DISTRIBUTION OF DAMPING AND ADDED MASS ALONG THE LENGTH OF A SHIPMODEL.

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Summary.

Forced heaving experiments were carried out with a seven-section model in still water, to investigate the distribution of damping and added mass along the length of a shipmodel.

The components of the vertical forces in phase with the heave displacement and the quadrature components on each of the seven sections were measured as a function of the frequency and the forward speed of the model. This allowed the determination of the sectional damping coëfficients and the sectional added masses, and their distribution along the length of the model.

The results show a fairly large influence of frequency and forward speed on the distribution of damping. There is some influence of frequency on the distribution of added mass; but the influence of forward speed is small. In some conditions negative sectional damping and added mass was observed.

The distribution of damping results in coëfficients of the heave velocity coupling terms, which depend on the forward speed. In the practical range of frequencies the coëfficients of the heave acceleration coupling terms are very small. The experimental results are compared with Grim's theoretical values for damping and added mass at zero speed.

1. Introduction.

During the last few years the methods for the evaluation of damping and added mass of ship like cross sections, oscillating in the free surface of a fluid, have been developed to a very satisfactory level. In this respect extremely useful work has been done by Ursell [1], Grim [2], Tasai [3, 4, 5], Porter [6], Paulling and Richardson [7]. The experiments with oscillating semi submerged cylinders which are reported in [4], [5] and [7] show that a good agreement exists between the theoretical and the experimental values at zero speed of advance.

The sectional damping coëfficients and the sectional added mass can be integrated over the length of the ship to determine these values for the ship. Also cross coupling coëfficients can be obtained by simple integration. Such a stripmethod however, neglects the influence of the forward speed of the ship and also three dimensional effects are ignored.

Earlier work [9] has shown that the damping coëfficients and the added mass of a shipmodel do not vary much with forward speed, at least for the purpose of calculating the pitching and heaving motions in the practical speed range. Tasai [3] used the stripmethod to compare the calculated damping and added mass of a shipmodel with experimental values published in [8] and [9]. His conclusion is that for added mass and added mass moment of inertia the three dimensional effect if very small. For pitch damping the three dimensional effect is small at resonance, but for heave damping the experiment gives 15% to 25% larger values than the theoretical stripmethod values.

In [9] the importance of the heave and pitch velocity cross coupling terms for the calculation of heaving and pitching motions was shown. The inclusion of such terms is clearly necessary to get agreement with measured shipmodel motions. Although the measuring methods which were employed in [9] to determine the cross coupling coëfficients cannot be regarded as completely satisfactory a definite dependence on speed was found.

The relatively small influence of speed on the total damping coëfficient and the total added mass of a shipmodel and the speed dependence of the cross coupling terms indicates that the distribution of the damping coëfficient and the added mass over the length of the model varies with forward speed.

This lead to the present experiment which makes use of a seven-section model. By oscillating this built up shipmodel in still water, the vertical components of the hydrodynamic forces on each separate section could be determined. In this way sectional damping coëfficients and added masses were determined for a range of oscillation frequencies and forward speeds.

2. The model.

The shipmodel is a parent model of the Series Sixty with a blockcoëfficient $C_B = 0.70$. The main particulars are summarized in Table 1.

The model is made of polyester reinforced with fibreglass and consists of seven separate sections of equal length. Each of the sections has two end bulkheads; the width of the slits between the sections is 1 mm. The individual sections are not fastened to each other but they are kept in their position by means of stiff vertical straingauge dynamometers, which are connected to a longitudinal steel box girder running above the shipmodel.

A whole model of the same size and form was used for comparison purposes. A body plan is given in figure 1.

TABLE 1.

Main particulars of the ship model.

Length between perpendiculars	2.258 m
Length on the waterline.	2.296 m
Breadth	0.323 m
Draught	0.129 m
Volume of displacement	0.0657 m^3
Blockcoëfficient	0.700
Waterplane area	0.372 m^2
Waterplane coëfficient	0.785
Coëfficient of midlength section	0.986
Prismatic coëfficient	0.710
L.C.B. forward $L_{pp}/2$	0.011 m
Centre of effort of waterplane aft. $L_{pp}/2$	0.038 m
Froude number of service speed	0.20

3. Experimental methods.

In figure 2 the principle of the experimental set-up is given The seven-section shipmodel is forced to oscillate in the vertical direction by means of a Scotch-Yoke mechanisme. Frequency and amplitude of the harmonic oscillation can be varied to cover a wide range. Each section is connected to the longitudinal steel box girder by means of carefully calibrated straingauge dynamometers. The dynamometers are insensitive to forces acting in other than their axial direction. Consequently only the vertical components of the total force on each section are measured.

The vertical forces acting on each section are separated into the components in phase with the displacement and into the quadrature components by means of an electronic analoge system which, in principle, is similar to that published by Tuckerman [10]. It was found however, that the sine-cosine potentiometers, as used by Tuckerman, are not reliable at high rotational speeds. Therefore the measured signal is multiplied by sin ωt and cos ωt by means of a sine-cosine synchro resolver connected to the main shaft of the mechanical oscillator. Averaging circuits with chopper stabilized amplifiers were used to determine the mean values of the in phase- and quadrature force components.

The system appeared to give accurate and consistent results. A high accuracy is needed in particular for measuring the damping forces, which are small in comparison with the inertial and restoring forces.

It should be noted that this system can resolve the measured forces into their Fourier components by driving the sine-cosine resolver at n-times the frequency of the main oscillator shaft, where n = 1, 2, 3 . . . . . .

Throughout the present experiments only the first harmonics of the measured forces are taken into account. The values for damping and added mass, derived from these first harmonics can be readily compared with theoretical results. Non linear effects however, may be fairly important as shown by the recent experiments of Tanaka and Kitagawa [11]. It was decided to study non linear effects in a later stage as the comparison with theoretical results seems the most urgent at this moment.

As only two channels were available for measuring the forces and the associated data reduction, repeated runs had to be made, under the same conditions of frequency and forward speed, to test all the seven sections.

4. Experimental results.

Measurements were carried out for frequencies up to $\omega = 14$ rad/sec. and for four speeds of advance, namely $F_n = .15, .20, .25, .30$. No experiments were carried out at zero speed, because serious wall effects could be expected from reflected wave systems, generated by the model motions. For the same reason frequency values lower than $\omega = 3$ to 4 rad/sec. are not considered.

The oscillation amplitude varied from 1 to 4 cm. This corresponds to a very large motion for the mid-ship sections but the end sections of a ship may meet such conditions in pitching.

Some typical examples of the measurements are given in the figures 3 and 4. In figure 3 the in phase and quadrature components of the vertical forces per unit amplitude of two heaving sections are plotted on a base of frequency. There is strong linearity with regard to the heave amplitude. A similar plot for the whole model is given in figure 4 for each of the two push-rods which connect the shipmodel to the oscillator.

The calculation of the damping coëfficients and the added mass from the measured quantaties is given in the Appendix. The results are summarised in Table 2, for each section of the seven-section model, as well as for the whole model. Table 2 shows that the sums of the section results agree very well with the total values which were determined with the whole model. This is illustrated also in figure 5 where the damping coëfficient and added mass for both cases ("sum of sections" and "whole model") are plotted as a function of speed and frequency. The conclusion may be that the influence of the slits between the sections is very small.

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TABLE 2a.

Sectional added mass.

$F_n = .15.$

m'_{zz} - kg. sec^2/m.

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	-1,21	0,59	-	0,54	0,87	0,41	-0,17	-	1,84
5	0,33	1,15	1,33	1,60	1,29	0,60	-0,05	6,25	6,49
6	0,31	0,66	1,08	1,38	1,26	0,65	0,02	5,36	5,37
7	0,28	0,58	1,03	1,35	1,26	0,70	0,08	5,28	5,19
8	0,24	0,60	1,09	1,37	1,28	0,76	0,10	5,44	5,26
9	0,21	0,64	1,19	1,41	1,31	0,81	0,12	5,69	5,55
10	0,20	0,69	1,29	1,48	1,34	0,85	0,14	5,99	5,91
11	0,18	0,74	1,36	1,54	1,39	0,86	0,16	6,23	6,12
12	0,18	0,78	1,40	1,60	1,45	0,90	0,17	6,48	6,39
13	0,19	0,82	1,44	1,66	1,51	0,94	0,17	6,73	6,69
14	0,23	0,84	1,47	1,70	1,56	0,95	0,16	6,91	6,88

$F_n = .20.$

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	0,59	0,83	1,29	1,59	1,15	0,22	-0,27	5,40	5,63
5	0,57	0,86	1,48	1,50	1,24	0,52	0,11	6,28	5,63
6	0,32	0,65	1,00	1,40	1,23	0,64	0	5,24	5,19
7	0,25	0,55	1,02	1,37	1,20	0,71	0,09	5,19	5,08
8	0,21	0,55	1,08	1,38	1,21	0,75	0,12	5,30	5,18
9	0,19	0,59	1,15	1,43	1,26	0,78	0,13	5,53	5,44
10	0,19	0,65	1,23	1,49	1,33	0,83	0,14	5,86	5,78
11	0,19	0,72	1,30	1,54	1,38	0,85	0,16	6,14	6.07
12	0,20	0,77	1,37	1,60	1,45	0,88	0,17	6,44	6,32
13	0,20	0,82	1,42	1,65	1,50	0,92	0,17	6,68	6,60
14	0,20	0,84	1,47	1,69	1,55	0,94	0,16	6,85	6,78

TABLE 2a.

Sectional added mass.

F_n = .25.

m'_{33} - kg sec^2/m.

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	0,86	1,09	1,26	1,66	1,20	0,16	-0,32	5,91	4,99
5	0,51	0,82	1,08	1,45	1,18	0,44	-0,14	5,34	5,06
6	0,33	0,65	1,01	1,38	1,19	0,55	-0,02	5,09	4,89
7	0,23	0,54	0,98	1,36	1,22	0,64	0,04	5,01	4,93
8	0,20	0,54	1,03	1,39	1,26	0,68	0,08	5,18	5,13
9	0,19	0,57	1,09	1,42	1,30	0,72	0,10	5,39	5,40
10	0,18	0,62	1,19	1,48	1,34	0,77	0,12	5,70	5,65
11	0,19	0,70	1,28	1,54	1,40	0,80	0,14	6,05	5,89
12	0,20	0,76	1,37	1,60	1,45	0,83	0,16	6,37	6,21
13	0,21	0,81	1,43	1,67	1,50	0,88	0,18	6,68	6,59
14	0,21	0,85	1,46	1,72	1,53	0,91	0,18	6,86	6,84

F_n = .30.

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	0,70	0,91	1,49	1,58	1,07	-0,10	-0,22	5,43	5,59
5	0,42	0,56	1,26	1,42	1,10	0,32	-0,03	5,05	4,68
6	0,25	0,44	1,15	1,39	1,07	0,45	0,07	4,82	4,51
7	0,19	0,40	1,12	1,41	1,06	0,51	0,12	4,81	4,66
8	0,16	0,42	1,14	1,45	1,08	0,58	0,13	4,96	4,93
9	0,15	0,47	1,18	1,46	1,16	0,64	0,14	5,20	5,23
10	0,15	0,55	1,26	1,47	1,22	0,68	0,17	5,50	5,48
11	0,16	0,62	1,34	1,52	1,28	0,74	0,18	5,84	5,82
12	0,17	0,69	1,41	1,57	1,35	0,81	0,19	6,19	6,18
13	0,19	0,77	1,46	1,62	1,40	0,86	0,20	6,50	6,47
14	0,21	0,83	1,49	1,67	1,45	0,89	0,20	6,74	6,77

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TABLE 2b.

Sectional damping coëfficients.

F_n = .15.

N'_{zz} - kg sec/m.

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	2,03	9,78	-	5,78	3,80	4,80	2,00	-	35,63
5	3,32	6,74	6,46	5,28	5,14	5,46	1,80	34,20	33,80
6	1,82	4,42	4,55	4,58	4,52	4,78	1,67	26,34	26,53
7	1,71	3,42	3,42	3,64	3,96	4,30	1,57	22,02	21,77
8	1,61	2,31	2,26	2,75	3,35	3,94	1,53	17,75	17,49
9	1,50	1,58	1,36	1,96	2,80	3,66	1,51	14,37	14,22
10	1,36	1,08	0,76	1,39	2,36	3,43	1,49	11,87	11,63
11	1,18	0,73	0,47	1,04	2,06	3,24	1,49	10,21	9,83
12	0,95	0,47	0,44	0,87	1,89	3,09	1,50	9,21	8,54
13	0,72	0,31	0,48	0,85	1,82	2,98	1,49	8,65	7,62
14	0,46	0,22	0,55	0,95	1,83	2,87	1,50	8,38	7,43

F_n = .20.

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	1,53	4,53	5,08	5,05	5,73	6,63	2,50	31,05	31,33
5	2,04	4,70	5,02	4,98	5,08	5,70	2,18	29,70	30,16
6	1,95	3,95	4,32	4,45	4,52	5,07	2,07	26,33	26,15
7	1,74	2,96	3,32	3,64	3,97	4,66	1,99	22,28	21,87
8	1,50	1,91	2,25	2,81	3,49	4,38	1,94	18,28	17,78
9	1,29	0,96	1,29	2,07	3,07	4,18	1,90	14,76	14,61
10	1,10	0,37	0,62	1,54	2,70	4,01	1,90	12,24	12,14
11	0,92	0,04	0,31	1,20	2,40	3,90	1,91	10,68	10,40
12	0,74	-0,15	0,21	1,01	2,18	3,84	1,93	9,76	9,03
13	0,53	-0,26	0,27	0,91	2,04	3,77	1,93	9,19	8,00
14	0,27	-0,31	0,44	0,86	2,01	3,67	1,92	8,86	7,44

TABLE 2b.

Sectional damping coëfficients.

F_n = .25.

N'_{zz} - kg.sec/m.

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	2,13	4,80	5,38	5,20	5,98	7,63	2,85	33,97	35,88
5	2,12	4,02	4,82	4,82	5,24	6,28	2,56	29,86	31,74
6	1,97	3,43	4,17	4,23	4,62	5,68	2,35	26,45	27,63
7	1,71	2,59	3,29	3,56	4,10	5,40	2,23	22,88	23,12
8	1,48	1,58	2,28	2,83	3,68	5,21	2,19	19,25	18,75
9	1,21	0,66	1,34	2,22	3,31	5,07	2,17	15,98	15,24
10	0,95	-0,06	0,60	1,68	3,00	4,96	2,20	13,33	12,69
11	0,73	-0,43	0,13	1,27	2,77	4,85	2,27	11,59	10,90
12	0,52	-0,56	-0,03	1,03	2,63	4,74	2,29	10,62	9,78
13	0,32	-0,54	0,02	0,92	2,57	4,62	2,30	10,21	9,00
14	0,15	-0,49	0,11	0,94	2,64	4,49	2,26	10,10	8,60

F_n = .30.

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	1,78	4,40	4,40	5,15	6,78	7,60	2,98	33,09	38,10
5	1,86	3,62	4,22	4,56	5,80	6,78	2,70	29,54	32,52
6	1,75	2,77	3,50	4,10	5,18	6,32	2,55	26,17	28,45
7	1,51	1,92	2,64	3,41	4,79	5,99	2,51	22,77	24,64
8	1,21	0,99	1,70	2,81	4,50	5,73	2,51	19,45	20,40
9	0,87	0,03	0,87	2,29	4,27	5,54	2,54	16,41	16,67
10	0,64	-0,87	0,17	1,88	4,07	5,42	2,59	13,90	13,95
11	0,47	-1,40	-0,32	1,57	3,90	5,35	2,63	12,20	11,85
12	0,42	-0,56	-0,63	1,37	3,72	5,28	2,66	11,26	10,42
13	0,45	-1,46	-0,73	1,23	3,56	5,19	2,66	10,90	9,96
14	0,56	-1,24	-0,54	1,16	3,39	5,03	2,62	10,98	10,46

5. Analysis of the test results.

The numerical values given in Table 2 are shown in graphical form in the figures 6 and 7. Sectional damping coëfficients N'_{zz} and sectional added masses m'_{zz} are plotted over the length of the shipmodel as a function of frequency and forward speed. The figures show that the distribution of the damping coëfficient changes with speed and frequency. The damping coëfficient of the forward part of the shipmodel increases when the speed is increasing. At the same time a decrease of the damping coëfficient of the afterbody is noticed. In some cases even "negative" damping occurs. A physical explanation of this phenomena is not readily at hand but apparently the water motion set up by the forward part of the ship has a strong influence on the conditions at the afterbody.
As noticed before the integral of the sectional damping coëfficients over the length of the shipmodel does not vary much with forward speed.

