimensions and other data in the experiment
$L_{pp}=46.79$ m, $B=9.14$ m, $D=4.72$ m

	Actual	Model
Disp.	873.49 tons	42.00 Kg
d_f	3.128 m	113.70 mm
d_a	3.768 m	137.00 mm
d_m	3.448 m	125.4 mm
KM	4.210 m	153.1 mm
KG	3.392 m	123.3 mm
GM	0.818 m	29.7 mm
GG_0	0.063 m	
G_0M	0.755 m	27.5 mm
T_0	8.60 sec (0.116 c/sec)	1.64 sec
T_{model}		1.58 sec (0.633 c/sec)

Model ship is of the scale 1 to 27.5 of the actual ship's.

3–2 *Outline of the model ship experiment*: The arrangement of the measuring apparatus is shown in Fig. 4 and the method of measuring irregular waves and ship rolling angles is as follows:

3–2–1 *Arrangement of the model ship and the measuring apparatus*:
Model ship: The ship center line plane is set in parallel with the crest of approaching waves.
Wave generator: Irregular long-crested waves are generated by a flapper type wave generator with an automatic wavemaker control system.

3–2–2 *Measurement of waves and rolling angles*:
Wave heights and slopes: At the station 1 in the diagram, wave heights and slopes were measured and recorded on the chart continuously. The wave slope is given as the derivative of the wave height with respect to the time variable.

3–3 *Statistical properties of the data*: For each measurement, the distribution of differences between every 1/5 seconds ($=\Delta t$) readings, and mean values of wave slopes and ship rolling angles are shown in Figs. 5–1 and –2. The chi-square test was applied against the Gaussian distribution. The power spectra of them are shown in Figs. 6–1, –2 and –3. As to the wave spectrum, it is found that the range of frequency of the significant power is from about 0.44 c/sec to 0.78 c/sec.

4. Analysis and discussion for the response function of ship rolling motion

4–1 *Numerical analysis of data*: According to the statistical characteristics of the data they can be looked as from a Gaussian random process, and the frequency response characteristics were calculated by the procedure described in the paper by Akaike [pp. 5–17 of this supplement]. In the calculation the wave and rolling angles were taken to represent the input $x(t)$ and output $y(t)$ of the dynamical system of ship motion respectively.

Constants adopted in the computation of the frequency response function are as follows:

time interval between adjacent data	$\Delta t = 1/5$ sec,
total number of records	$M = 1000$,
maximum lag used for the computation	$h = 125$,
number of shift of the center of lag window for the estimation of cross-spectra	$K = \begin{cases} 30 & \text{(for Figs. 7 and 8)} \\ 0 & \text{(for Fig. 9).} \end{cases}$

The results are shown in Figs. 7–1, –2, –3 and 8–1, –2, –3, in which window

W_1 or the weighting factors $a_0=0.5132$, $a_1=-a_1=0.2434$ and $a_2=-a_2=0$ were used.

4–2 *On wave heights and slopes*: The relation between the wave height and slope, which was calculated by taking wave heights as input and slopes as output, indicates that the amplitude gain is linearly increasing with frequency and the phase shift is almost constant in the frequency range from 0.44 c/sec to 0.80 c/sec (see Figs. 9–1, -2 and -3). From this and the relation of the coherency and relative error in Figs. 7–3 and 8–3, we can conclude that only this range of frequency, 0.44 c/sec to 0.80 c/sec, can be used for deducing any proper physical meaning of the motion in our experiment.

4–3 *Coherency and relative error*: The reason of the relatively low coherency of the results may be explained by the following:

1) Existence of the distance between the two stations where wave heights and rolling angles were measured; the distance is about 2 meter along the same direction with the wave propagation.

2) The model ship was not kept at one place. It was left freely drifting according to wave actions.

3) Non-linearity of the ship rolling response.

4) Effect to the measuring of ship rolling angles of the swaying of the model ship.

5. Conclusion

When we consider the coherency, the relative error, and the effectiveness of generated waves, from the calculated response characteristics for the effective frequency range, we get the following conclusion:

1) On the amplitude gain:

From Figs. 7 and 8, it can be said that the maximum values of amplitude gain are nearly on the natural frequency of the motion (see Table 1). The dotted curve in Fig. 7–1 shows the response function of the model ship to regular waves in the experimental tank. This response curve to regular waves is given for the wave slope with 3.6 degrees which is 1/10 of the maximum value of the wave slope (see Fig. 3). Comparing these response curves we can see that a fairly good agreement is obtained between the results obtained by the two methods, but a remarkable difference of gain can be seen at the frequency 0.64 c/sec.

