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PREDICTION OF THE AMOUNT OF SHIPPING WATER

by

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Synopsis

This study is an attempt to assess the quantity of water when a vessel is shipping green water in regular waves and the associated statistical properties in case of irregular seas. The report begins with a comprehensive introduction and, in order to become familiar with the problems involved, a concise state of the art report on this phenomenon as a result of a small scale literature survey.

The report continues with the development ot a mathematical model taking into account the most important parameters governing the process of shipment of water. Next the data of two series of model experiments are presented and compared with the analytical results calculated according to the mathematical model both for regular and irregular head waves. In this investigation the occurring discrepancies are subject to discussion in order to improve the understanding in the accuracy and consequently the applicability of the underlying simplified theory.

The report of this preliminary study is concluded with general conclusions and suggestions for future work in this field.

1 Introduction

This project has been prompted by the entry into service of heavy-load vessels which under article 6 (2) of the international loadline conference (ILLC-66) are exempted from the obligation to close the hatchway openings by means of hatches. Up till now, the rule has been that vessels seeking to qualify for such an exemption had to submit to a series of model tests whereby the quantities of water shipped by them are measured in extreme sea conditions. The freeboard ultimately assigned and partly dependent upon the results of the model tests should, however, be in excess of or equal to the freeboard laid down by the ILLC-66. Three vessels have hitherto gone through this procedure [1], all three have been operating without difficulties for some considerable time, whilst another three have recently entered service. All the vessels concerned have been designed in such a way that they are employable in both the "open" and the "closed" condition, with the corresponding conventional freeboard.

The quantity of shipped water should be taken into account in assessing stability.

Another aspect is the available potential for discharging flooded water (either naturally or mechanically) and its capacity.

Partly through lack of experience, it has hitherto been impossible to formulate accurate criteria for the freeboard to be assigned to vessels navigating in such an "open condition".

The present project aims at developing a calculating method which should enable a prediction of the quantity of water expected to be shipped per time unit in specified operational conditions. This calculating method should ultimately restrict the number of model tests required in the design phase and, if possible, also provide a basis on which to develop criteria.

There are, however, other types of vessels for which the said study may be important, notably supply vessels. This type of vessel is characterised by a pronounced asymetric location of the superstructure in the longitudinal direction. This has a strongly adverse effect on the transverse stability when the vessel is considered to be free-trimming at heeling angles whereby the deck is immersed. In view of the relatively small freeboard of the long working deck aft and the relatively high breadth-draught ratio, the effect on the stability curve is considerable, as calculations have more than once borne out.

Moreover, pipes carried as deck cargo are reputed to be capable of retaining large quantities of shipped water for some considerable time.

The revision of the stability regulations concerning supply vessels operating under IMCO rules has made allowance for the aforesaid aspects in that, for instance, stability calculations should include 30% of the net volume of the pipes. This percentage rate may, however, be reduced in case of an increase in the local freeboard. This is the result of a proposal contained in [2], which sets out and applies an approximative method of calculating the expected volume of water shipped by a supply vessel navigating in following waves. The present study should incorporate a verification and, if possible, semi-empirical corrections of this method.

It may furthermore be mentioned that the capability of working on deck is strongly affected by the amount of water shipped, for which reason a minimum freeboard aft has been stipulated for supply vessels.

Apart from the preceding applications, the present study may also be of more general interest. In this connection may be thought of a future loadline study concerning the determination of freeboard, sheer and bow-height in connection with the location of the ship's openings, the minimum strength of closing devices and the height of platform. This latter also in view of the working capability on deck and of deck traffic.

Such a comprehensive study should be carried out on an international level as proposed in [3].

Fairly recently, the freeboard regulations applicable to vessels operating on the Great Lakes have been revised; they are now based entirely on the principle of seakeeping computations. In a nutshell, this implies that freeboard, sheer and bow height are determined in such a way that a certain probability of shipping water is not exceeded, whereby the ship is assumed to sail in irregular longitudinal waves corresponding to a specified sea condition. The computations have been elaborated in conformity with the suggestions contained in a Dutch contribution to the ILLC-66 (see Fig. 1). If similar considerations should be used in an international study based on systematic comparative calculations, it would lead to an alleviation of the requirements imposed on vessels of greater lengths, whereas they may be expected to become more onerous for smaller vessels on certain points such as, for instance, on the bow height. The great advantage, however, lies in the fact that, contrary to the present regulations which are principally based on experience, the newly developed loadline regulations will be based on criteria which may be considered as known data.

This well-founded approximation, correlated with the experience gained from the current regulations, affords a better basis for the policy to be adopted in connection with vessels of a deviating type. This already takes place on a limited scale in the case of vessels which have a limited area of operation in combination with wind force limitations.

2 Summary of literature survey

In view of the nature of the project any consultation of literature must perforce be limited in extent, because most references are concerned with calculations of the probability of shipping water in longitudinal waves.

The basic formulae may, inter alia, be found in reference [4], they are given below in a slightly modified form:

Probability of shipping water per oscillation:

$$P(s_e > F_e = \exp\left(-F_e^2/2m_{0s}\right) \qquad (1)$$

Probability of shipping water per time unit:

$$N = (2\pi)^{-1}(m_{2s}/m_{0s})^{1/2} \exp\left(-F_e^2/2m_{0s}\right) \qquad (2)$$

Conditional probability of excess of the static water pressure per oscillation:

$$P(q > q_0) = \exp\left[-\{(q_0+F_e)^2 - F_e^2\}/2m_{0s}\right] \quad \text{for } q_0 > 0 \text{ and } s_e > F_e \qquad (3)$$

Probability of excess of the static water pressure per oscillation:

$$P(q > q_0) = \exp\left[-(q_0+F_e)^2/2m_{0s}\right] \quad \text{voor} \quad q_0 > 0 \qquad (4)$$

with q and q_0 = static water pressure in tonnes/sq.m.