The added mass distribution has a somewhat different character. It has less speed dependence than the distribution of damping but there is a shift forward of the distribution curve for increasing frequencies. "Negative" added mass is found for the bow section at low frequencies. For higher frequencies the influence of frequency becomes very small.

The first moment of the distribution curves with respect to the centre of gravity of the model gives the coëfficients of the heave velocity and the heave acceleration coupling terms, respectively E and D. As shown in figure 8 the coëfficient of the heave velocity coupling term depends on the forward speed of the shipmodel, as could be expected from the shift of the damping distribution curves with speed. The coëfficient of the heave acceleration term are nearly speed independent, whereas for $\omega < 6$ rad/sec they are negligibly small.

In figure 8 a comparison is made between the cross coupling coëfficients derived from the damping coëfficient and added mass distributions on the one hand, and the corresponding directly measured values as found from the tests with the whole model. Considering the absolute magnitude of these second order coëfficients, the agreement is very satisfactory.

The experimental values for the damping coëfficient and the added mass are compared with Grim's theoretical values for zero speed [1]. In figure 9 this comparison is made for the whole model and it follows that the calculated added mass agrees very well with the mean of the experimental values at the various forward speeds.

Grim's damping coëfficients for zero speed are smaller than the experimental values, but at resonance ($\omega \approx 7$) the difference is less than 10%.

Due to the influence of forward speed the difference between theory and experiment is considerably larger for the individual sections as can be concluded from figure 10, where the damping coëfficients and the added masses are plotted for each section.

Finally the distribution of Grim's values over the length of the model is given in figure 11 for zero forward speed. It is noticed that the theoretical prediction for zero speed gives a shift of the damping coëfficient distribution toward the afterbody for increasing frequencies resulting in a negative velocity coupling coëfficient. The speed range from $F_n = 0$ to $F_n = .15$ is too large to permit extrapolation of the experimental cross coupling coëfficients, but such a negative coëfficient could certainly be in line with the experimental values, which were found in the speed range $F_n = .15$ to $F_n = .30$.

Comparison with the results of earlier measurements on the same model reveal some differences [9]. It must be remarked, however, that in the present case only the first harmonic of the exciting force function is taken into account. In [9] the assumption was made that the exciting force function was purely harmonic. By representing this function simply by an amplitude, a frequency and a phase angle some influence of the higher harmonics could have entered in the determination of the coëfficient of the motion equations.

Golovato's experiments [8] show the influence of non linear damping terms in heave, as do the tests by Tanaka and Kitagawa [11] for pitching. From this last paper it follows that the linearized quadratic damping can increase the linear damping coëfficient by some 20% at resonance.

The damping coëfficients found with the present experiments are 15 to 20% lower at resonance than the earlier results. The added mass values agree fairly well and also the heave velocity cross coupling coëfficients agree satisfactorily with the earlier results in the range $\omega = 7$ to 10 rad/sec.

APPENDIX.

Experimental determination of the damping coëfficient and the added mass.

The shipmodel performs a forced harmonic oscillation in the vertical direction with an amplitude r and a circular frequency ω, thus:

$$z = r \sin \omega t. \tag{1}$$

The linearized equations of motion will be:

$$\left.\begin{aligned} a\ddot{z} + b\dot{z} + cz &= F_1 \sin(\omega t + \alpha_1) \\ D\ddot{z} + E\dot{z} + Gz &= M_1 \sin(\omega t + \beta_1) \end{aligned}\right\} \tag{2}$$

where:

- a = total mass including added mass,
- b = damping coëfficient,
- c = restoring force coëfficient,
- D, E, G = cross coupling coëfficients,
- F_1 = amplitude of first harmonic of exciting force,
- M_1 = amplitude of first harmonic of exciting moment
- α_1 ; β_1 = phase angles.

Substitution of (1) in (2) gives:

$$\left.\begin{aligned} -ar\omega^2 + cr &= F_1 \cos \alpha_1 \\ br\omega &= F_1 \sin \alpha_2 \\ -Dr\omega^2 + Gr &= M_1 \cos \beta_1 \\ Er\omega &= M_1 \sin \beta_1 \end{aligned}\right\} \tag{3}$$

The in-phase and quadrature components of the exciting force are measured by means of straingauge dynamometers and a data reduction system. In case of the whole model, the exciting force is measured in each of the two push-rods of the oscillator, at equal distances from the centre of gravity of the model. Thus:

$$F_1 \cos \alpha_1 = (F_1 \cos \alpha_1)^{(1)} + F_1 \cos \alpha_1)^{(2)}$$

and:

$$M_1 \cos \beta_1 = \left\{ (F_1 \cos \alpha_1)^{(1)} - (F_1 \cos \alpha_1)^{(2)} \right\} \frac{\ell}{2}$$

where ℓ is the distance between the two push-rods. Similar expressions are valid for the quadrature components: c en G are found from:

$$c = \frac{F_1}{r} \text{ and } G = \frac{M_1}{r}$$

as a function of the forward speed of the model.

The added mass m_{zz}, is found from:

$$m_{zz} = a - \rho\nabla ,$$

where $\rho\nabla$ is the mass of the model.

In case of the seven section model only the first two equations of (3) are used for each individual section. An estimation of the sectional damping coëfficient distribution $N'_{zz}(x)$ and the sectional added mass distribution $m'_{zz}(x)$ is found by using the relations:

$$N_{zz}(\text{section}) = \int_0^{L/7} N'_{zz}(x)\, dx$$

$$m_{zz}(\text{section}) = \int_0^{L/7} m'_{zz}(x)\, dx.$$

It is also assumed that the distributions over the length of the shipmodel are given by smooth curves (see figures 6 and 7).

The forces in phase with the heave displacement and those 90 degrees out of phase with the displacement (quadrature components) are found by multiplying the total measured vertical force by $\sin\omega t$ and $\cos\omega t$ and by taking the time average of the result, thus:

$$F_1 \cos\alpha_1 = \frac{2}{T}\int_0^T \sin\omega t.\ \sum_1^p {}^n F_n \sin(n\omega t + \alpha_n) dt$$

$$F_1 \sin\alpha_1 = \frac{2}{T}\int_0^T \cos\omega t.\ \sum_1^p {}^n F_n \sin(n\omega t + \alpha_n) dt$$

The exciting force function is nearly harmonic and p can be limited to 2 or 3. In a similar way the n th harmonics can be found by multiplying the force function by $\sin n\omega t$ and $\cos n\omega t$.

A non linear set of equations, replacing (2) is proposed by Tanaka and Kitagawa [11] namely:

$$a\ddot{z} + b_1\dot{z} + b_2\dot{z}|\dot{z}| + c_1 z + c_2 z^2 + c_3 z^3 = \sum_1^3{}^n F_n \sin(n\omega t + \alpha_n)$$

$$D\ddot{z} + E_1\dot{z} + E_2\dot{z}\,|\dot{z}| + Gz = \sum_1^3{}^n M_n \sin(n\omega t + \alpha_n) \qquad (4)$$

The non linear terms in (4), however, are not considered in the present paper. The inclusion of the term $c_3 z^3$ introduces an additional first harmonic term since:

$$c_3 z^3 = c_3 r^3 \sin^3 \omega t = c_3 r^3 (\tfrac{3}{4} \sin \omega t - \tfrac{1}{4} \sin 3\omega t).$$

It was found, however, that c_3 is negligibly small for the whole model as well as for each section, and consequently no correction is necessary in the first equation of (3).

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LIST OF SYMBOLS.

a - Total mass including added mass.

b - Damping coëfficient (also N_{zz}).

c - Restoring force coëfficient.

C_B - Blockcoëfficient.

DEG - Cross coupling coëfficients.

F_1 - Amplitude of first harmonic of exciting force.

Fn - Froude number.

l - Horizontal distance between push-rods.

L - Length of shipmodel.

M_1 - Amplitude of first harmonic of exciting moment.

m_{zz} - Added mass for whole model or for a section with length $\frac{1}{7}$ L.

m'_{zz} - Sectional added mass.

N'_{zz} - Sectional damping coëfficient.

N_{zz} - Damping coëfficient for whole model or for a section with length $\frac{1}{7}$ L.

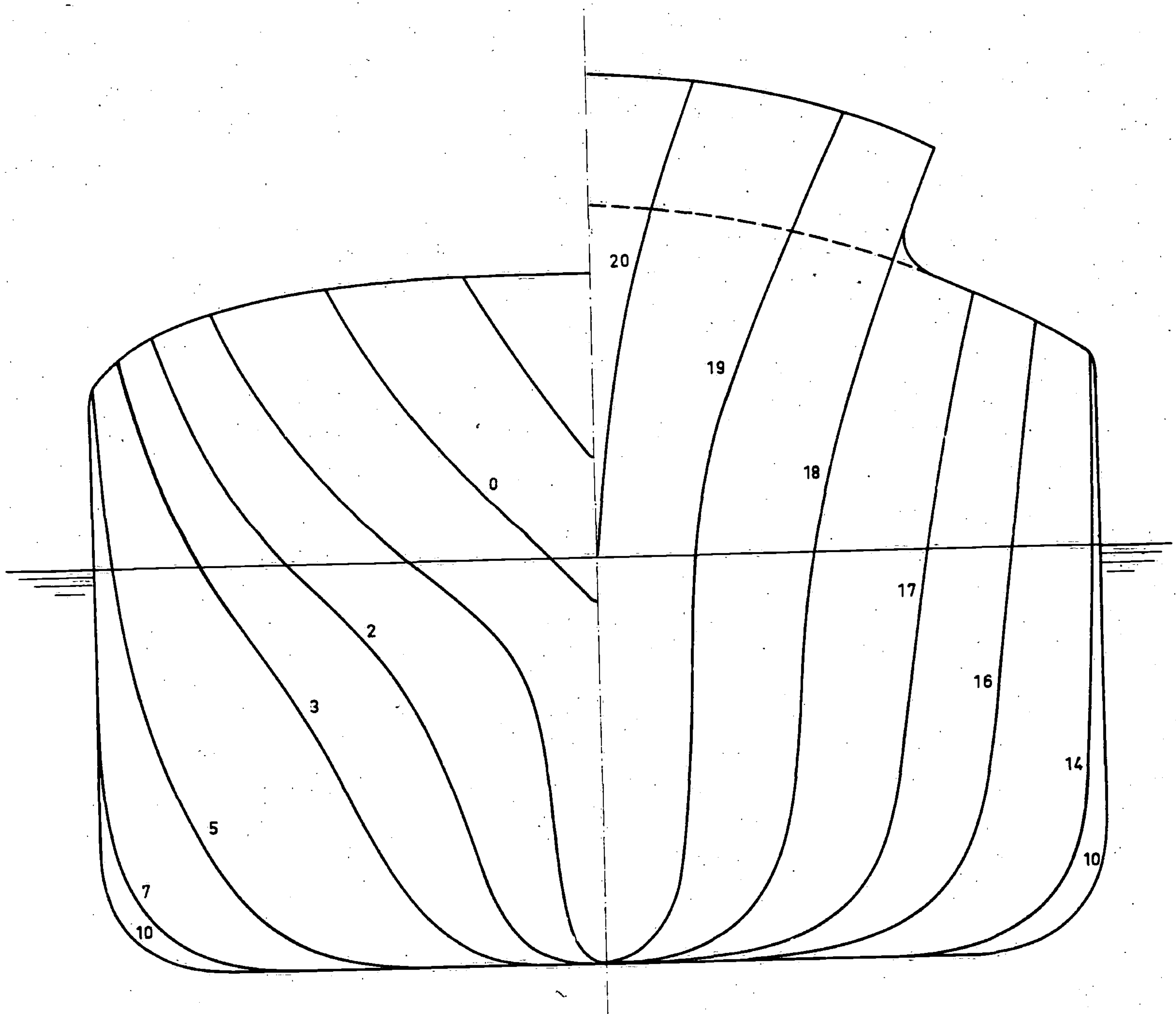
z - Heave displacement.

α_1, β_1 - Phase angles.

ρ - Density of water.

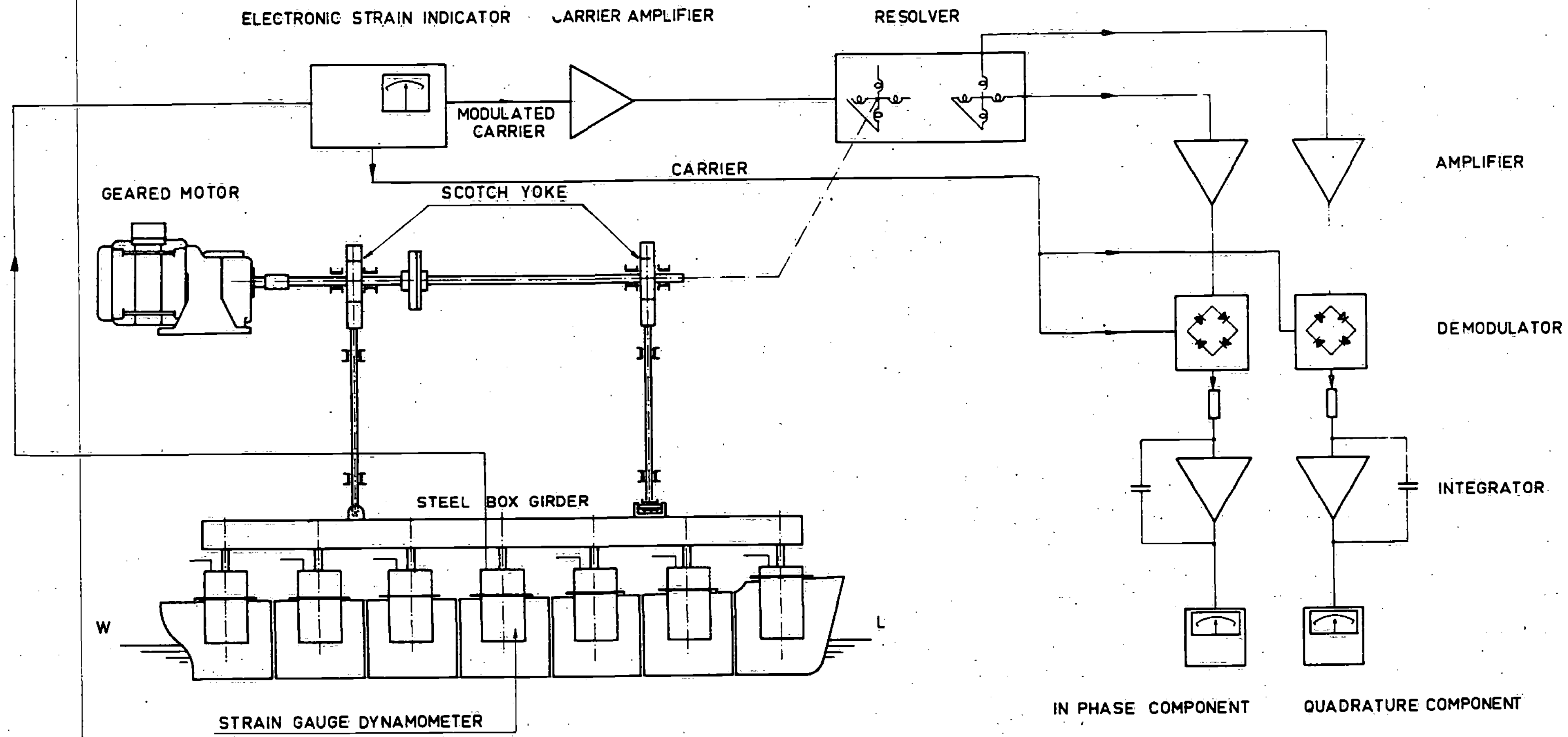
∇ - Volume of displacement.

ω - Circular frequency.