2) On the phase shift:

Figs. 7–2 and 8–2 indicate that the shapes of the phase shift curves are generally resembling each other, as was described in section 3. This is expected from the definitions of the wave height and slope (see Fig. 9).

Generally speaking, it is concluded that the method described in this paper can practically be used to deduce the response functions of a real ship in a seaway, by taking waves as input and rolling angles as output of the system. Better results of the coherency will be obtained, as was already discussed in section 4, by improving the measuring apparatus and their arrangement. However, in an actual seaway, there may be many inevitable difficulties for performance of experiments. It is expected that not only the ship response characteristic is deduced by the present analysis, but also the intrinsic nature of experiment will be clarified by examining values of the coherency and relative error.

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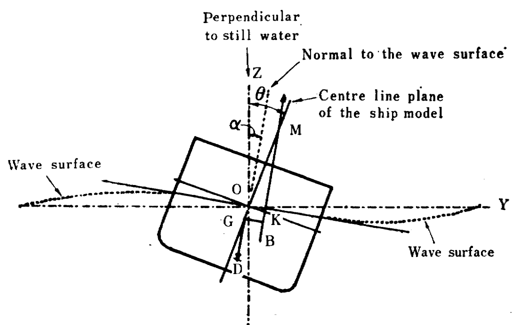


α : Wave slope
θ : Angle of rolling
B : Center of buoyancy
G : Center of gravity
GK: Restoring lever for buoyancy force