N = expected number of times of shipping water/sec

F_e = local effective freeboard in m

s_e = amplitude of the local effective relative motion in m

m_{0s} = variance of the local relative motion in sq.m (area of the spectrum of the local relative motion)

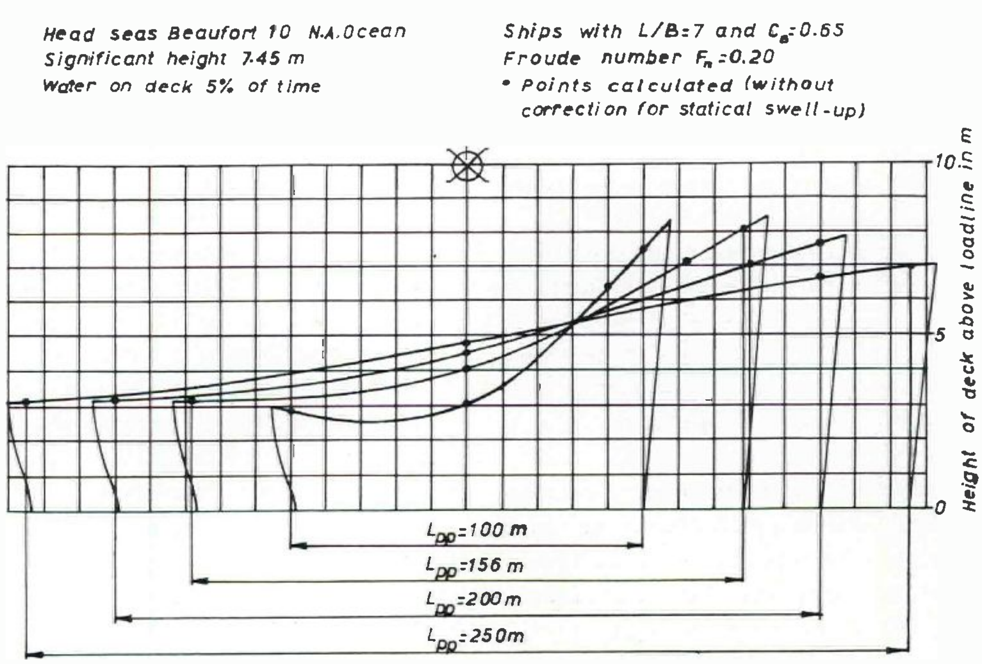

Fig. 1. Deckheight above water for equal probability of water on deck.

m_{2s} = second moment of the spectrum of the local relative motion in sq.m/sq.sec

For completeness, it may be noted that the probability density functions of the time-intervals between two successive water shipments and of the number of water shipments in a given time lapse may probably be described by an exponential distribution and a Poisson distribution respectively.

The studies as described in references [5], [6], [7] and [8] have in principle been made on basis of the Raleigh distribution in (1). The various aspects to be taken into account are as follows:

a. static swell-up consisting of sinkage, trim and height of the bow wave in still water (see Fig. 2);
b. dynamic swell-up consisting of a change in wave-amplitude as a result of the ship's vertical oscillation in the wave (see Fig. 2);
c. various other aspects such as: short-term predictions versus long-term predictions and the consequent choice of sea spectra, short-crestedness versus long-crestedness (see Fig. 3), systematic variation of the principal parameters such as ship's length, ship's speed and other ship parameters.

Special mention may be made of reference [8], which systematically examines by means of calculations the effect of ship's length, rate of speed, radius of longitudinal gyration, block coefficient and section shape (see Fig. 4) on the incidence of shipping water.

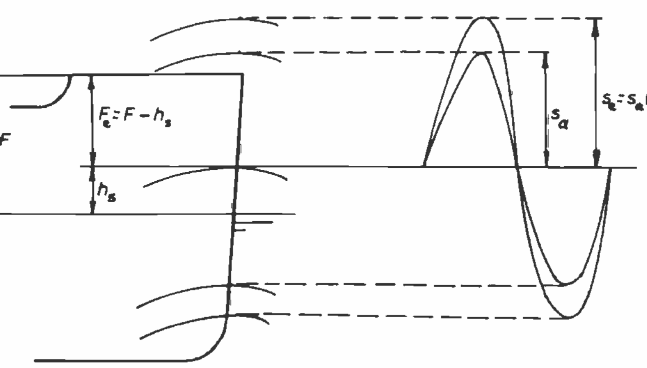

Fig. 2. Definition of statical and dynamical swell-up.

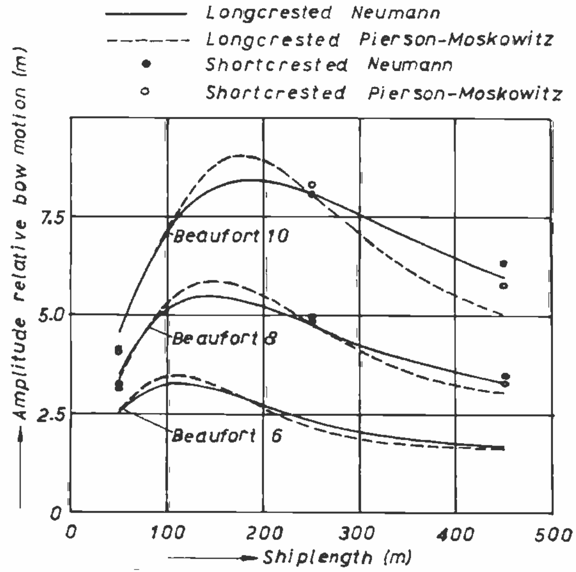

Fig. 3. (from ref. [5]): Bow motion in irregular head seas.

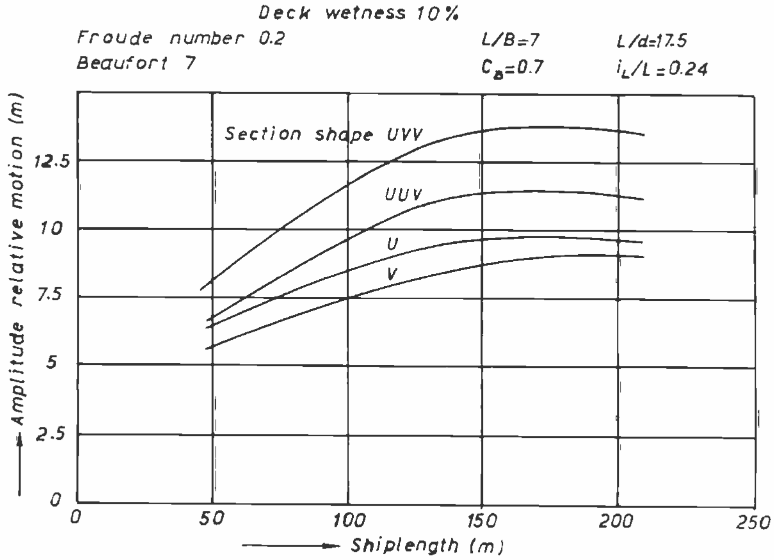

Fig. 4. (from ref. [8]): Curves of equal probability of immersion.