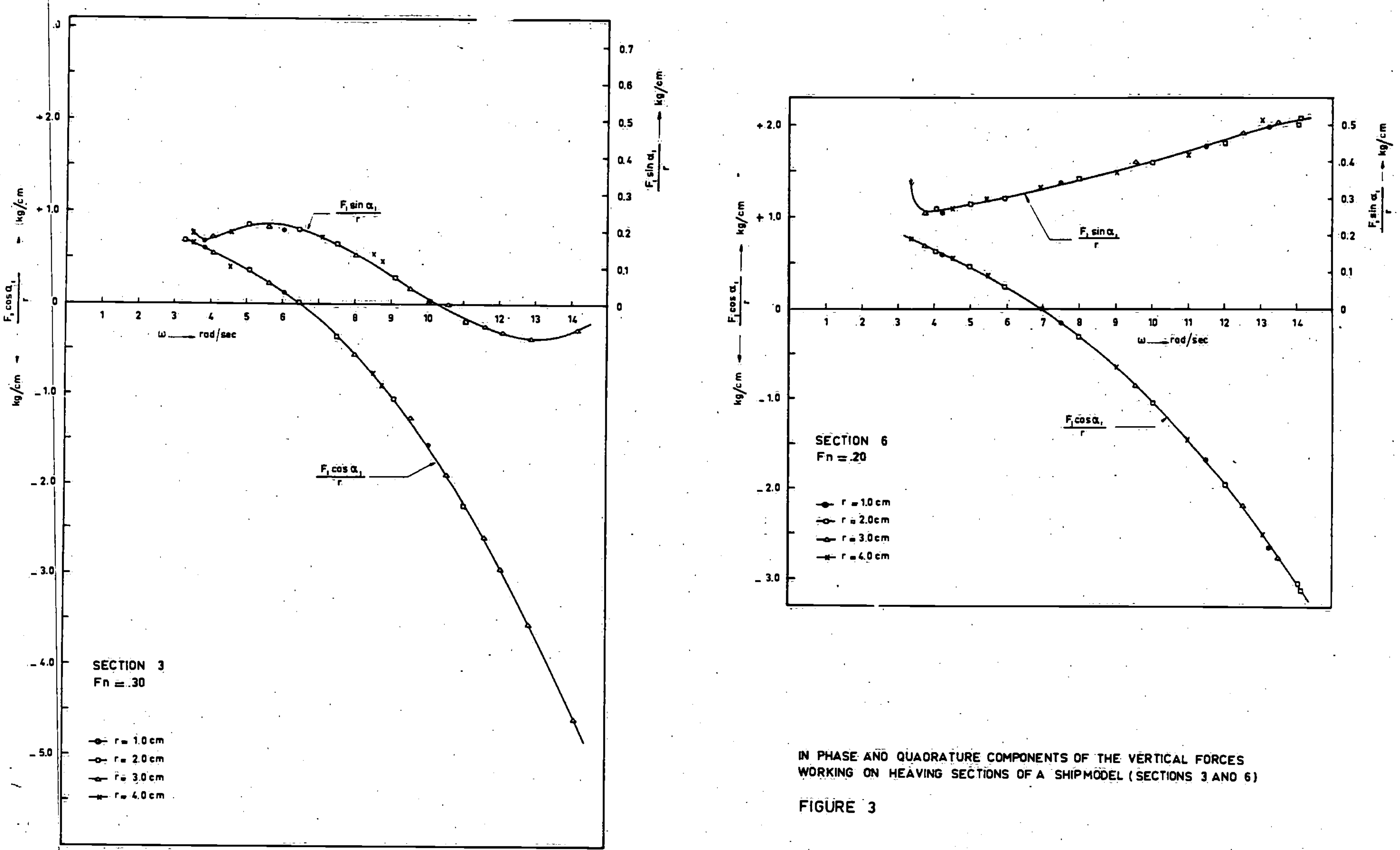
BODY PLAN

FIGURE 1



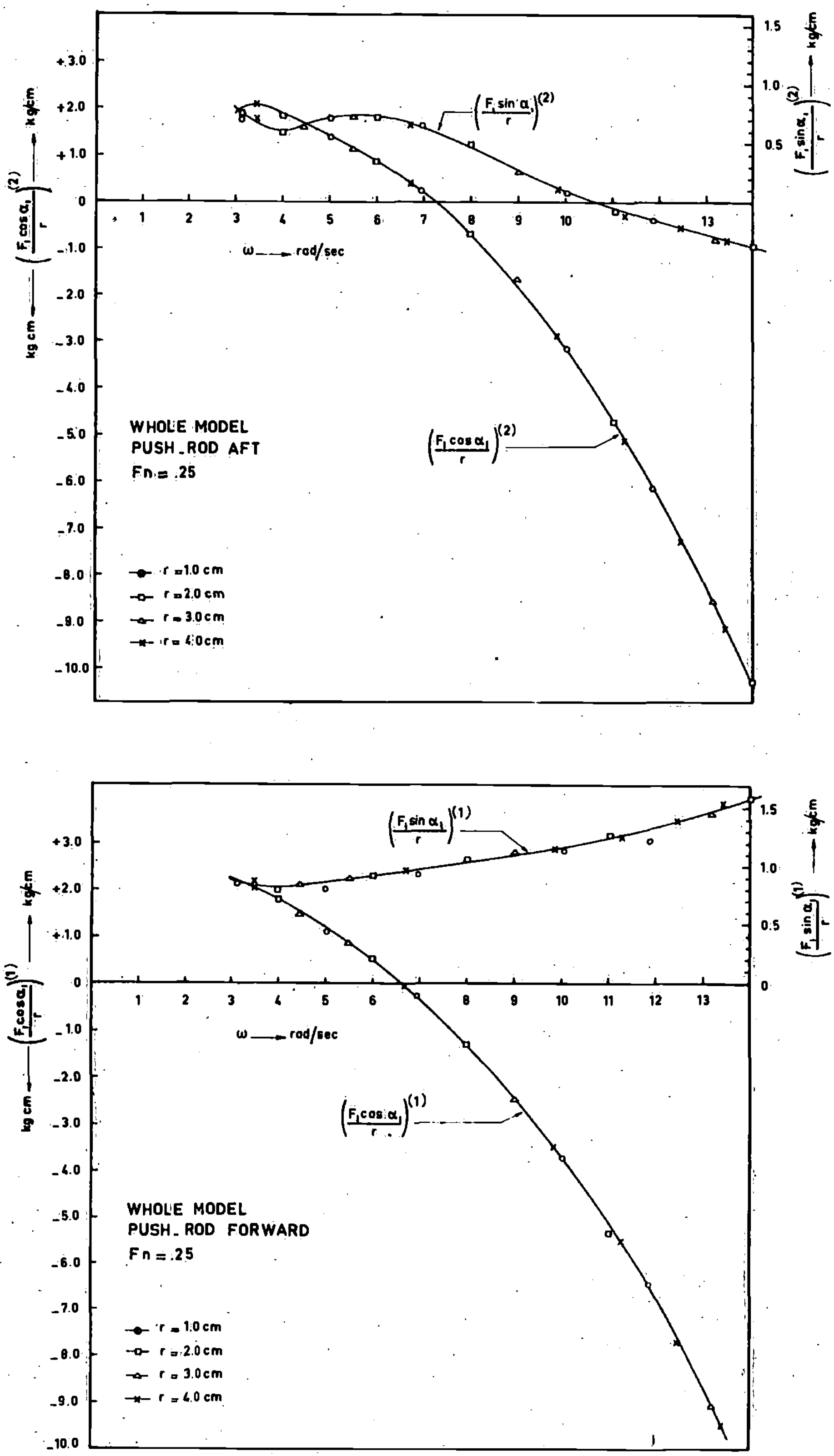
PRINCIPLE OF EXPERIMENTAL SET_UP

FIGURE 2



IN PHASE AND QUADRATURE COMPONENTS OF THE VERTICAL FORCES WORKING ON HEAVING SECTIONS OF A SHIPMODEL (SECTIONS 3 AND 6)

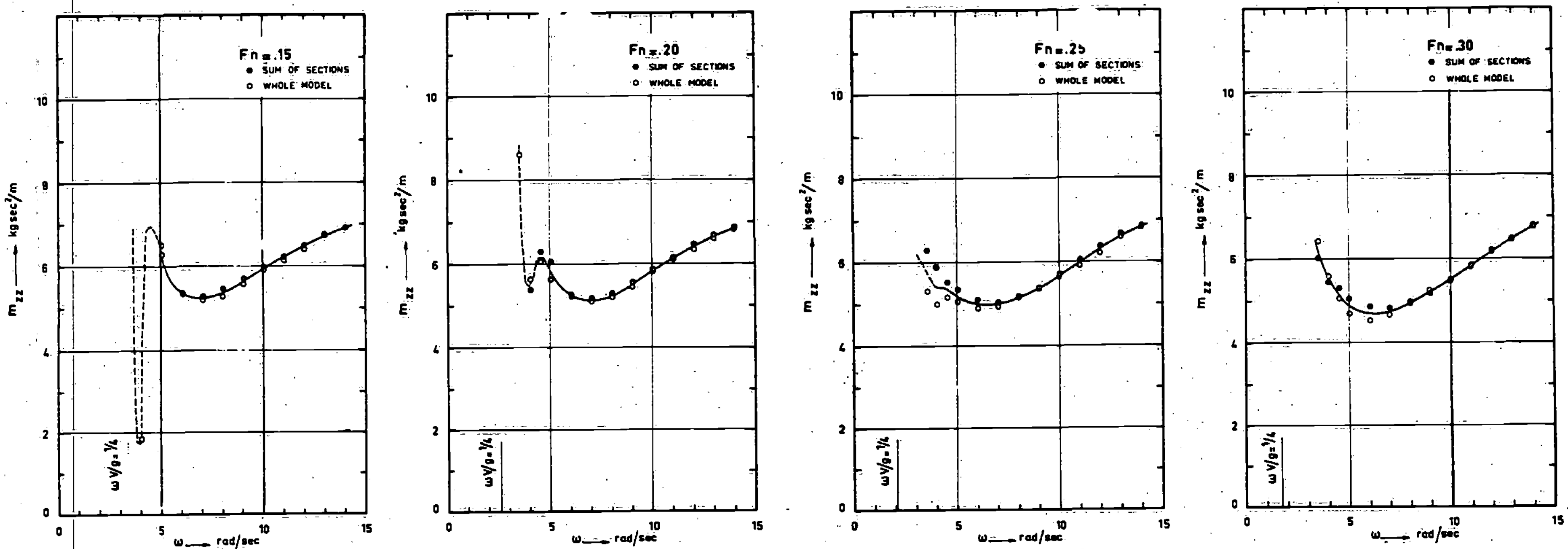
FIGURE 3



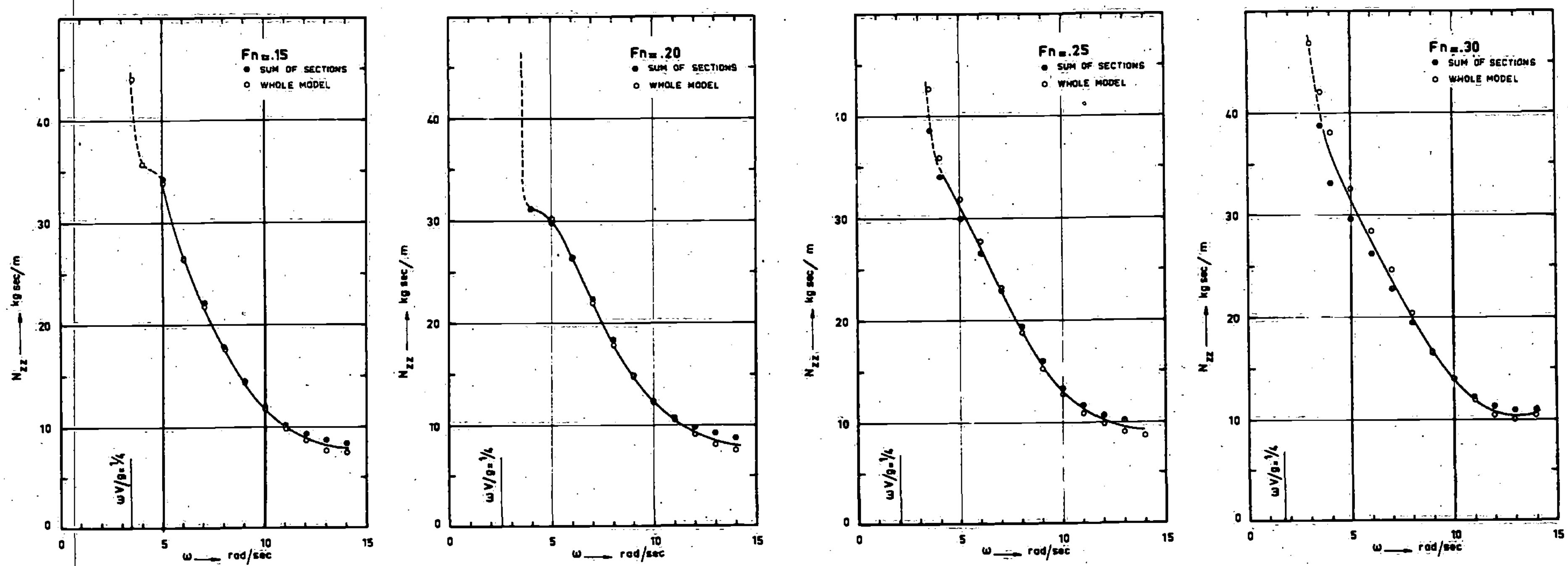
IN PHASE AND QUADRATURE COMPONENTS OF THE VERTICAL FORCES WORKING ON A HEAVING SHIP MODEL