Fig. 1 Diagram for rolling motion in waves

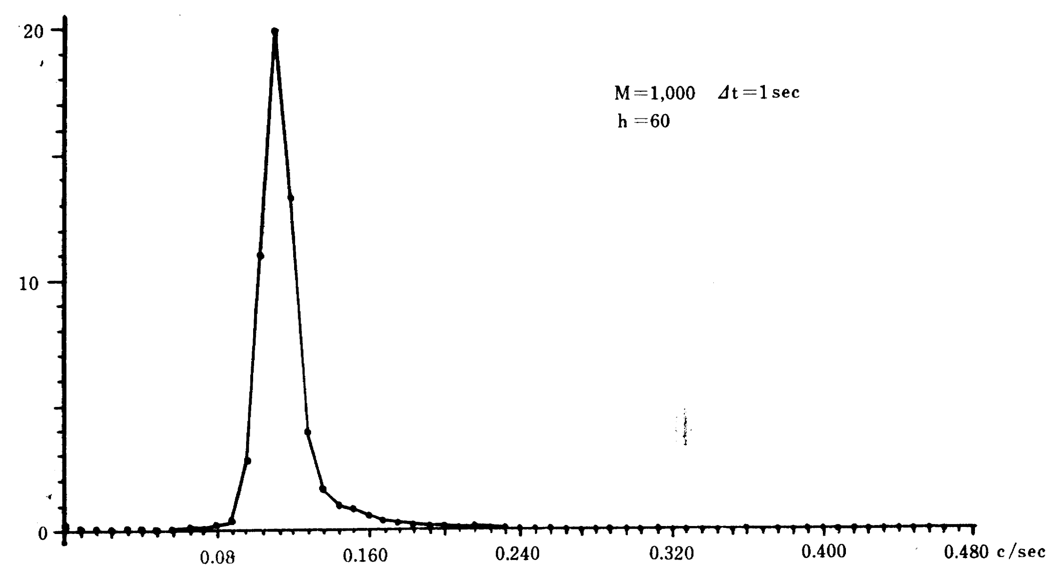


Fig. 2 Power spectrum in an actual ship experiment

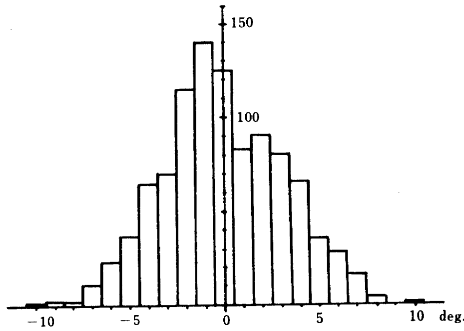
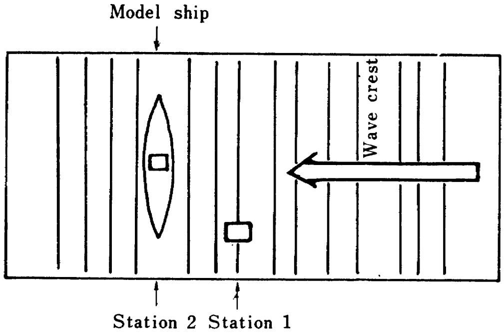
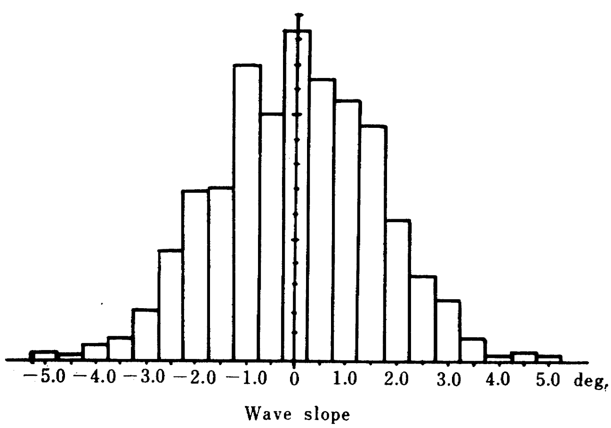


Fig. 3 Distribution of rolling angles in an actual ship experiment

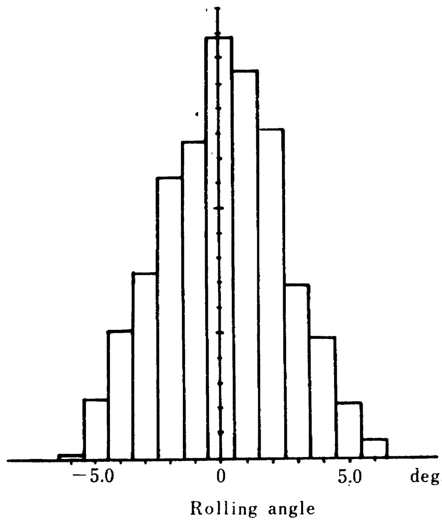


Station 1: The place where wave heights and slopes are measured.
Station 2: Ship body; the place where rolling angle is measured, ship can be drifted by wave action freely.

Fig. 4 Arrangement of apparatus in a model ship experiment



5-1. Distribution of wave slope



5-2. Distribution of ship rolling angles

Fig. 5 Distribution of wave slopes and ship rolling angles in a model ship experiment