A different approach is found in reference [9] which seeks a very practical solution, but without making use of the spectral theory. An interesting aspect in it is the empirical method of assessing the influence of knuckle (see Fig. 5 and 6) using the following formula:

Equivalent freeboard (with knuckle) = actual freeboard (without knuckle) $\times f_0/f_k$ (5)

in which indices 0 and k represent respectively cases without knuckle and with knuckle whilst f is given by the following formula:

$$f = L/b \times h/D \times \sin\theta \qquad (6)$$

θ = minimum slope of section at knuckle or deck edge
L = distance from FP at which this minimum θ occurs
b = half beam at knuckle or deck edge at this section
h = height of knuckle or deck edge above keel at this section
D = depth of ship at this section

A source in which the correction factors for static and dynamic swell-up are quantified is found with Tasaki, who e.g. in reference [10] gives the following formula for static swell-up:

$$h_s = \frac{3}{4}\cdot\frac{B}{L_e}\cdot L\cdot F_n^2 \qquad (7)$$

where L_e represents the length of "entrance" on the waterline and F_n = Froude Number. An obvious deduction from this is:

$$F_e = F - h_s \qquad (8)$$

where F represents the local geometrical freeboard increased, if necessary, by the height of the bulwark. However, formula (7) is applicable only to a location in way of the bow wave and presents no solution to the rest of the ship's own wave system. Fig. 7 shows that the reduction in the geometrical freeboard caused by a static bow wave may have a considerable impact. Furthermore the degrees of sinkage and trim are unlikely to be correctly represented in the value of h_s. In general, however, the effect of trim is considered to be of minor importance and can therefore be neglected.

Various measurements have shown that Tasaki's bow wave correction yields good results. A case in point is the m.v. "S. A. van der Stel" as shown in Fig. 8.

In reference [10] Tasaki also gives a correction factor for the dynamic swell-up. Written as a fraction of s_a it reads:

$$h_d = \tfrac{1}{3}(c_b - 0.45)\,\omega_e\sqrt{L/g} \qquad (9)$$

with the following restrictions:

a. $0.16 < F_n < 0.29$
b. $0.6 \leqslant c_b \leqslant 0.8$
c. $1.6 < \omega_e^2 L/g < 2.6$

with

c_b = block coefficient
ω_e = (circle) frequency of encounter
s_a = amplitude of relative motion with regard to the undisturbed wave

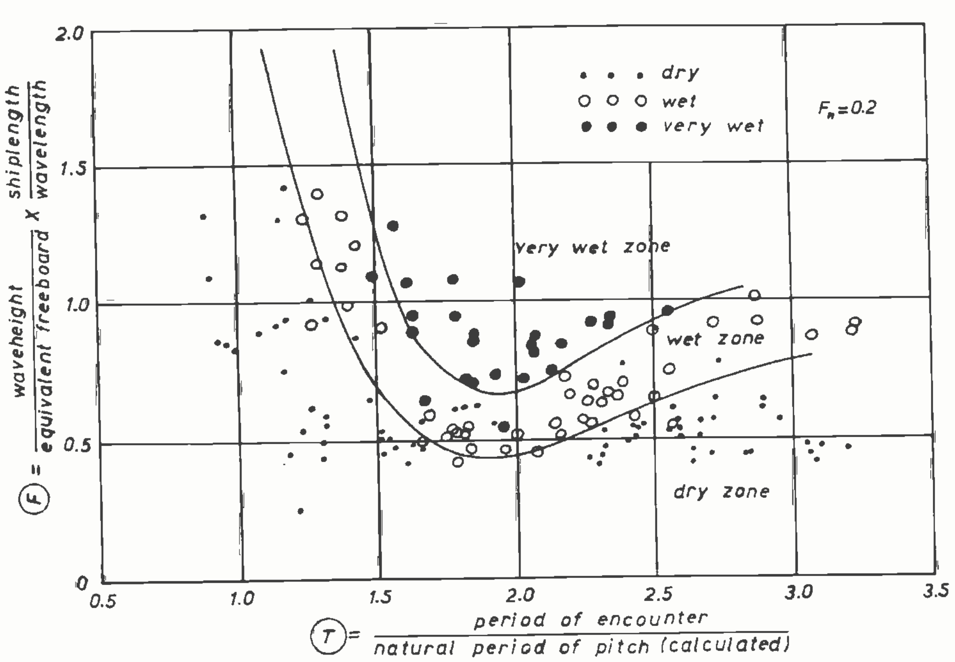

Fig. 5. (from ref. [9]): Non-dimensional plotting of wetness. All variants.

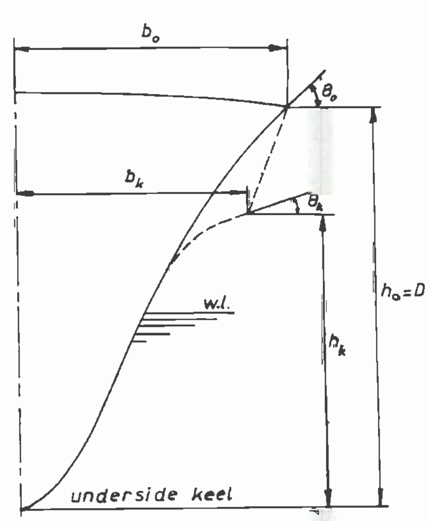

Fig. 6. (from ref. [9]): Definition of knuckle shape.

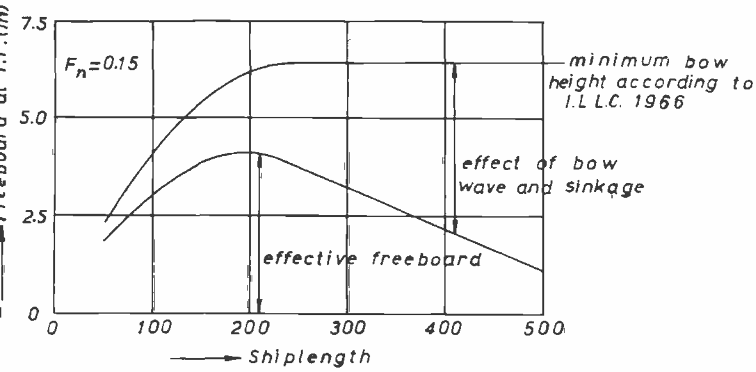

Fig. 7. (from ref. [5]): Bowheight and effective freeboard as function of shiplength.