FIGURE 4

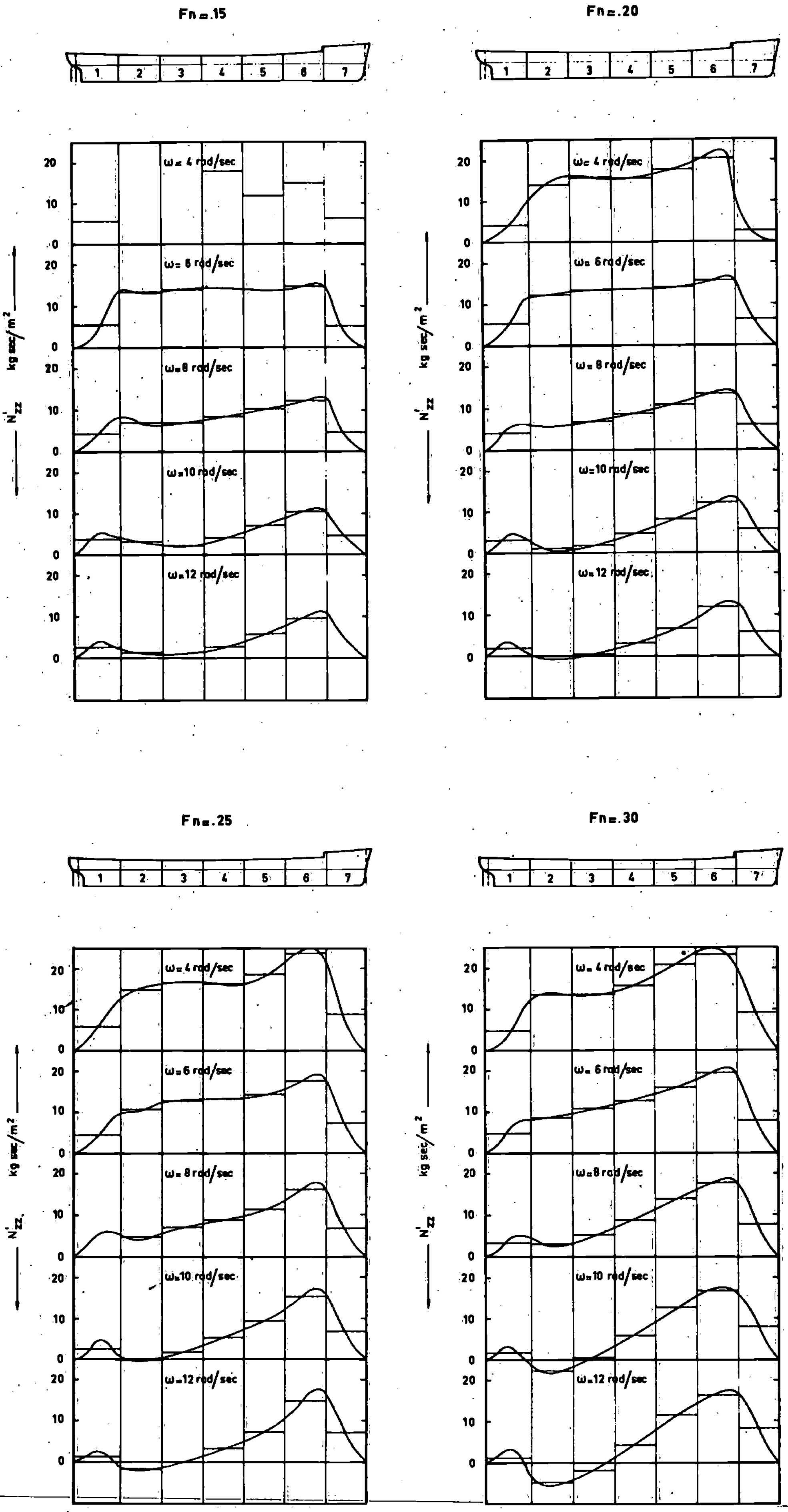
ADDED MASS AS A FUNCTION OF SPEED AND CIRCULAR FREQUENCY



DAMPING COEFFICIENT AS A FUNCTION OF SPEED AND CIRCULAR FREQUENCY

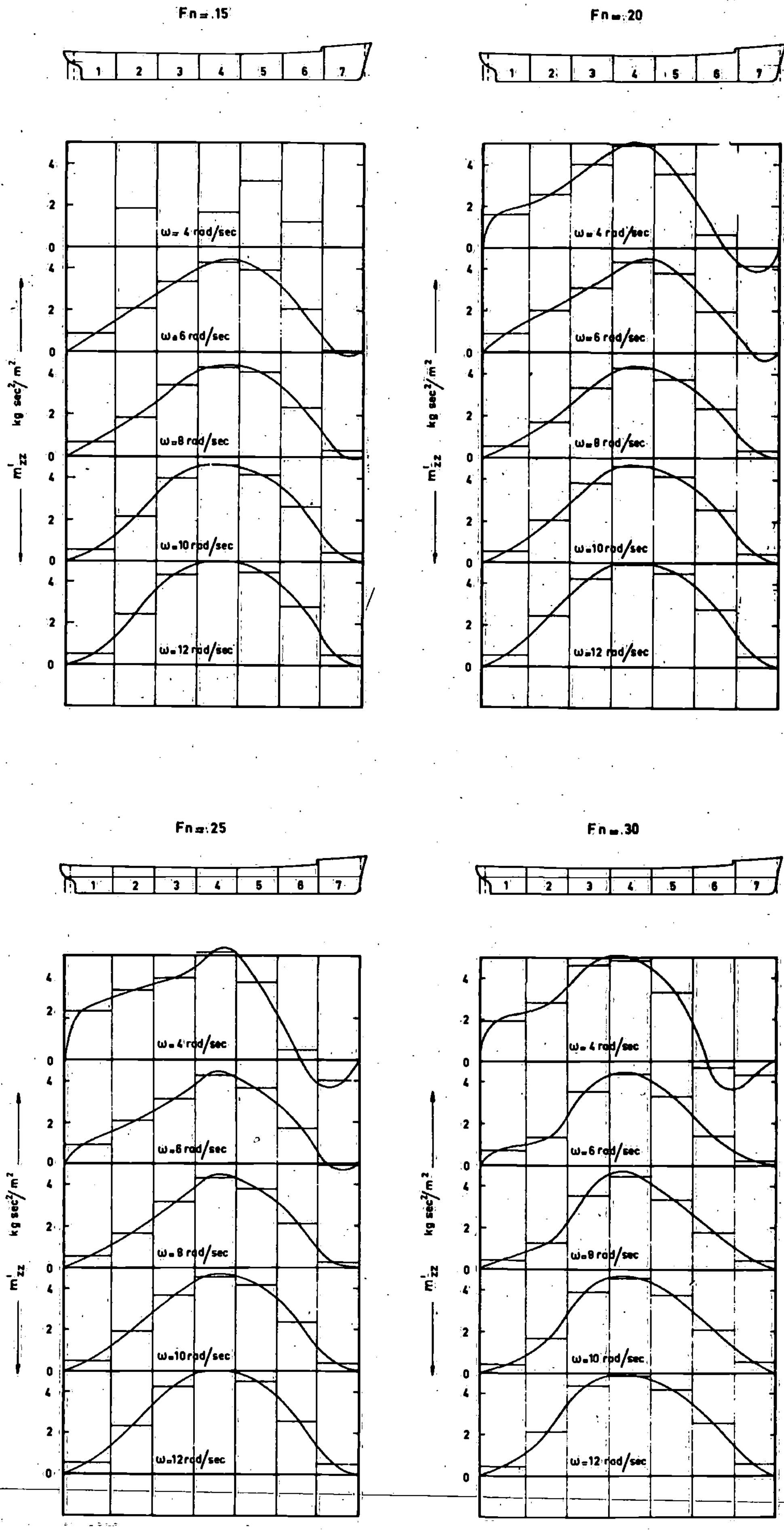


COMPARISON OF THE SUMS OF SECTION RESULTS AND THE WHOLE MODEL RESULTS **FIGURE 5**



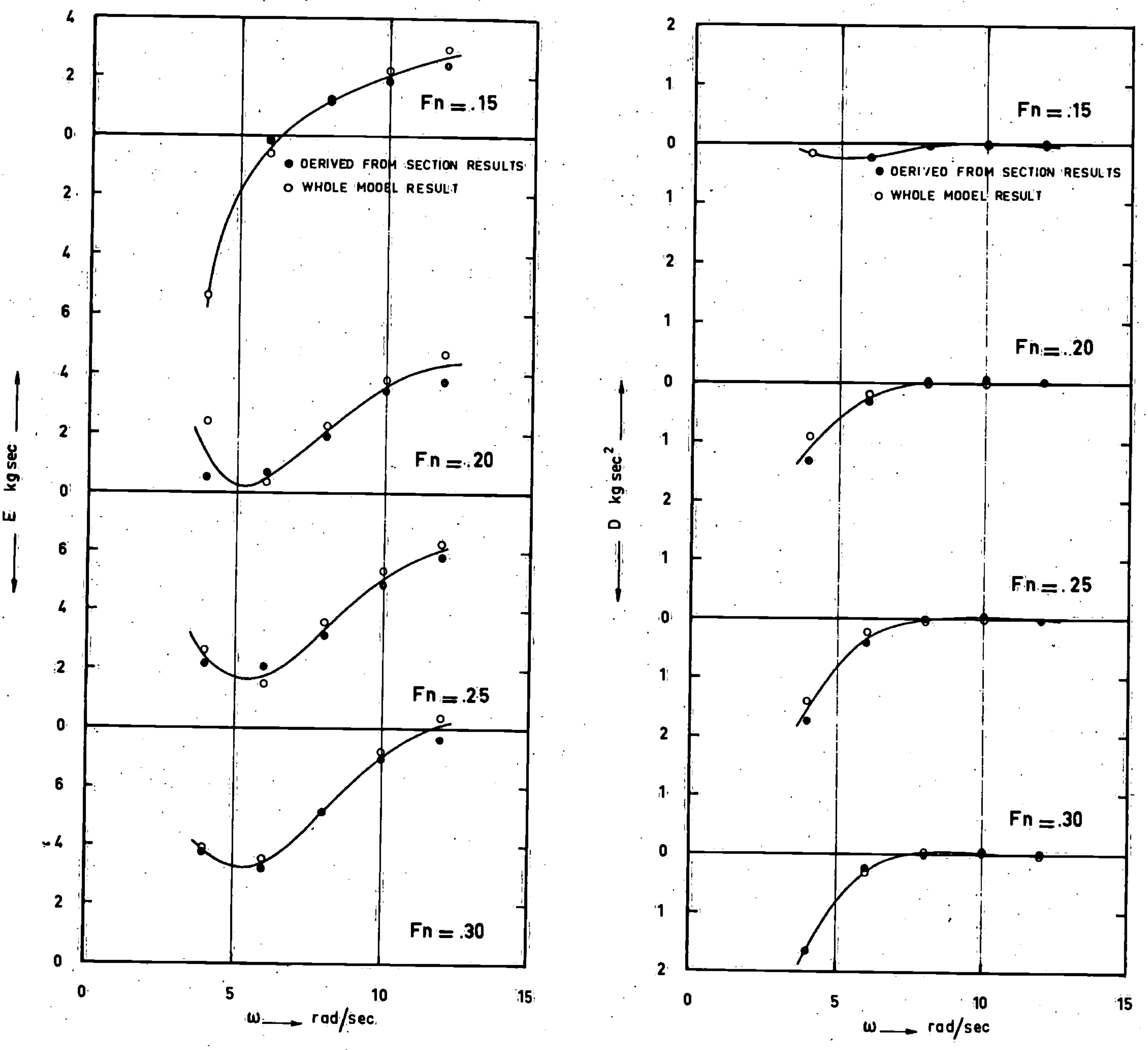
DISTRIBUTION OF SECTIONAL DAMPING COEFFICIENT OVER THE LENGTH OF A SHIPMODEL

FIGURE 6



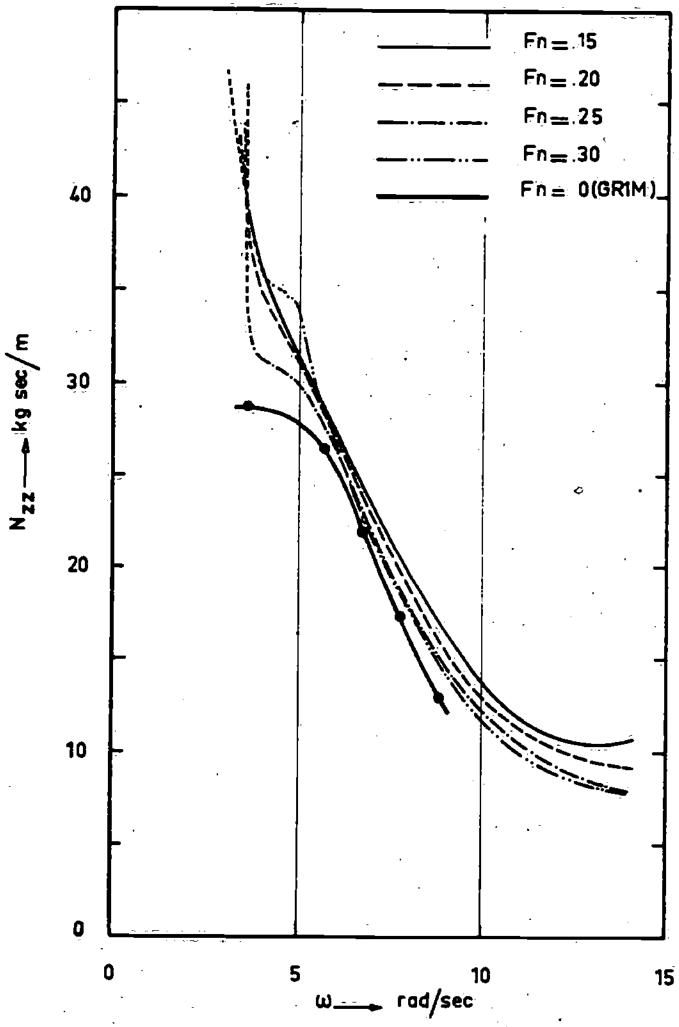
DISTRIBUTION OF SECTIONAL ADDED MASS OVER THE LENGTH OF A SHIP MODEL

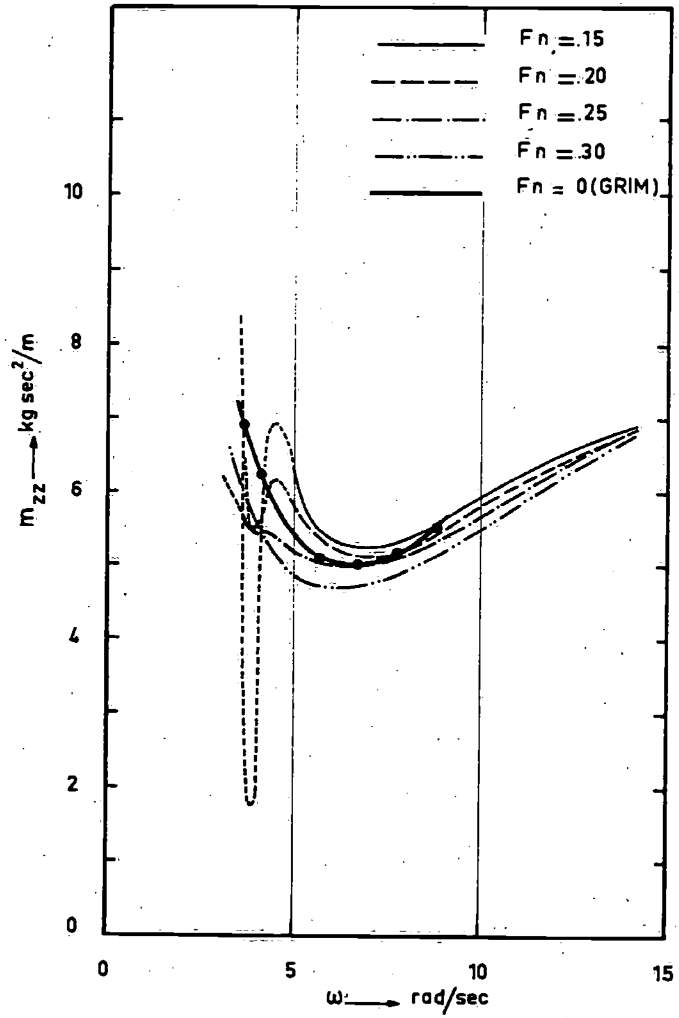
FIGURE 7



CROSS_COUPLING COEFFICIENTS

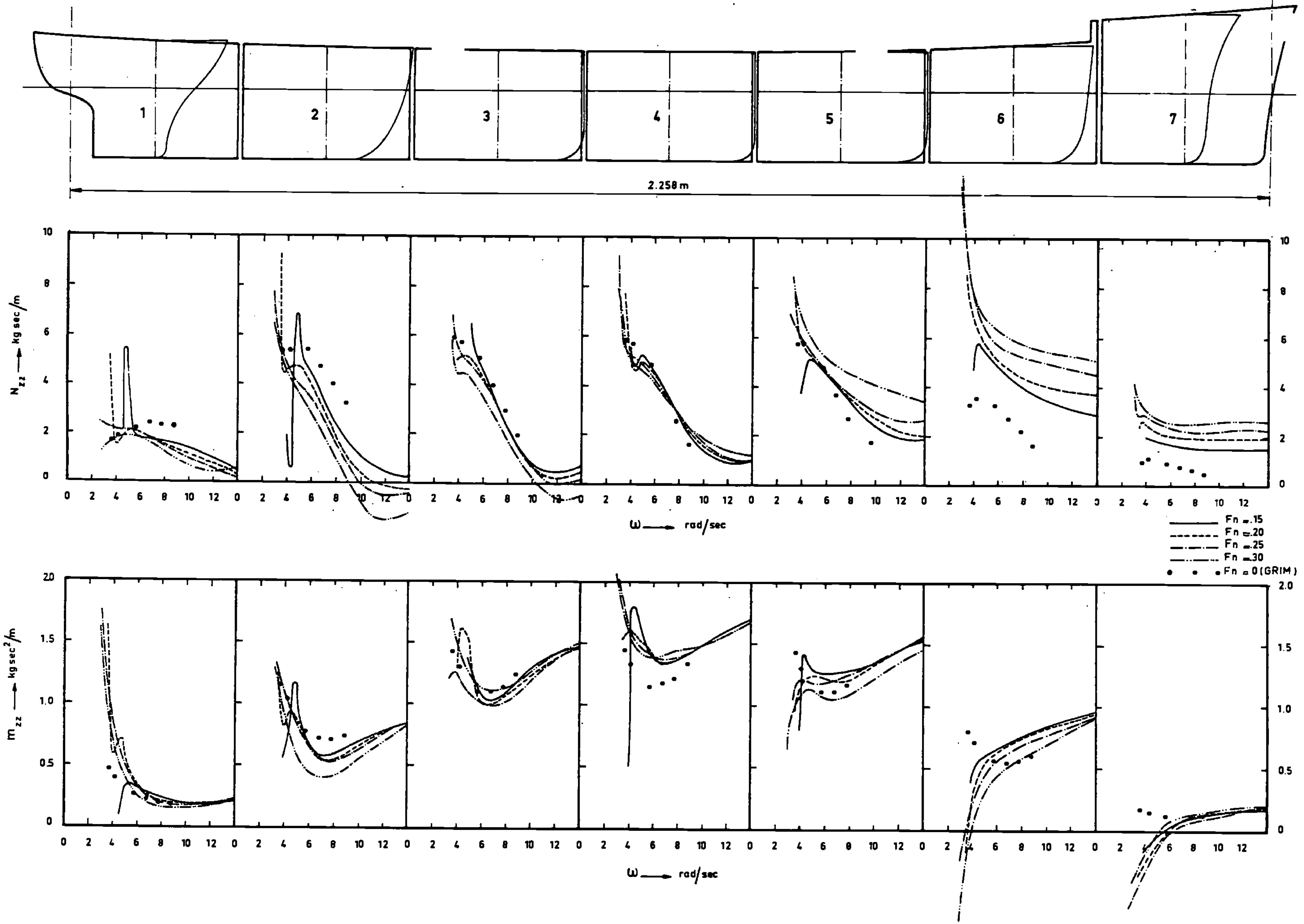
FIGURE 8





COMPARISON OF THE EXPERIMENTAL DAMPING COEFFICIENT AND ADDED MASS WITH GRIM'S VALUES FOR ZERO SPEED

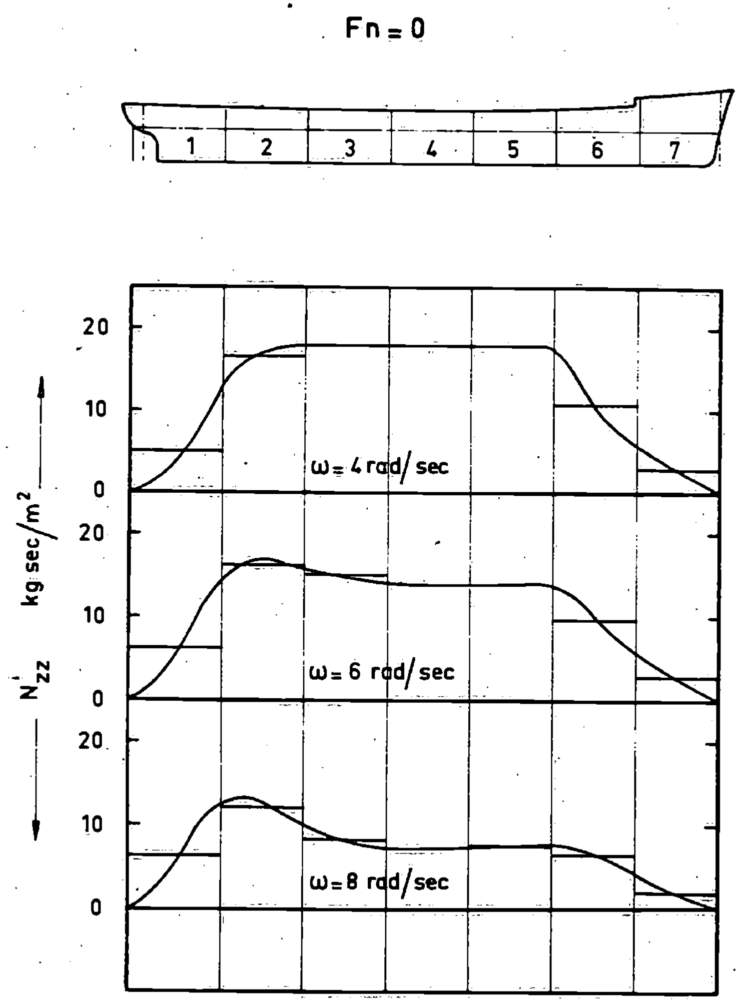
FIGURE 9



COMPARISON OF THE EXPERIMENTAL DAMPING COEFFICIENT AND ADDED MASS FOR EACH SECTION WITH GRIM'S VALUES FOR ZERO SPEED

FIGURE 10

DISTRIBUTION OF DAMPING AND ADDED MASS ACCORDING TO GRIM



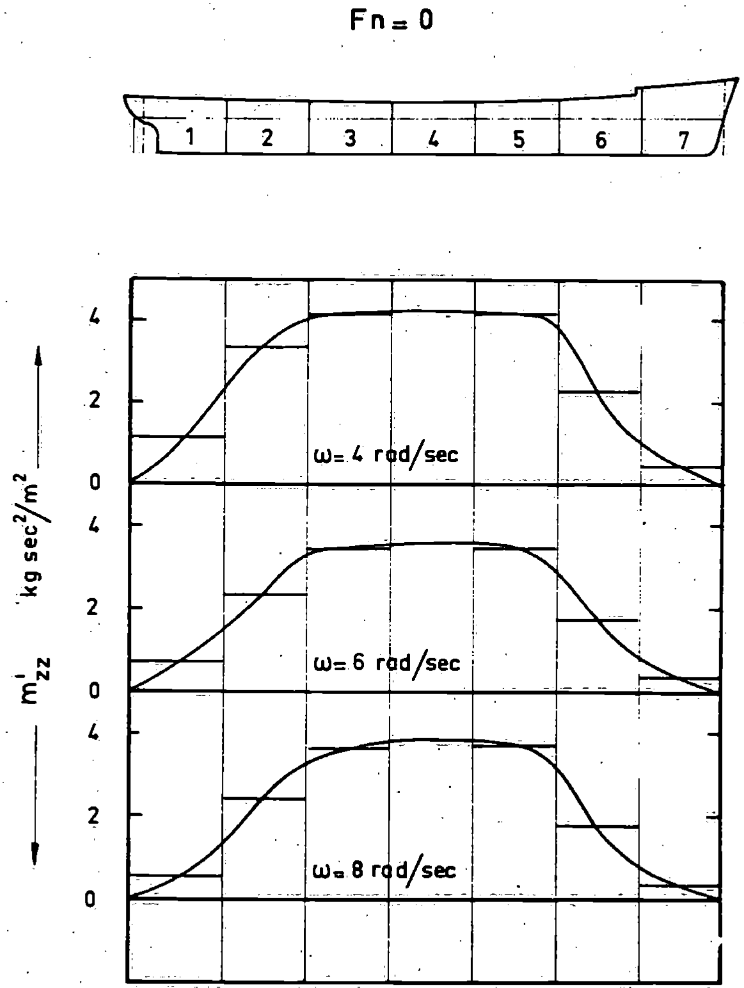


FIGURE 11

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DISTRIBUTION OF DAMPING AND ADDED MASS ALONG THE LENGTH OF A SHIPMODEL

(Verdeling van demping en toegevoegde massa over de lengte van een scheepsmodel)

by

Prof. Ir. J. GERRITSMA and W. BEUKELMAN

Shipbuilding Laboratory, Technological University Delft

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Issued by the Council

CONTENTS

DISTRIBUTION OF DAMPING AND ADDED MASS ALONG THE LENGTH OF A SHIPMODEL*)

by

Prof. Ir. J. GERRITSMA and W. BEUKELMAN

Summary

Forced heaving experiments were carried out with a seven-section model in still water, to investigate the distribution of damping and added mass along the length of a shipmodel.

The components of the vertical forces in phase with the heave displacement and the quadrature components on each of the seven sections were measured as a function of the frequency and the forward speed of the model. This allowed the determination of the sectional damping coefficients and the sectional added masses, and their distribution along the length of the model.

The results show a fairly large influence of frequency and forward speed on the distribution of damping. There is some influence of frequency on the distribution of added mass, but the influence of forward speed is small. In some conditions negative sectional damping and added mass was observed.

The distribution of damping results in coefficients of the heave velocity coupling terms, which depend on the forward speed. In the practical range of frequencies the coefficients of the heave acceleration coupling terms are very small. The experimental results are compared with Grim's theoretical values for damping and added mass at zero speed.

1. Introduction

During the last few years the methods for the evaluation of damping and added mass of ship like cross sections, oscillating in the free surface of a fluid, have been developed to a very satisfactory level. In this respect extremely useful work has been done by Ursell [1], Grim [2], Tasai [3, 4, 5], Porter [6], Paulling and Richardson [7]. The experiments with oscillating semi submerged cylinders which are reported in [4], [5] and [7] show that a good agreement exists between the theoretical and the experimental values at zero speed of advance.

The sectional damping coefficients and the sectional added mass can be integrated over the length of the ship to determine these values for the ship. Also cross coupling coefficients can be obtained by simple integration. Such a stripmethod however, neglects the influence of the forward speed of the ship and also three dimensional effects are ignored.

Earlier work [9] has shown that the damping coefficients and the added mass of a shipmodel do not vary much with forward speed, at least for the purpose of calculating the pitching and heaving motions in the practical speed range. Tasai [3] used the stripmethod to compare the calculated damping and added mass of a shipmodel with experimental values published in [8] and [9]. His conclusion is that for added mass and added mass moment of inertia the three dimensional effect is very small. For pitch damping the three dimensional effect is small at resonance, but for heave damping the experiment gives 15 % to 25 % larger values than the theoretical stripmethod values.