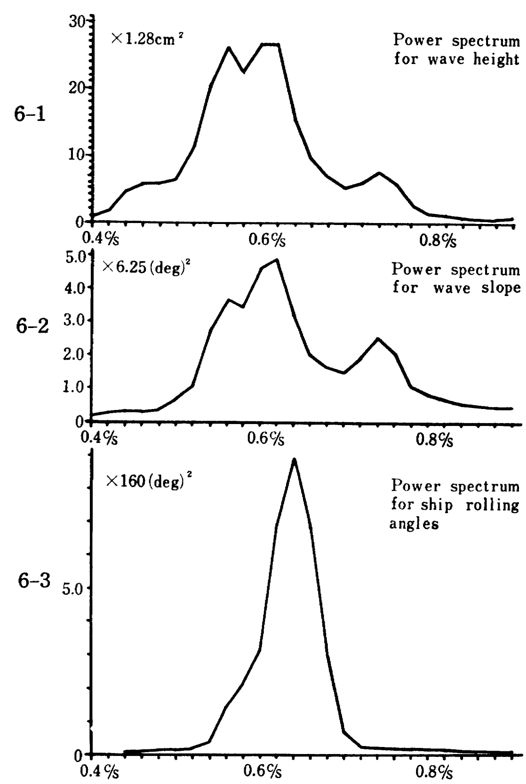


Fig. 6 Power spectra for wave heights, slopes and ship rolling angles

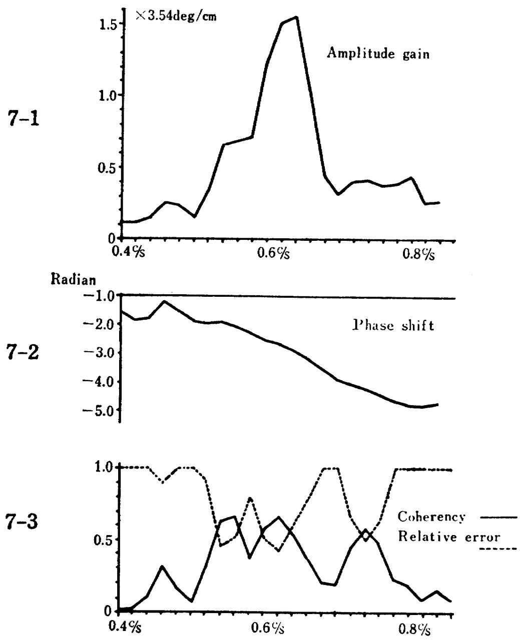


Fig. 7 Response characteristics for wave heights×ship rolling angles

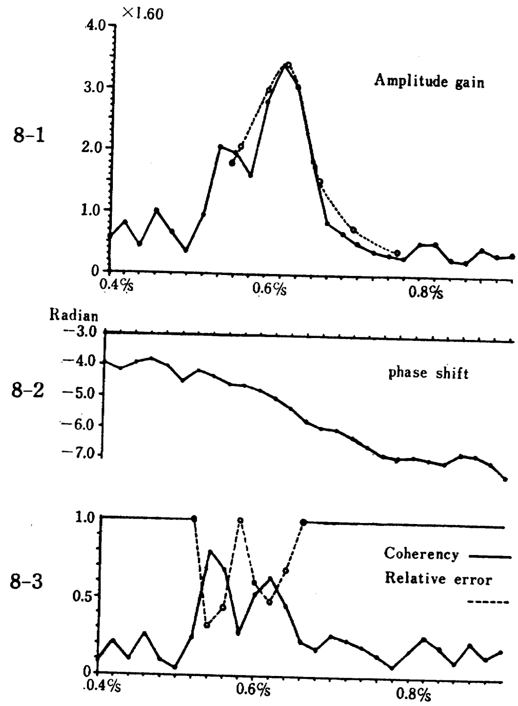


Fig. 8 Response characteristics for wave slopes×ship rolling angles

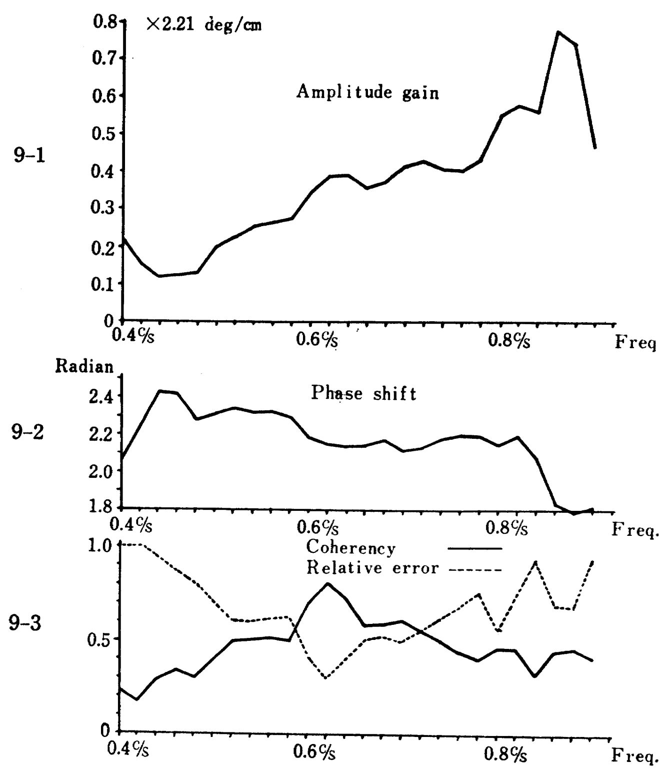


Fig. 9 Relation between wave heights and slopes