This empirical formula is based on the results of forced oscillations with models in still water.

If strictly maintained, the restrictions, especially those mentioned in c. may render any practical application fairly useless. Although the abovementioned empirical formula (9) shows a fair measure of agreement with theoretical calculations (see Fig. 9) carried out on Lewis forms by Tasaki in reference [13], a comparison with a number of random results of other model tests turns out unfavourable.

A further study, aiming to obtain a better prediction of the dynamic swell-up, is certainly justified. In this connection may be referred to the more fundamental approach contained in references [11], [12] and [13], whereby [11] deals with the physical aspects of a non-oscillating ship in longitudinal regular waves and [12] tries out the theory by means of model tests.

The results showed a negative value for the dynamic swell-up in cases where relative motion was caused solely by vertical oscillation of the wave.

If h_d is expressed as a fraction of s_a and if s_a and h_d are taken to present a phase difference of 180°, the following relation is found:

$$s_e = s_a(1 + h_d) \tag{10}$$

Tasaki's approximate formula for the dynamic swell-up applies only to the bow. The theory in reference [11] leads one to expect that the dynamic swell-up decreases in a positive direction aft.

As regards the deck load caused by shipping water, reference [14] gives an interesting extension to formula (3) by including in the calculation the vertical acceleration of shipped water with regard to the deck. In a calculation example it is shown that the load depending on the ship's speed is considerably more than the load resulting from calculations based on static assumptions.

In so far as is known, reference [15], again from the hand of Tasaki, is the only reference going further into the aspect about the volume of shipped water. By means

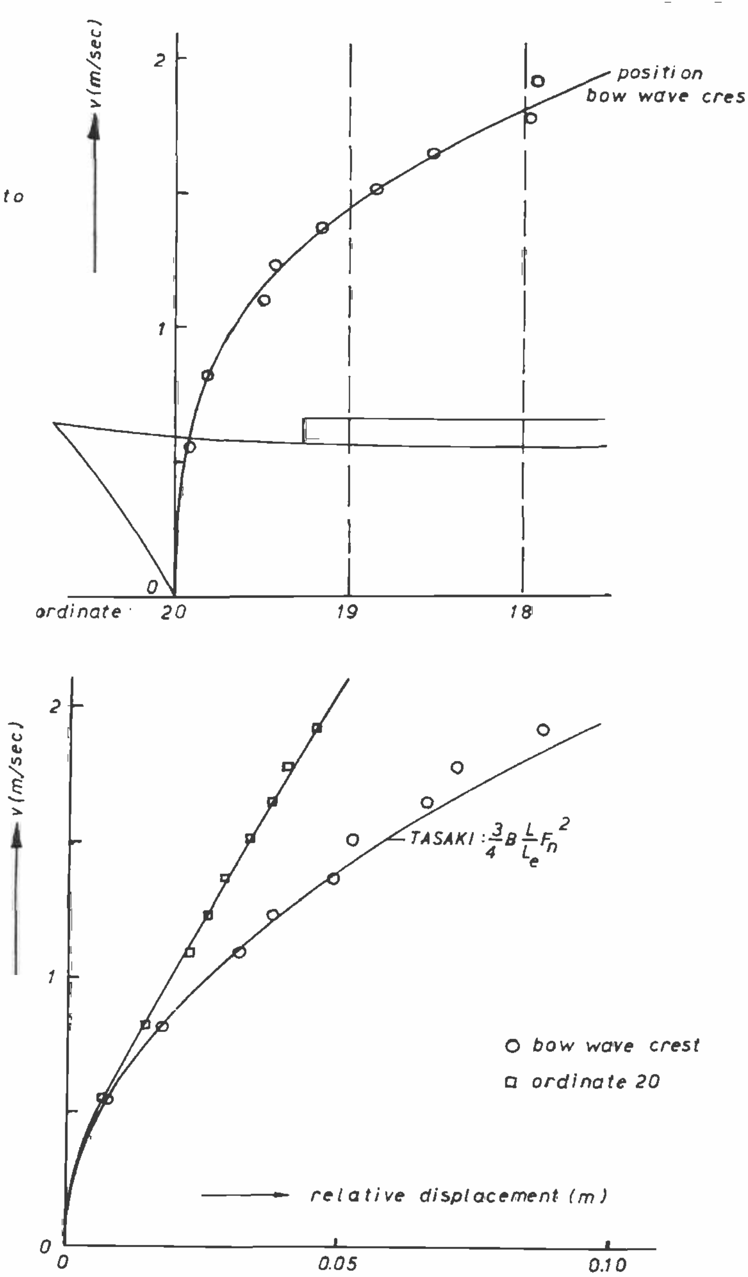

Fig. 8. Relative displacement in still water of a model of "m.s. van der Stel".

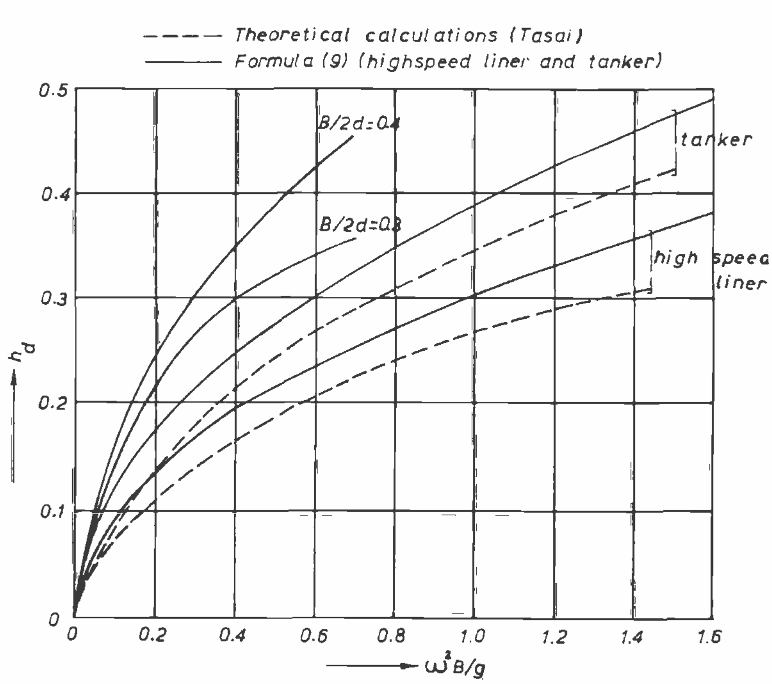

Fig. 9. (from ref. [10]: Comparison between measured and estimated swell-up of water surface at bow in forced oscillation tests.