In [9] the importance of the heave and pitch velocity cross coupling terms for the calculation of heaving and pitching motions was shown. The inclusion of such terms is clearly necessary to get agreement with measured shipmodel motions. Although the measuring methods which were employed in [9] to determine the cross coupling coefficients cannot be regarded as completely satisfactory a definite dependence on speed was found.

The relatively small influence of speed on the total damping coefficient and the total added mass of a shipmodel and the speed dependence of the cross coupling terms indicate that the distribution of the damping coefficient and the added mass over the length of the model varies with forward speed.

This lead to the present experiment which makes use of a seven-section model. By oscillating this built up shipmodel in still water, the vertical components of the hydrodynamic forces on each separate section could be determined. In this way sectional damping coefficients and added masses were determined for a range of oscillation frequencies and forward speeds.

2. The model

The shipmodel is a parent model of the Series Sixty with a blockcoefficient $C_B = 0.70$. The main particulars are summarized in Table 1.

The model is made of polyester reinforced with fibreglass and consists of seven separate sections of equal length. Each of the sections has two end bulkheads; the width of the slits between the sections is 1 mm. The individual sections are not fastened to each other but they are kept in their position by means of stiff vertical straingauge dynamometers,

*) Publication No. 21, Shipbuilding Laboratory, Delft.

TABLE 1. Main particulars of the ship model

Length between perpendiculars	2.258	m
Length on the waterline	2.296	m
Breadth	0.323	m
Draught	0.129	m
Volume of displacement	0.0657	m^3
Blockcoefficient	0.700	
Waterplane area	0.572	m^2
Waterplane coefficient	0.785	
Coefficient of midlength section	0.986	
Prismatic coefficient	0.710	
L.C.B. forward $L_{PP}/2$	0.011	m
Centre of effort of waterplane after $L_{PP}/2$	0.038	m
Froude number of service speed	0.20	

which are connected to a longitudinal steel box girder running above the shipmodel.

A whole model of the same size and form was used for comparison purposes. A body plan is given in figure 1.

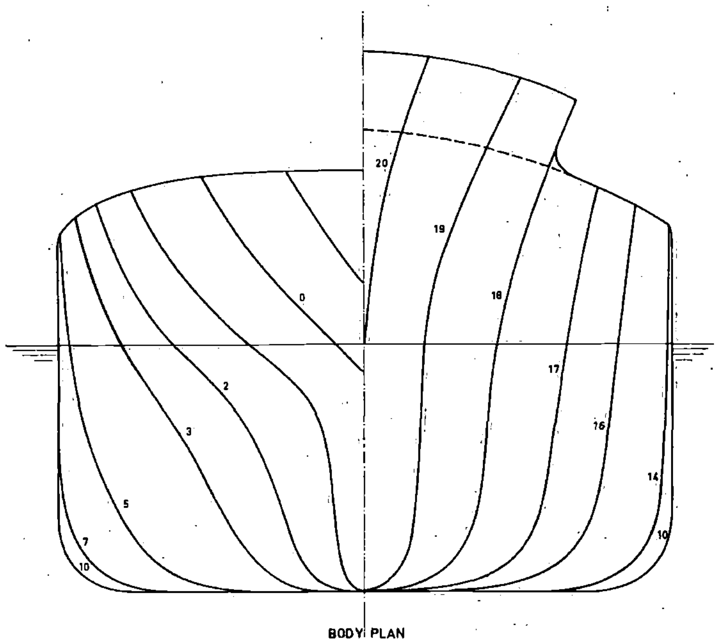


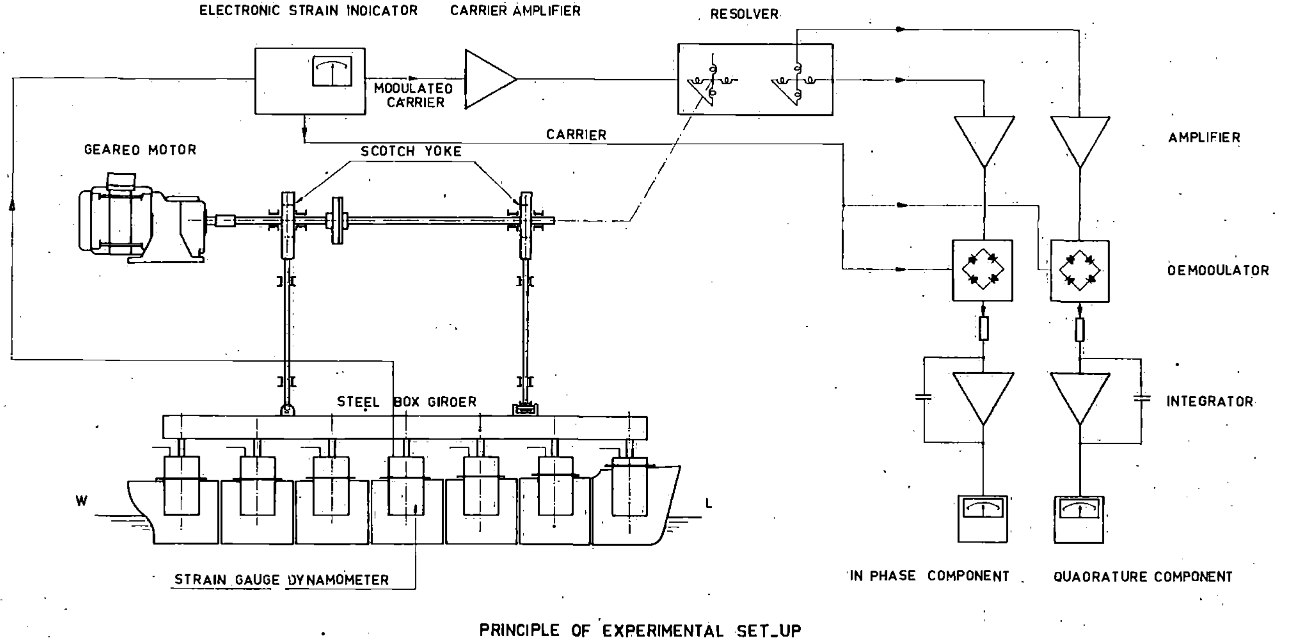
Figure 1

003-015

3. Experimental methods

In figure 2 the principle of the experimental set-up is given. The seven-section shipmodel is forced to oscillate in the vertical direction by means of a Scotch-Yoke mechanism. Frequency and amplitude of the harmonic oscillation can be varied to cover a wide range. Each section is connected to the longitudinal steel box girder by means of carefully calibrated straingauge dynamometers. The dynamometers are insensitive to forces acting in other than their axial direction. Consequently only the vertical components of the total force on each section are measured.

The vertical forces acting on each section are separated into the components in phase with the displacement and into the quadrature components by means of an electronic analoge system which, in principle, is similar to that published by Tuckerman [10]. It was found however, that the sine-cosine potentiometers, as used by Tuckerman, are not reliable at high rotational speeds. Therefore the measured signal is multiplied by sin ωt and cos ωt by means of a sine-cosine synchro resolver connected to the main shaft of the mechanical oscillator.



PRINCIPLE OF EXPERIMENTAL SET_UP

Figure 2

003-006

Averaging circuits with chopper stabilized amplifiers were used to determine the mean values of the in phase- and quadrature force components.

The system appeared to give accurate and consistent results. A high accuracy is needed in particular for measuring the damping forces, which are small in comparison with the inertial and restoring forces.

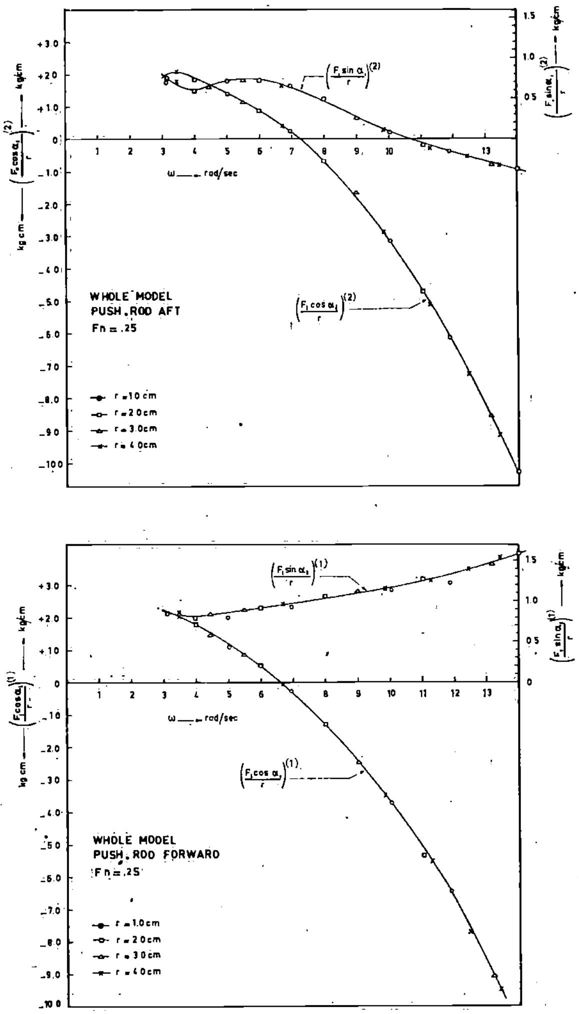
It should be noted that this system can resolve the measured forces into their Fourier components by driving the sine-cosine resolver at n-times the frequency of the main oscillator shaft, where $n = 1, 2, 3 \ldots\ldots$

Throughout the present experiments only the first harmonics of the measured forces are taken into account. The values for damping and added mass, derived from these first harmonics can be readily compared with theoretical results. Non linear effects however, may be fairly important as shown by the recent experiments of Tanaka and Kitagawa [11]. It was decided to study non linear effects in a later stage as the comparison with theoretical results seems the most urgent at this moment.