of model tests with a tanker ($L = 190$ m, $c_b = 0.80$), whereby the shape of the bow varied with regard to flare, a semi-empirical formula was developed:

$$V = \tfrac{1}{2} v T_e s_e^2 (s_e/F_e - 1)^{5/2} \quad \text{voor} \quad s_e/F_e < 1.1 \qquad (11)$$

where:

V = volume of shipped water per oscillation in cu.m

v = ship's speed in m/sec

T_e = period of encounter in sec

However, the approximate formula (11) can only be applied to shipping water over the bow. Fig. 10 shows a correlation of the approximate formula with the results of model tests, and Fig. 11 gives a calculation example of the effect of v and F on V.

The present study, including the model tests and calculations, is based on a case of longitudinal waves for the following reasons:

a. It concerns generally a comparative study.
b. The number of calculations and tests should be kept limited, whereby in the case of calculations it should be taken into account that the accuracy of the relative motion will be very dubious as a result of the ship's rolling motion.
c. The stability properties, in particular the initi l stability, can play an important role in a ship's rolling behaviour.

In operating conditions, the initial stability can vary considerably, both statically and dynamically, which makes it to a certain degree an unpredictable factor.

In the special case of fishing-vessels, which are under the obligation to guarantee a safe working platform in certain sea conditions, proposals have been submitted to the IMCO concerning a "protected freeboard".

This protected freeboard is based on a certain probability of water being shipped in transverse irregular waves, which obviously is also a function of the initial stability.

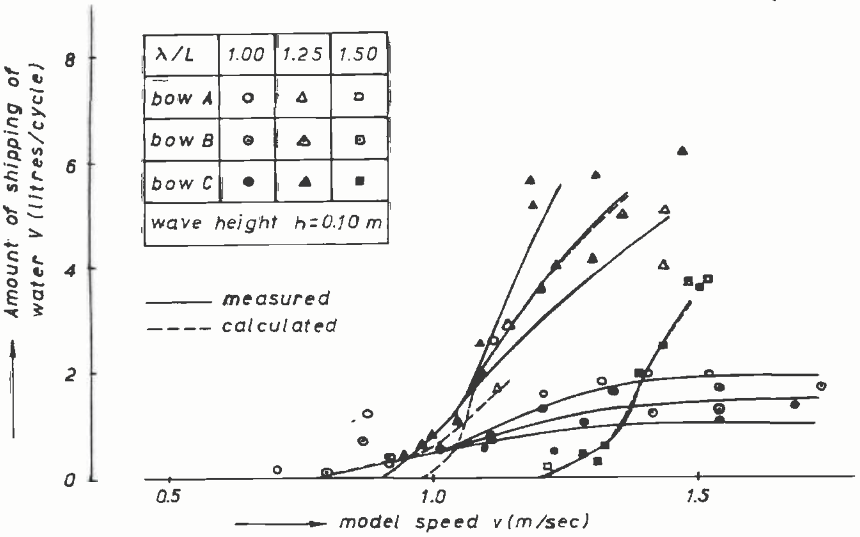

Fig. 10. (from ref. [15]): Amount of shipping of water per cycle.

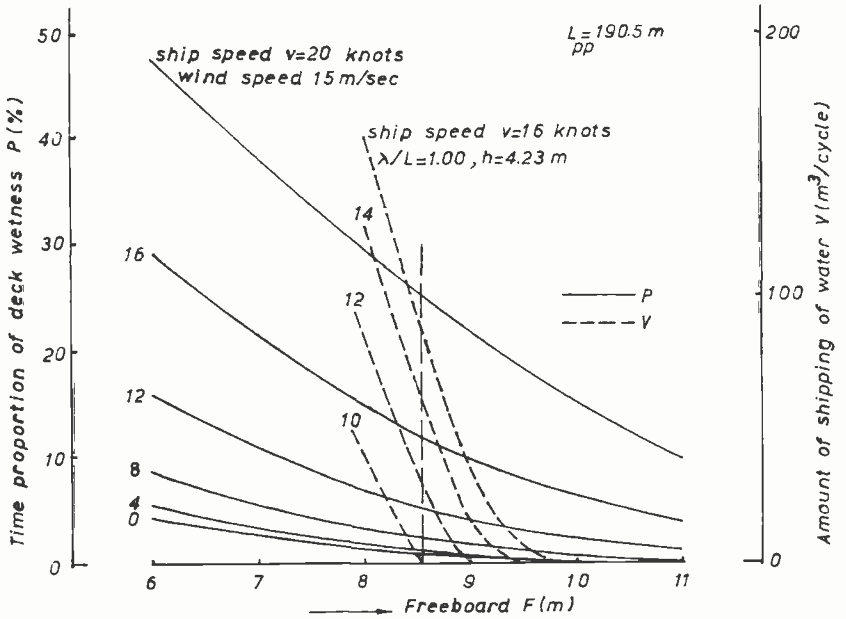

Fig. 11. (from ref. [15]): Influence of freeboard on time proportion of deck wetness and amount of shipping of water.

3 Development of a mathematical model

The theory developed below aims to determine the volume of shipped water per oscillation in longitudinal regular waves, it being assumed that the exposed deck has sufficient capacity to "absorb" the volume of water shipped.