As only two channels were available for measuring the forces and the associated data reduction, repeated runs had to be made, under the same conditions of frequency and forward speed, to test all the seven sections.

4. Experimental results

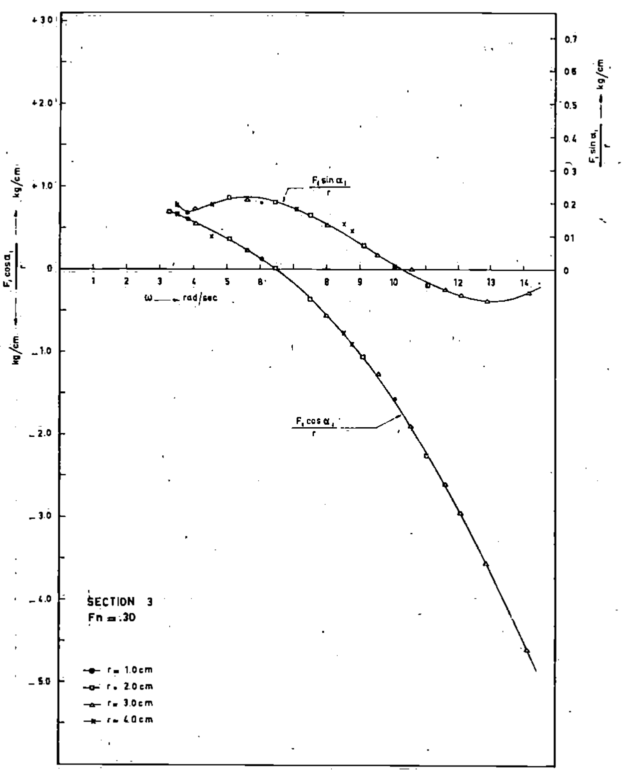
Measurements were carried out for frequencies up to $\omega = 14$ rad/sec. and for four speeds of advance,

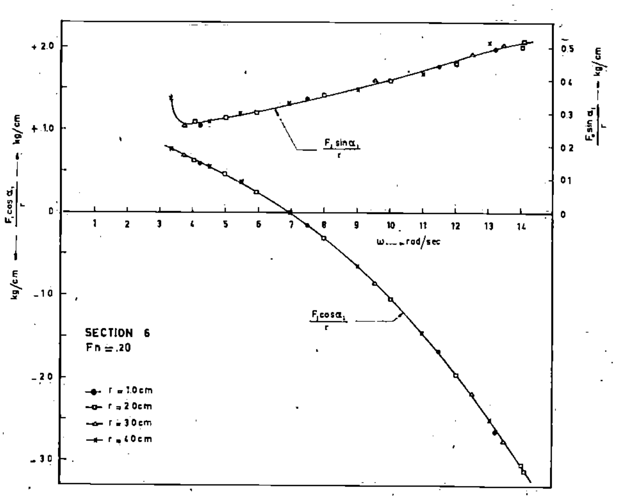


IN PHASE AND QUADRATURE COMPONENTS OF THE VERTICAL FORCES WORKING ON A HEAVING SHIP MODEL

Figure 4

003-013





IN PHASE AND QUADRATURE COMPONENTS OF THE VERTICAL FORCES WORKING ON HEAVING SECTIONS OF A SHIPMODEL (SECTIONS 3 AND 6)

Figure 3

003-014

namely $Fn = .15, .20, .25, .30$. No experiments were carried out at zero speed, because serious wall effects could be expected from reflected wave systems, generated by the model motions. For the same reason frequency values lower than $\omega = 3$ to 4 rad/sec. are not considered.

The oscillation amplitude varied from 1 to 4 cm. This corresponds to a very large motion for the mid-ship sections but the end sections of a ship may meet such conditions in pitching.

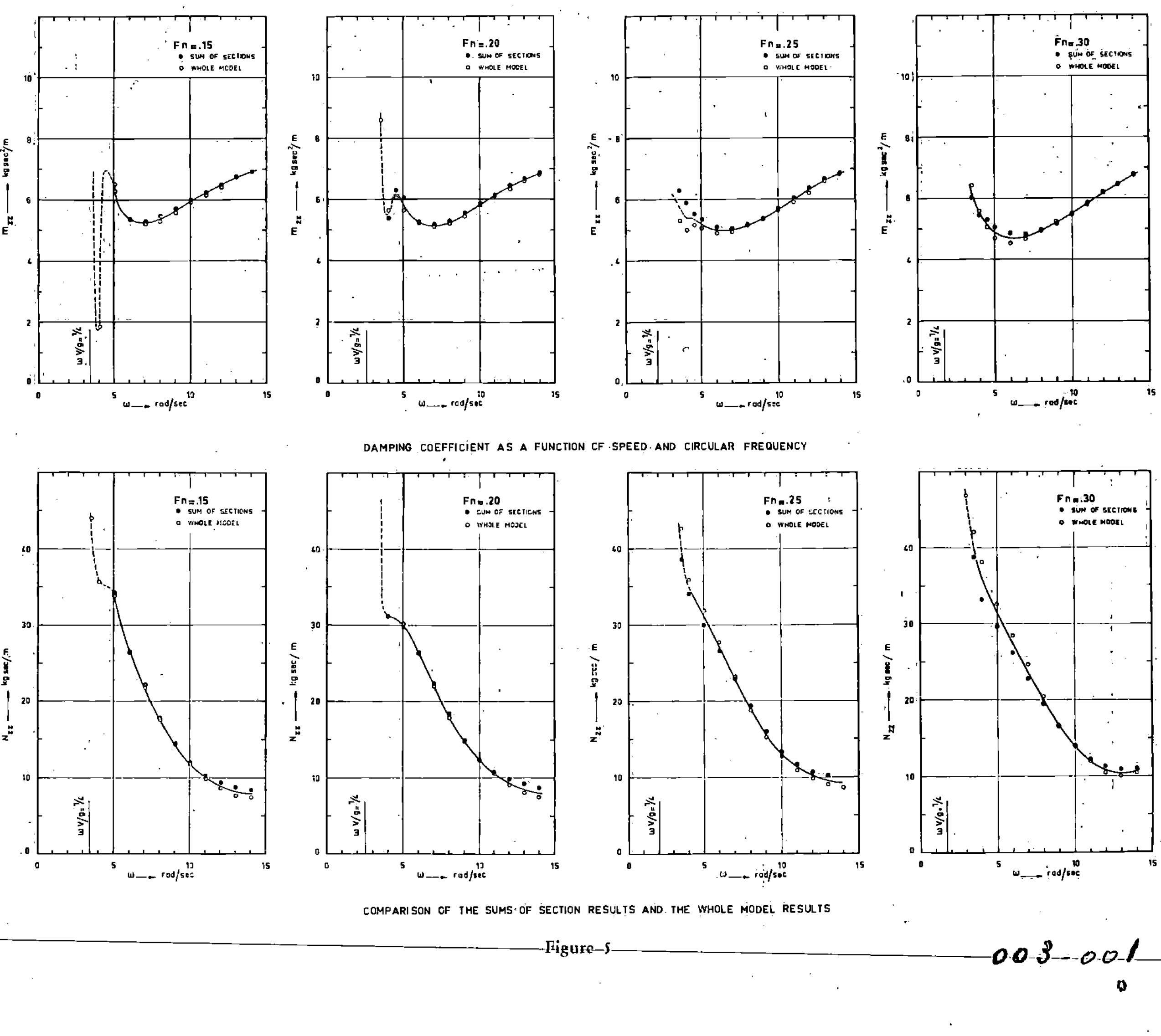
Some typical examples of the measurements are given in the figures 3 and 4. In figure 3 the in phase and quadrature components of the vertical forces per unit amplitude of two heaving sections are plotted on a base of frequency. There is strong linearity with regard to the heave amplitude. A similar plot for the whole model is given in figure 4 for each of the two push-rods which connect the shipmodel to the oscillator.

The calculation of the damping coefficients and the added mass from the measured quantaties is given in the Appendix. The results are summarized in Table 2, for each section of the seven-section model, as well as the whole model. Table 2 shows that the sums of the section results agree very well with the total values which were determined with the whole model. This is illustrated also in figure 5 where the damping coefficient and added mass for both cases ("sum of sections" and "whole model") are plotted as a function of speed and frequency. The conclusion may be that the influence of the slits between the sections is very small.

5. Analysis of the test results

The numerical values given in Table 2 are shown in graphical form in the figures 6 and 7. Sectional damping coefficients N'_{zz} and sectional added masses m'_{zz} are plotted over the length of the shipmodel as a function of frequency and forward speed. The figures show that the distribution of the damping coefficient changes with speed and frequency. The damping coefficient of the forward part of the shipmodel increases when the speed is increasing. At the

ADDED MASS AS A FUNCTION OF SPEED AND CIRCULAR FREQUENCY



COMPARISON OF THE SUMS OF SECTION RESULTS AND THE WHOLE MODEL RESULTS

Figure 5

003-00-1

TABLE 2a. Sectional added mass

$Fn = .15$

m_{zz} — kg sec^2/m

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	−1,21	0,59	—	0,54	0,87	0,41	−0,17	—	1,84
5	0,33	1,15	1,33	1,60	1,29	0,60	−0,05	6,25	6,49
6	0,31	0,66	1,08	1,38	1,26	0,65	0,02	5,36	5,37
7	0,28	0,58	1,03	1,35	1,26	0,70	0,08	5,28	5,19
8	0,24	0,60	1,09	1,37	1,28	0,76	0,10	5,44	5,26
9	0,21	0,64	1,19	1,41	1,31	0,81	0,12	5,69	5,55
10	0,20	0,69	1,29	1,48	1,34	0,85	0,14	5,99	5,91
11	0,18	0,74	1,36	1,54	1,39	0,86	0,16	6,23	6,12
12	0,18	0,78	1,40	1,60	1,45	0,90	0,17	6,48	6,39
13	0,19	0,82	1,44	1,66	1,51	0,94	0,17	6,73	6,69
14	0,23	0,84	1,47	1,70	1,56	0,95	0,16	6,91	6,88

$Fn = .20$

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	0,59	0,83	1,29	1,59	1,15	0,22	−0,27	5,40	5,63
5	0,57	0,86	1,48	1,50	1,24	0,52	0,11	6,28	5,63
6	0,32	0,65	1,00	1,40	1,23	0,64	0	5,24	5,19
7	0,25	0,55	1,02	1,37	1,20	0,71	0,09	5,19	5,08
8	0,21	0,55	1,08	1,38	1,21	0,75	0,12	5,30	5,18
9	0,19	0,59	1,15	1,43	1,26	0,78	0,13	5,53	5,44
10	0,19	0,65	1,23	1,49	1,33	0,83	0,14	5,86	5,78
11	0,19	0,72	1,30	1,54	1,38	0,85	0,16	6,14	6,07
12	0,20	0,77	1,37	1,60	1,45	0,88	0,17	6,44	6,32
13	0,20	0,82	1,42	1,65	1,50	0,92	0,17	6,68	6,60
14	0,20	0,84	1,47	1,69	1,55	0,94	0,16	6,85	6,78

$Fn = .25$

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	0,86	1,09	1,26	1,66	1,20	0,16	−0,32	5,91	4,99
5	0,51	0,82	1,08	1,45	1,18	0,44	−0,14	5,34	5,06
6	0,33	0,65	1,01	1,38	1,19	0,55	−0,02	5,09	4,89
7	0,23	0,54	0,98	1,36	1,22	0,64	0,04	5,01	4,93
8	0,20	0,54	1,03	1,39	1,26	0,68	0,08	5,18	5,13
9	0,19	0,57	1,09	1,42	1,30	0,72	0,10	5,39	5,40
10	0,18	0,62	1,19	1,48	1,34	0,77	0,12	5,70	5,65
11	0,19	0,70	1,28	1,54	1,40	0,80	0,14	6,05	5,89
12	0,20	0,76	1,37	1,60	1,45	0,83	0,16	6,37	6,21
13	0,21	0,81	1,43	1,67	1,50	0,88	0,18	6,68	6,59
14	0,21	0,85	1,46	1,72	1,53	0,91	0,18	6,86	6,84

$Fn = .30$

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	0,70	0,91	1,49	1,58	1,07	−0,10	−0,22	5,43	5,59
5	0,42	0,56	1,26	1,42	1,10	0,32	−0,03	5,05	4,68
6	0,25	0,44	1,15	1,39	1,07	0,45	0,07	4,82	4,51
7	0,19	0,40	1,12	1,41	1,06	0,51	0,12	4,81	4,66
8	0,16	0,42	1,14	1,45	1,08	0,58	0,13	4,96	4,93
9	0,15	0,47	1,18	1,46	1,16	0,64	0,14	5,20	5,23
10	0,15	0,55	1,26	1,47	1,22	0,68	0,17	5,50	5,48
11	0,16	0,62	1,34	1,52	1,28	0,74	0,18	5,84	5,82
12	0,17	0,69	1,41	1,57	1,35	0,81	0,19	6,19	6,18
13	0,19	0,77	1,46	1,62	1,40	0,86	0,20	6,50	6,47
14	0,21	0,83	1,49	1,67	1,45	0,89	0,20	6,74	6,77

TABLE 2b. Sectional damping coefficients

$Fn = .15$

N_{zz} — kg sec/m

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	2,03	9,78	—	5,78	3,80	4,80	2,00	—	35,63
5	3,32	6,74	6,46	5,28	5,14	5,46	1,80	34,20	33,80
6	1,82	4,42	4,55	4,58	4,52	4,78	1,67	26,34	26,53
7	1,71	3,42	3,42	3,64	3,96	4,30	1,57	22,02	21,77
8	1,61	2,31	2,26	2,75	3,35	3,94	1,53	17,75	17,49
9	1,50	1,58	1,36	1,96	2,80	3,66	1,51	14,37	14,22
10	1,36	1,08	0,76	1,39	2,36	3,43	1,49	11,87	11,63
11	1,18	0,73	0,47	1,04	2,06	3,24	1,49	10,21	9,83
12	0,95	0,47	0,44	0,87	1,89	3,09	1,50	9,21	8,54
13	0,72	0,31	0,48	0,85	1,82	2,98	1,49	8,65	7,62
14	0,46	0,22	0,55	0,95	1,83	2,87	1,50	8,38	7,43