Shipping of water occurs if (see Fig. 12):

$$v_n + v_t \cos\beta + v_l \sin\beta > 0 \qquad (12)$$

which may also be presented as:

$$v_t + v_l \,\mathrm{tg}\,\beta + v_n\sqrt{1+\mathrm{tg}^2\beta} > 0 \qquad (13)$$

If the relative motion is:

$$s = s_e \cos\omega_e t \qquad (14)$$

and using the following symbols:

- v = ship's speed
- s_e = amplitude of local effective relative motion
- F_e = local effective freeboard
- ω_e = (circle) frequency of encounter
- ω = wave circle frequency
- x_0 = amplitude of the surge motion
- r = wave amplitude
- ε = phase difference between wave and relative motion
- ε_x = phase difference between surge motion and wave
- g = gravitational acceleration
- t = time

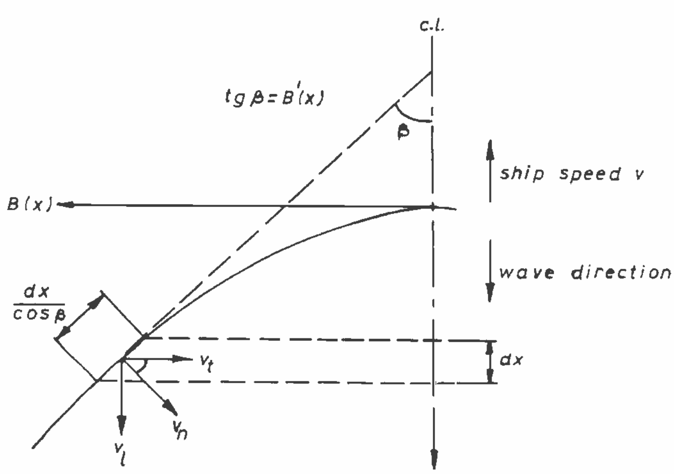

Fig. 12. Top view of exposed weather deck.

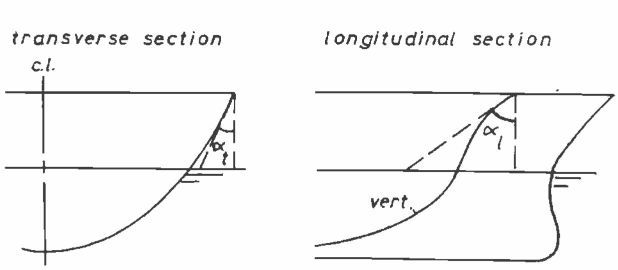

Fig. 13. Definition of transverse and longitudinal flare.

The speed components v_l, v_t and v_n can be written as follows, flare being represented by tg α_t and tg α_l and defined as indicated in Fig. 13:

$$v_l = v - x_0\omega_e \sin(\omega_e t + \varepsilon_x) + \omega r \cos(\omega_e t + \varepsilon) + s_e\omega_e \,\mathrm{tg}\,\alpha_l \sin\omega_e t \qquad (15)$$

The longitudinal speed component of a water particle in relation to a ship's coordinate system consists of four terms, namely: ship's speed, surge speed, orbital speed in the wave with disregard of the Smith-effect and a (negative) contribution from the longitudinal flare, which is only manifest in case of $\dot{s} > 0$ or in $-\varphi < \omega_e t < 0$ whereby $\varphi = \arccos \cdot F_e/s_e$

$$v_t = s_e\omega_e \,\mathrm{tg}\,\alpha_t \sin\omega_e t \qquad (16)$$

The transverse speed component of a water particle in relation to a ship's coordinate system consists of a (negative) contribution from the transverse flare, which is manifest only in case of $\dot{s} < 0$

$$v_n = \tfrac{2}{3}[g(s_e\cos\omega_e t - F_e)]^{1/2} \qquad (17)$$

The normal speed component v_n of a water particle in relation to a ship's coordinate system consists of the average outflow speed which is proportional to the root pressure-height above the exposed deck. According to [16], however, the effective pressure height is equal to $\frac{4}{9}(s_e\cos\omega_e t - F_e)$, because the basic equations are (Fig. 14):

$$\begin{aligned} y &= (u - \sqrt{gz})t \\ u &= 2(\sqrt{gz_0} - \sqrt{gz}) \end{aligned} \qquad (18)$$

Substitution for u yields:

$$y = (2\sqrt{gz_0} - 3\sqrt{gz})t \qquad (19)$$

and the equation $y = 0$ yields:

$$z = \tfrac{4}{9}z_0 \qquad (20)$$

The volume of water V which per oscillation is shipped over the sides can now be presented as follows:

$$\begin{aligned} V &= 2\int_x \frac{dx}{\cos\beta}\int_t (v_n + v_t\cos\beta + v_l\sin\beta)(s_e\cos\omega_e t - F_e)\,dt \\ &= 2\int_x dx\int_t (v_t + v_l\,\mathrm{tg}\,\beta + v_n\sqrt{1+\mathrm{tg}^2\beta})(s_e\cos\omega_e t - F_e)\,dt \end{aligned} \qquad (21)$$

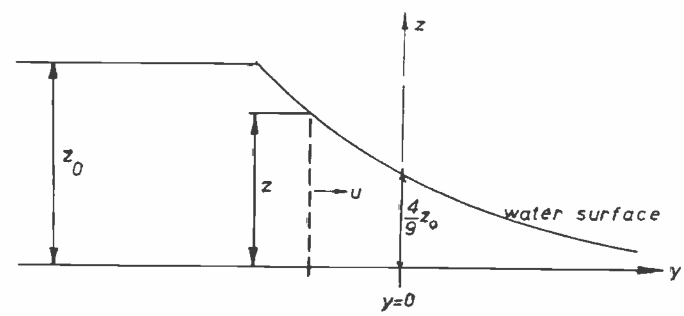

Fig. 14. (from ref. [16]): Effective height of pressure.

Substitution for the speed components yields:

$$V=2\int_{x=-\varphi/k}^{x=\varphi/k}\mathrm{d}x\left[\frac{8}{27}\sqrt{g(1+\mathrm{tg}^2\beta)}\int_{t=-\varphi/\omega_e}^{t=\varphi/\omega_e}(s_e\cos\omega_e t-F_e)^{3/2}\,\mathrm{d}t+\right.$$

$$+\,\mathrm{tg}\,\beta\int_{t=-\varphi/\omega_e}^{t=\varphi/\omega_e}(s_e\cos\omega_e t-F_e)\{v-x_0\omega_e\sin(\omega_e t+\varepsilon_x)+\omega r\cos(\omega_e t+\varepsilon)\}\,\mathrm{d}t+$$

$$\left.+\,s_e\omega_e(\mathrm{tg}\,\alpha_t+\mathrm{tg}\,\alpha_l\,\mathrm{tg}\,\beta)\int_{t=-\varphi/\omega_e}^{t=\varphi/\omega_e}(s_e\cos\omega_e t-F_e)\sin\omega_e t\,\mathrm{d}t\right] \tag{22}$$

Working out the integrals gives:

$$\mathrm{tg}\,\beta\int_{t=-\varphi/\omega_e}^{t=\varphi/\omega_e}(s_e\cos\omega_e t-F_e)\{v-x_0\omega_e\sin(\omega_e t+\varepsilon_x)+\omega r\cos(\omega_e t+\varepsilon)\}\,\mathrm{d}t=$$

$$=\frac{2vF_e\,\mathrm{tg}\,\beta}{\omega_e}(\mathrm{tg}\,\varphi-\varphi)+\left(\frac{F_e\omega r\cos\varepsilon\,\mathrm{tg}\,\beta}{\omega_e}+x_0F_e\sin\varepsilon_x\,\mathrm{tg}\,\beta\right)(\varphi\sec\varphi-\sin\varphi)=$$

$$=\frac{2vF_e\,\mathrm{tg}\,\beta}{\omega_e}\left\{\left(\frac{s_e^2}{F_e^2}-1\right)^{1/2}-\arccos\frac{F_e}{s_e}\right\}+$$

$$+\left(\frac{F_e\omega r\cos\varepsilon\,\mathrm{tg}\,\beta}{\omega_e}+x_0F_e\sin\varepsilon_x\,\mathrm{tg}\,\beta\right)\left\{\frac{s_e}{F_e}\arccos\frac{F_e}{s_e}-\left(1-\frac{F_e^2}{s_e^2}\right)^{1/2}\right\} \tag{23}$$

and $$\frac{8}{27}\sqrt{g(1+\mathrm{tg}^2\beta)}\int_{t=-\varphi/\omega_e}^{t=\varphi/\omega_e}(s_e\cos\omega_e t-F_e)^{3/2}\,\mathrm{d}t=$$

$$\approx\frac{28}{81\omega_e}\sqrt{g(1+\mathrm{tg}^2\beta)}\cdot F_e^{3/2}\,\frac{\varphi(1-\cos\varphi)^{3/2}}{\cos^{3/2}\varphi}\approx\frac{28}{81\omega_e}\sqrt{g(1+\mathrm{tg}^2\beta)}\cdot F_e^{3/2}\left(\frac{s_e}{F_e}-1\right)^{3/2}\arccos\frac{F_e}{s_e} \tag{24}$$

and $$s_e\omega_e(\mathrm{tg}\,\alpha_t+\mathrm{tg}\,\alpha_l\,\mathrm{tg}\,\beta)\int_{t=-\varphi/\omega_e}^{t=\varphi/\omega_e}(s_e\cos\omega_e t-F_e)\sin\omega_e t\,\mathrm{d}t=$$

$$=-\tfrac{1}{2}F_e^2(\mathrm{tg}\,\alpha_t+\mathrm{tg}\,\alpha_l\,\mathrm{tg}\,\beta)\sec^2\varphi(1-\cos\varphi)^2=-\tfrac{1}{2}F_e^2(\mathrm{tg}\,\alpha_t+\mathrm{tg}\,\alpha_l\,\mathrm{tg}\,\beta)\left(\frac{s_e}{F_e}-1\right)^2 \tag{25}$$

Formula (24) is an approximate solution presented in reference [17] as follows:

$$\int_{t=-\varphi/\omega_e}^{t=\varphi/\omega_e}(\cos\omega_e t-F_e/s_e)^{3/2}\,\mathrm{d}t=\frac{1}{\omega_e}\int_{\omega_e t=-\varphi}^{\omega_e t=\varphi}(\cos\omega_e t-\cos\varphi)^{3/2}\,\mathrm{d}(\omega_e t)=$$

$$=\frac{2}{\omega_e}\int_{\omega_e t=0}^{\omega_e t=\varphi}(\cos\omega_e t-\cos\varphi)^{3/2}\mathrm{d}(\omega_e t)\approx\frac{1}{\omega_e}(1.182-0.0439\varphi)\varphi(1-\cos\varphi)^{3/2}$$

with the practical approximation of:

$$\frac{7}{6\omega_e}\varphi(1-\cos\varphi)^{3/2}$$

The rate of error in the approximate solution is $<5\%$, which is in every way acceptable.

The total result can also be presented as follows:

$$V=2\int_{x=-\varphi/k}^{x=\varphi/k}\mathrm{d}x\left(\frac{\mathrm{d}V_1}{\mathrm{d}x}+\frac{\mathrm{d}V_2}{\mathrm{d}x}+\frac{\mathrm{d}V_3}{\mathrm{d}x}+\frac{\mathrm{d}V_4}{\mathrm{d}x}+\frac{\mathrm{d}V_5}{\mathrm{d}x}\right) \tag{26}$$

where:

$$\frac{\mathrm{d}V_1}{\mathrm{d}x}=\frac{2vF_e\,\mathrm{tg}\,\beta}{\omega_e}\left\{\left(\frac{s_e^2}{F_e^2}-1\right)^{1/2}-\arccos\frac{F_e}{s_e}\right\}$$

$$\frac{\mathrm{d}V_2}{\mathrm{d}x}=\frac{F_e\omega r\cos\varepsilon\,\mathrm{tg}\,\beta}{\omega_e}\left\{\frac{s_e}{F_e}\arccos\frac{F_e}{s_e}-\left(1-\frac{F_e^2}{s_e^2}\right)^{1/2}\right\}$$

$$\frac{\mathrm{d}V_3}{\mathrm{d}x}=x_0F_e\sin\varepsilon_x\,\mathrm{tg}\,\beta\left\{\frac{s_e}{F_e}\arccos\frac{F_e}{s_e}-\left(1-\frac{F_e^2}{s_e^2}\right)^{1/2}\right\}$$

$$\frac{\mathrm{d}V_4}{\mathrm{d}x} = -\tfrac{1}{2}F_e^2(\mathrm{tg}\,\alpha_t + \mathrm{tg}\,\alpha_l\,\mathrm{tg}\,\beta)\left(\frac{s_e}{F_e} - 1\right)^2$$

$$\frac{\mathrm{d}V_5}{\mathrm{d}x} = \frac{28}{81\omega_e}\sqrt{g(1+\mathrm{tg}^2\beta)}\cdot F_e^{3/2}\left(\frac{s_e}{F_e} - 1\right)^{3/2}\arccos\frac{F_e}{s_e}$$

In which V_1 represents the contribution as a result of the ship's speed, V_2 the contribution as a result of the orbital speed in the wave, V_3 the contribution as a result of the surge speed, V_4 the contribution as a result of the flare and V_5 the contribution as a result of the pressure height. By way of detail may be added that $V_1 = 0$ if $v = 0$ and $V_3 = 0$ if $\mathrm{tg}\,\alpha_t = \mathrm{tg}\,\alpha_l = 0$.