$Fn = .20$

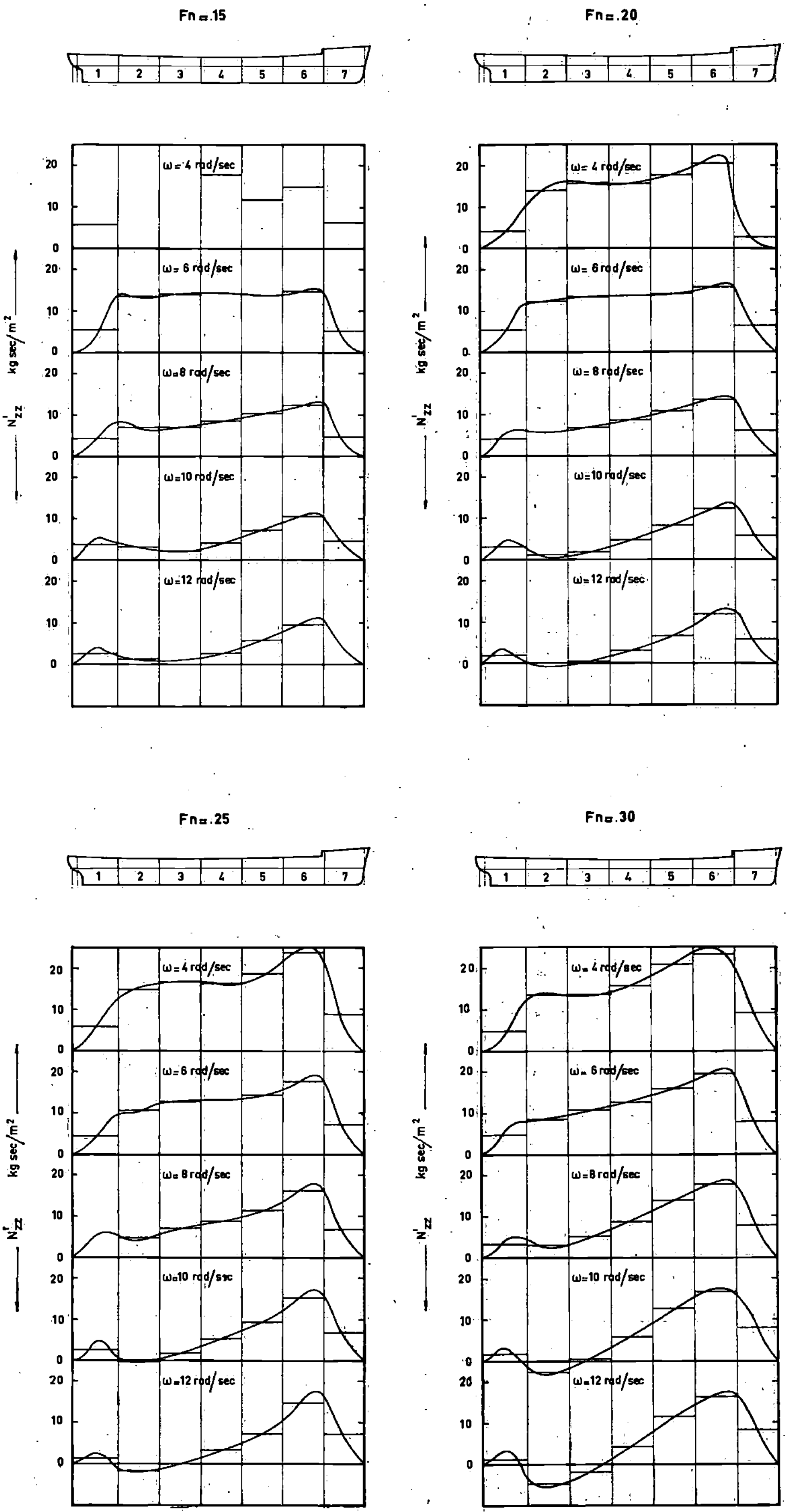
ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	1,53	4,53	5,08	5,05	5,73	6,63	2,50	31,05	31,33
5	2,04	4,70	5,02	4,98	5,08	5,70	2,18	29,70	30,16
6	1,95	3,95	4,32	4,45	4,52	5,07	2,07	26,33	26,15
7	1,74	2,96	3,32	3,64	3,97	4,66	1,99	22,28	21,87
8	1,50	1,91	2,25	2,81	3,49	4,38	1,94	18,28	17,78
9	1,29	0,96	1,29	2,07	3,07	4,18	1,90	14,76	14,61
10	1,10	0,37	0,62	1,54	2,70	4,01	1,90	12,24	12,14
11	0,92	0,04	0,31	1,20	2,40	3,90	1,91	10,68	10,40
12	0,74	−0,15	0,21	1,01	2,18	3,84	1,93	9,76	9,03
13	0,53	−0,26	0,27	0,91	2,04	3,77	1,93	9,19	8,00
14	0,27	−0,31	0,44	0,86	2,01	3,67	1,92	8,86	7,44

$Fn = .25$

ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	2,13	4,80	5,38	5,20	5,98	7,63	2,85	33,97	35,88
5	2,12	4,02	4,82	4,82	5,24	6,28	2,56	29,86	31,74
6	1,97	3,43	4,17	4,23	4,62	5,68	2,35	26,45	27,63
7	1,71	2,59	3,29	3,56	4,10	5,40	2,23	22,88	23,12
8	1,48	1,58	2,28	2,83	3,68	5,21	2,19	19,25	18,75
9	1,21	0,66	1,34	2,22	3,31	5,07	2,17	15,98	15,24
10	0,95	−0,06	0,60	1,68	3,00	4,96	2,20	13,33	12,69
11	0,73	−0,43	0,13	1,27	2,77	4,85	2,27	11,59	10,90
12	0,52	−0,56	−0,03	1,03	2,63	4,74	2,29	10,62	9,78
13	0,32	−0,54	0,02	0,92	2,57	4,62	2,30	10,21	9,00
14	0,15	−0,49	0,11	0,94	2,64	4,49	2,26	10,10	8,60

$Fn = .30$

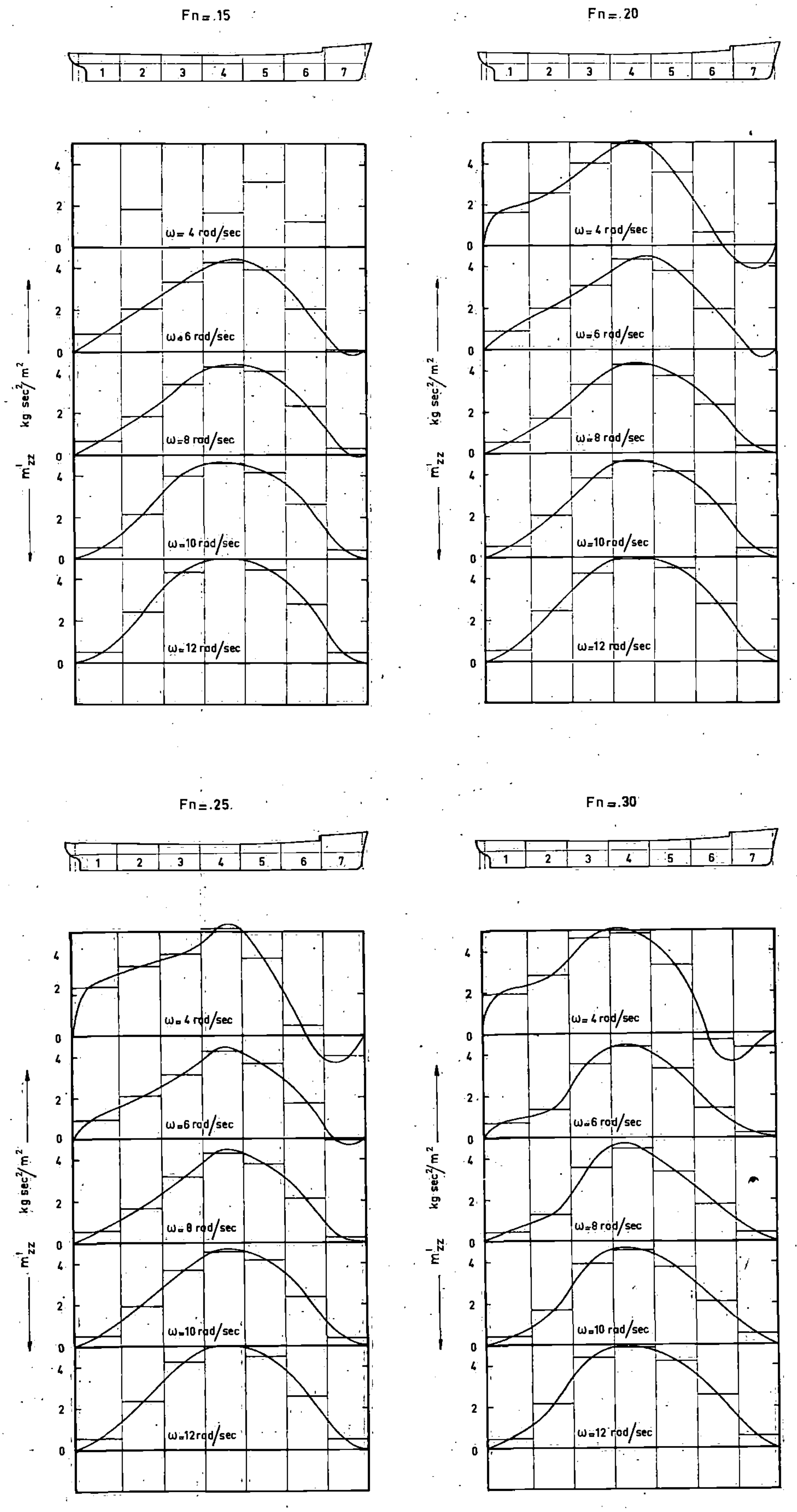
ω rad/sec	1	2	3	4	5	6	7	sum of sections	whole model
4	1,78	4,40	4,40	5,15	6,78	7,60	2,98	33,09	38,10
5	1,86	3,62	4,22	4,56	5,80	6,78	2,70	29,54	32,52
6	1,75	2,77	3,50	4,10	5,18	6,32	2,55	26,17	28,45
7	1,51	1,92	2,64	3,41	4,79	5,99	2,51	22,77	24,64
8	1,21	0,99	1,70	2,81	4,50	5,73	2,51	19,45	20,40
9	0,87	0,03	0,87	2,29	4,27	5,54	2,54	16,41	16,67
10	0,64	−0,87	0,17	1,88	4,07	5,42	2,59	13,90	13,95
11	0,47	−1,40	−0,32	1,57	3,90	5,35	2,63	12,20	11,85
12	0,42	−0,56	−0,63	1,37	3,72	5,28	2,66	11,26	10,42
13	0,45	−1,46	−0,73	1,23	3,56	5,19	2,66	10,90	9,96
14	0,56	−1,24	−0,54	1,16	3,39	5,03	2,62	10,98	10,46



DISTRIBUTION OF SECTIONAL DAMPING COEFFICIENT OVER THE LENGTH OF A SHIPMODEL

Figure 6

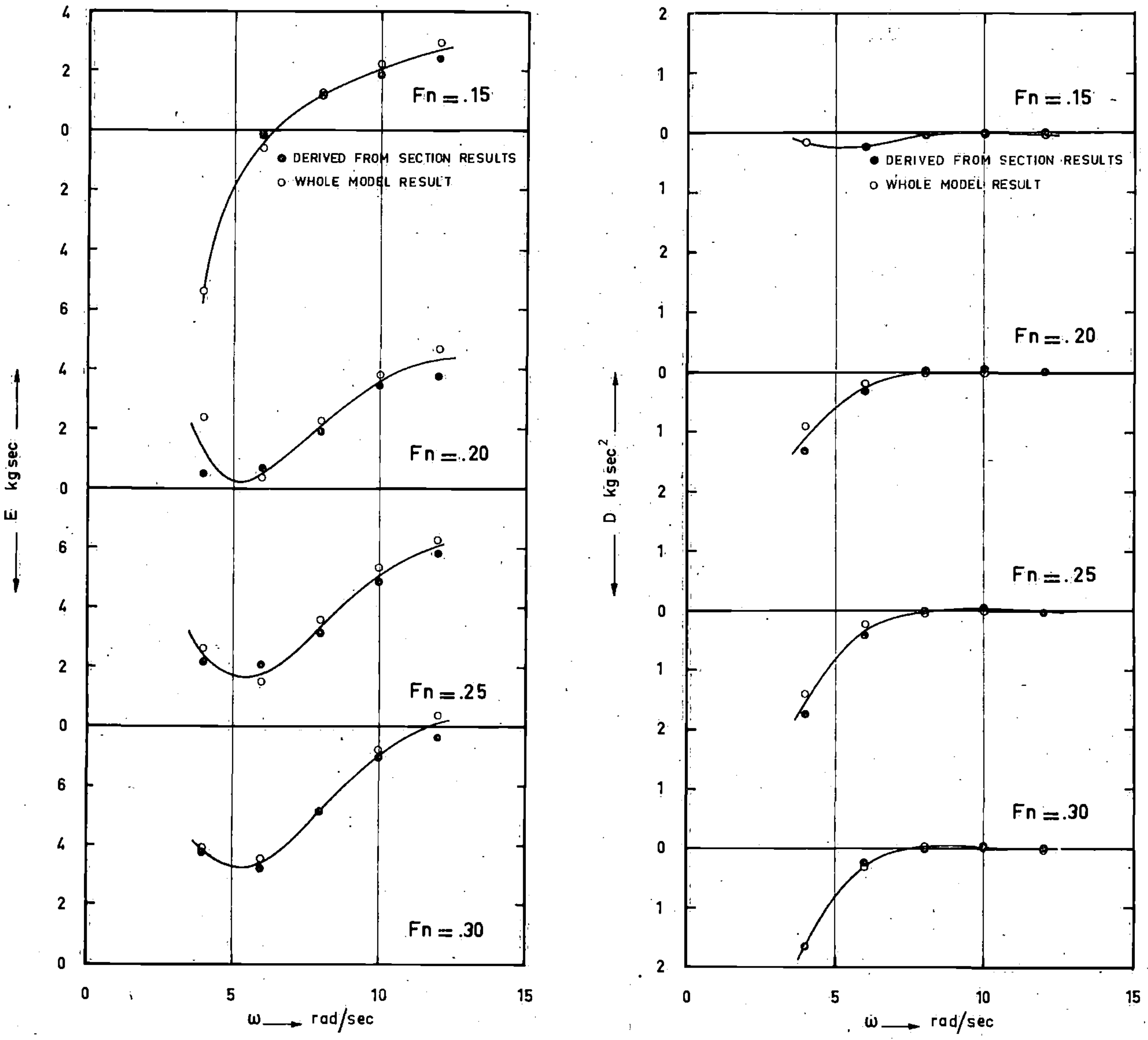
003 - 002



DISTRIBUTION OF SECTIONAL ADDED MASS OVER THE LENGTH OF A SHIPMODEL

Figure 7

003 - 003



CROSS_COUPLING COEFFICIENTS

003-007

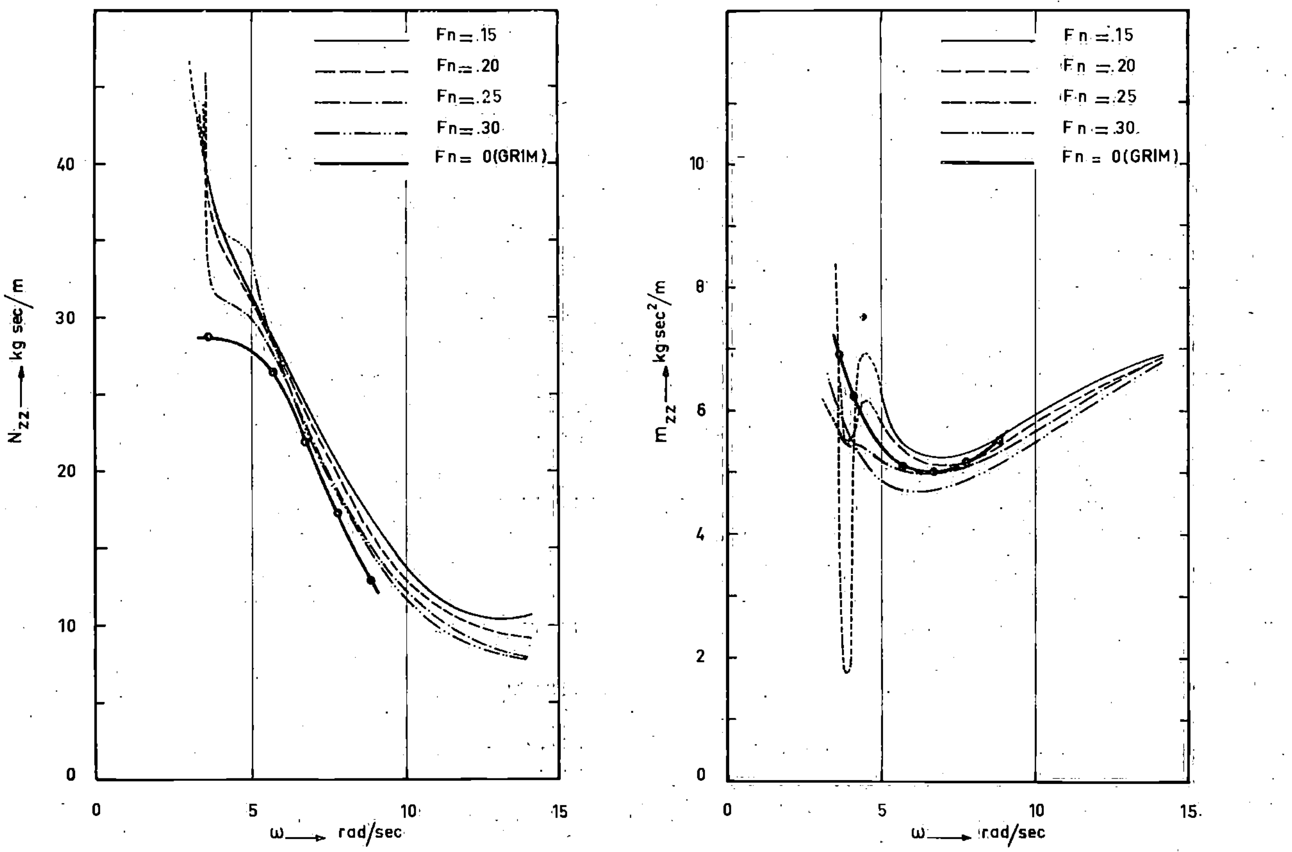
Figure 8

same time a decrease of the damping coefficient of the afterbody is noticed. In some cases even „negative" damping occurs. A physical explanation of this phenomena is not readily at hand but apparently the water motion set up by the forward part of the ship has a strong influence on the conditions at the afterbody. As noticed before the integral of the sectional damping coefficients over the length of the shipmodel does not vary much with forward speed.

The added mass distribution has a somewhat different character. It has less speed dependence than the distribution of damping but there is a shift forward of the distribution curve for increasing frequencies. "Negative" added mass is found for the bow section at low frequencies. For higher frequencies the influence of frequency becomes very small.

The first moment of the distribution curves with respect to the centre of gravity of the model gives the coefficients of the heave velocity and the heave acceleration coupling terms, respectively E and D. As shown in figure 8 the coefficient of the heave velocity coupling term depends on the forward speed of the shipmodel, as could be expected from the shift of the damping distribution curves with speed. The coefficients of the heave acceleration term are nearly speed independent, whereas for $\omega > 6$ rad/sec. they are negligibly small.

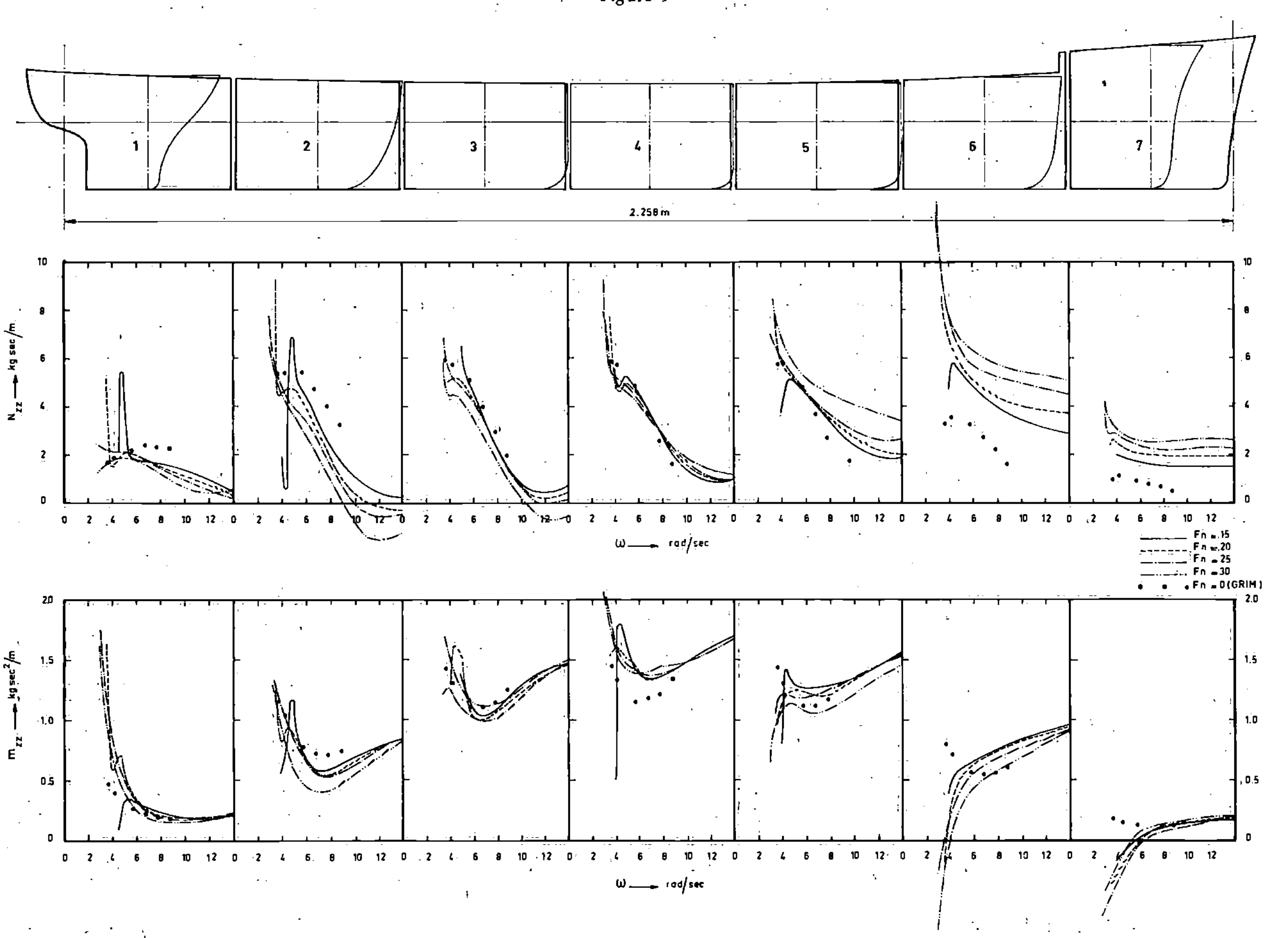
In figure 8 a comparison is made between the cross coupling coefficients derived from the damping coefficient and added mass distributions on the one hand, and the corresponding directly measured



COMPARISON OF THE EXPERIMENTAL DAMPING COEFFICIENT AND ADDED MASS WITH GRIM'S VALUES FOR ZERO SPEED

003 - 008

Figure 9



COMPARISON OF THE EXPERIMENTAL DAMPING COEFFICIENT AND ADDED MASS FOR EACH SECTION WITH GRIM'S VALUES FOR ZERO SPEED

Figure 10

003 - 009

values as found from the tests with the whole model. Considering the absolute magnitude of these second order coefficients, the agreement is very satisfactory.

The experimental values for the damping coefficient and the added mass are compared with Grim's theoretical values for zero speed [1]. In figure 9 this comparison is made for the whole model and it follows that the calculated added mass agrees very well with the mean of the experimental values at the various forward speeds.

Grim's damping coefficients for zero speed are smaller than the experimental values, but at resonance ($\omega \approx 7$) the difference is less than 10 %.

Due to the influence of forward speed the difference between theory and experiment is considerably larger for the individual sections as can be concluded from figure 10, where the damping coefficients and the added masses are plotted for each section.
Finally the distribution of Grim's values over the length of the model is given in figure 11 for zero forward speed. It is noticed that the theoretical prediction for zero speed gives a shift of the damping coefficient distribution towards the afterbody for increasing frequencies resulting in a negative velocity coupling coefficient. The speed range from $Fn = 0$ to $Fn = .15$ is too large to permit extrapolation of the experimental cross coupling coëfficients, but such a negative coefficient could certainly be in line with the experimental values, which were found in the speed range $Fn = .15$ to $Fn = .30$.

Comparison with the results of earlier measurements on the same model reveal some differences [9]. It must be remarked, however, that in the present case only the first harmonic of the exciting force function is taken into account. In [9] the assumption was made that the exciting force function was purely harmonic. By representing this function simply by an amplitude, a frequency and a phase angle some influence of the higher harmonics could have entered in the determination of the coefficient of the motion equations.

Golovato's experiments [8] show the influence of non linear damping terms in heave, as do the tests by Tanaka and Kitagawa [11] for pitching. From this last paper it follows that the linearized quadratic damping can increase the linear damping coefficient by some 20 % at resonance.

The damping coefficients found with the present experiments are 15 to 20 % lower at resonance than

DISTRIBUTION OF DAMPING AND ADDED MASS ACCORDING TO GRIM

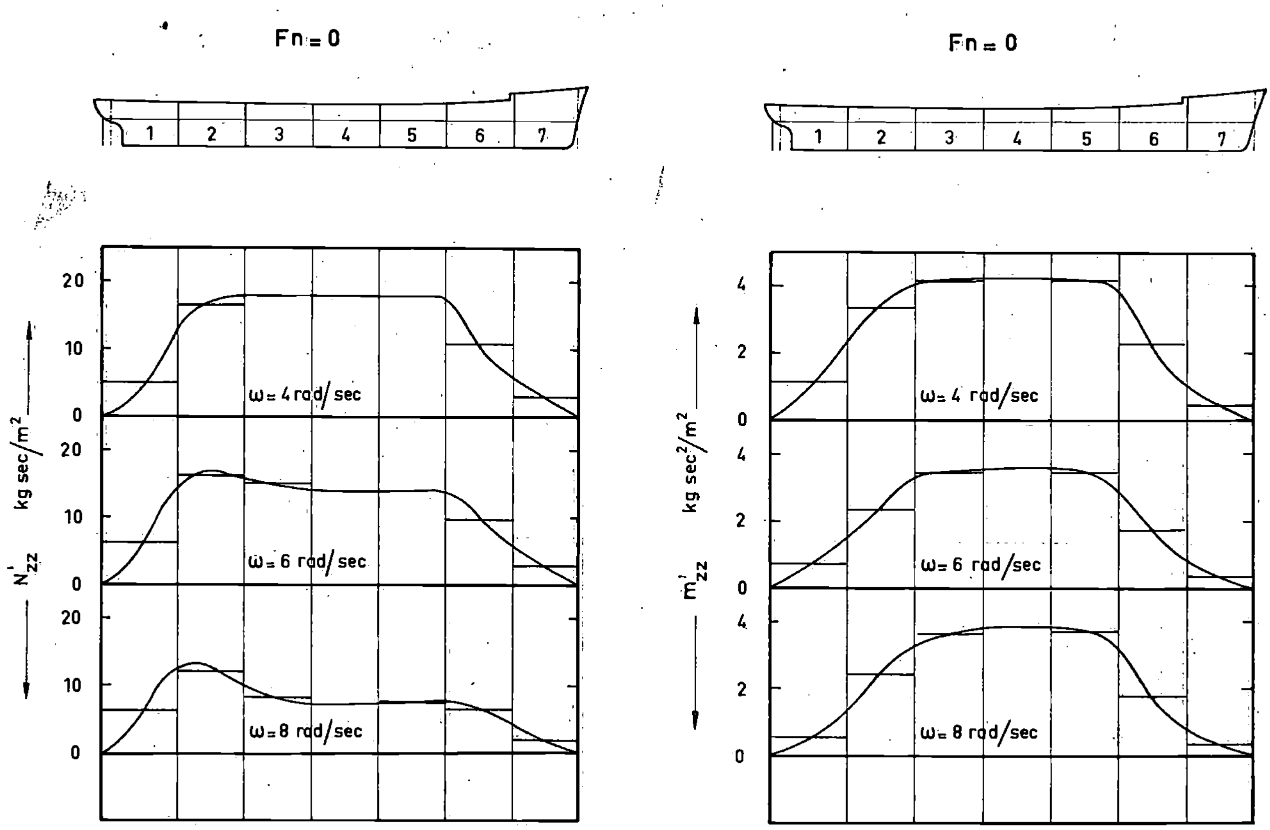


Figure 11

0-0-3 - 0-0-4

the earlier results. The added mass values agree fairly well and also the heave velocity cross coupling coefficients agree satisfactorily with the earlier results in the range $\omega = 7$ to 10 rad/sec.

APPENDIX

Experimental determination of the damping coefficient and the added mass

The shipmodel performs a forced harmonic oscillation in the vertical direction with an amplitude r and a circular frequency ω, thus:

$$z = r \cos \omega t \qquad \ldots\ldots\ldots (1)$$

The linearized equations of motion will be:

$$a\ddot{z} + b\dot{z} + cz = F_1 \sin (\omega t + \alpha_1)$$
$$D\ddot{z} + E\dot{z} + Gz = M_1 \sin (\omega t + \beta_1)$$
$$\ldots\ldots\ldots (2)$$

where:

a = total mass including added mass,
b = damping coefficient,
c = restoring force coefficient,
D, E, G = cross coupling coefficients,
F_1 = amplitude of first harmonic of exciting force,
M_1 = amplitude of first harmonic of exciting moment,
α_1, β_1 = phase angles.

Substitution of (1) in (2) gives:

$$\left.\begin{aligned} -a\, r\, \omega^2 + c\, r &= F_1 \cos \alpha_1 \\ b\, r\, \omega &= F_1 \sin \alpha_2 \\ -D\, r\, \omega^2 + G\, r &= M_1 \cos \beta_1 \\ E\, r\, \omega &= M_1 \cos \beta_1 \end{aligned}\right\} \quad \ldots\ldots (3)$$

The in-phase and quadrature components of the exciting force are measured by means of straingauge dynamometers and a data reduction system. In case of the whole model, the exciting force is measured in each of the two push-rods of the oscillator, at equal distances from the centre of gravity of the model. Thus:

$$F_1 \cos \alpha_1 = (F_1 \cos \alpha_1)^{(1)} + (F_1 \cos \alpha_1)^{(2)}$$

and:

$$M_1 \cos \beta_1 = \{ (F_1 \cos \alpha_1)^{(1)} - (F_1 \cos \alpha_1)^{(2)} \} \frac{l}{2}$$

where l is the distance between the two push-rods. Similar expressions are valid for the quadrature components: c and G are found from:

$$c = \frac{F_1}{r} \text{ and } G = \frac{M_1}{r}$$

as a function of the forward speed of the model.

The added mass m_{zz}, is found from:

$$m_{zz} = a - \varrho \nabla,$$

where $\varrho \nabla$ is the mass of the model.

In case of the seven section model only the first two equations of (3) are used for each individual section. An estimation of the sectional damping coefficient distribuion N'_{zz} (x) and the sectional added mass distribution m'_{zz} (x) is found by using the relations:

$$N_{zz} \text{ (section)} = \int_0^{L/7} N'_{zz} (x)\, dx$$

$$m_{zz} \text{ (section)} = \int_0^{L/7} m'_{zz} (x)\, dx.$$

It is also assumed that the distributions over the length of the shipmodel are given by smooth curves (see figures 6 and 7).

The forces in phase with the heave displacement and those 90 degrees out of phase with the displacement (quadrature components) are found by multiplying the total measured vertical force by $\sin \omega t$ and $\cos \omega t$ and by taking the time average of the result, thus:

$$F_1 \cos \alpha_1 = \frac{2}{T} \int_0^T \sin \omega t . \sum_1^p n\, F_n\, (n\, \omega\, t + \alpha_n)\, dt$$

$$F_1 \sin \alpha_1 = \frac{2}{T} \int_0^T \cos \omega t . \sum_1^p n\, F_n\, (n\, \omega\, t + \alpha_n)\, dt$$

The exciting force function is nearly harmonic and p can be limited to 2 or 3. In a similar way the n th harmonics can be found by multiplying the force function by $\sin n\, \omega\, t$ and $\cos n\, \omega\, t$.

A non linear set of equations, replacing (3) is proposed by Tanaka and Kitagawa [11] namely:

$$a\ddot{z} + b_1\dot{z} + b_2\dot{z}\,|\dot{z}| + c_1 z + c_2 z^2 + c_3 z^3 =$$
$$= \sum_1^3 n\, F_n \sin\, (n\, \omega\, t + \alpha_n)$$

$$D\ddot{z} + E_1\dot{z} + E_2\dot{z}\,|\dot{z}| + Gz =$$
$$= \sum_1^3 n\, M_n \sin\, (n\, \omega\, t + \alpha_n)$$
$$\ldots\ldots\ldots (4)$$

The non linear terms in (4), however, are not considered in the present paper. The inclusion of the term $c_3 z^3$ introduces an additional first harmonic term since:

$$c_3 z^3 = c_3 r^3 \sin^3 \omega\, t = c_3 r^3 \left(\tfrac{3}{4} \sin \omega\, t - \tfrac{1}{4} \sin 3\, \omega\, t\right).$$

It was found, however, that c_3 is negligibly small for the whole model as well as for each section, and consequently no correction is necessary in the first equation of (3).

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List of symbols

a = Total mass including added mass.
b = Damping coefficient (also N_{zz}).
c = Restoring force coefficient.
C_B = Blockcoefficient.
D, E, G = Cross coupling coefficients.
F_1 = Amplitude of first harmonic of exciting force.
Fn = Froude number.
l = Horizontal distance between push-rods.
L = Length of shipmodel.
M_1 = Amplitude of first harmonic of exciting moment.
m_{zz} = Added mass for whole model or for a section with length $1/7$ L.
m'_{zz} = Sectional added mass.
N'_{zz} = Sectional damping coefficient.
N_{zz} = Damping coefficient for whole model or for a section with length $1/7$ L.
z = Heave displacement.
α_1, β_1 = Phase angles.
ϱ = Density of water.
∇ = Volume of displacement.
ω = Circular frequency.

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