If necessary, a further refinement can be obtained by correcting the longitudinal flare for the influence of the effective angle of pitch.

In the special case of a certain effective breadth B_e being available for $x = 0$, the volume of water shipped over the bow is (see Fig. 15):

$$V = B_e\left[\int\limits_{t=-\varphi/\omega_e}^{t=\varphi/\omega_e}(s_e\cos\omega_e t - F_e)\left\{v - x_0\omega_e\sin(\omega_e t + \varepsilon_x) + \omega r\cos(\omega_e t + \varepsilon) + \right.\right.$$

$$\left.\left. + \frac{8}{27}\sqrt{g}(s_e\cos\omega_e t - F_e)^{1/2} + s_e\omega_e\,\mathrm{tg}\,\alpha_l\sin\omega_e t\right\}\mathrm{d}t\right] \qquad (27)$$

Elaboration of this formula yields the known solution of Formula (26) with the substitutions $\mathrm{tg}\,\alpha_t = 0$ and $\tfrac{1}{2}B_e = \mathrm{tg}\,\beta\cdot\mathrm{d}x\,(\beta = \pi/2)$:

$$V = B_e\left[\frac{2vF_e}{\omega_e}\left\{\left(\frac{s_e^2}{F_e^2} - 1\right)^{1/2} - \arccos\frac{F_e}{s_e}\right\} + \right.$$

$$+\left[\frac{F_e\omega r\cos\varepsilon}{\omega_e} + x_0F_e\sin\varepsilon_x\right)\left\{\frac{s_e}{F_e}\arccos\frac{F_e}{s_e} - \left(1 - \frac{F_e^2}{s_e^2}\right)^{1/2}\right\}$$

$$\left. - \tfrac{1}{2}F_e^2\,\mathrm{tg}\,\alpha_l\left(\frac{s_e}{F_e} - 1\right)^2 + \frac{28}{81\omega_e}\sqrt{g}\cdot F_e^{3/2}\left(\frac{s_e}{F_e} - 1\right)^{3/2}\arccos\frac{F_e}{s_e}\right] \qquad (28)$$

This case does not require any integration over the length-co-ordinate, which is a considerable simplification, for numerical integration over x is a laborious procedure considering that F_e, s_e, ε, $\mathrm{tg}\,\alpha_t$, $\mathrm{tg}\,\alpha_l$ and $\mathrm{tg}\,\beta$ are, in principle, functions of x. A case is also conceivable in which water is shipped both over the sides and over the bow (see Fig. 16). In such a case the volumes can be added up, whereby for water shipped over the sides integration over x runs from $x = 0$.

It should be noted that $V = 0$ in case $S_e/F_e \leqslant 1$ or if the flow rate has no positive value.

In order to assess the ship's behaviour with regard to shipping of water in irregular waves, the formulae for V can be simply converted into V/r whereby:

$$s_e/F_e = s_e/r\cdot r/F_e \qquad (29)$$

which implies that if the transfer function of the relative motion is known, the transfer function of V can be calculated with the potential use of the spectral theory. Fig. 17 shows an example of a transfer function for a specific $F_e/r > 1$.

If it is assumed that the Rayleigh distribution applies, the frequency curves of V can be determined whereby r (or F_e/r) functions as a parameter (see Fig. 18). It is now possible to determine numerically the probability of excess for an arbitrary value of V_j as follows:

$$F(V_j) = \sum_{r_i = \frac{1}{2}\Delta r_i}^{r_i = \frac{F_e}{(s_e/r)_{max}} - \frac{1}{2}\Delta r_i}\frac{r_i}{m_{0_r}}\exp\left(-\frac{r_i^2}{2m_{0_r}} - \frac{V_j^2}{2m_{0V_{r_i}}}\right)\Delta r_i \qquad (30)$$

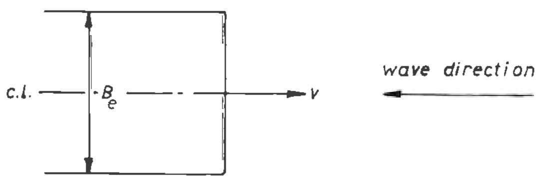

Fig. 15. Definition of effective breadth.

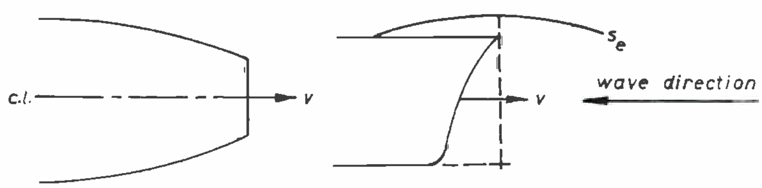

Fig. 16. Particular bow shape.

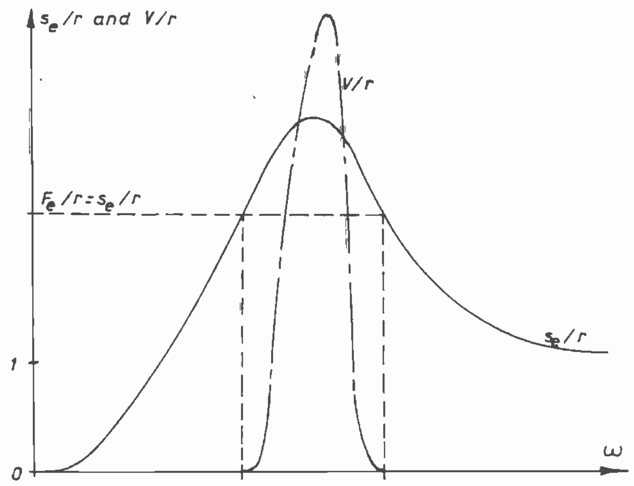

Fig. 17. Response curves of s_e and V.

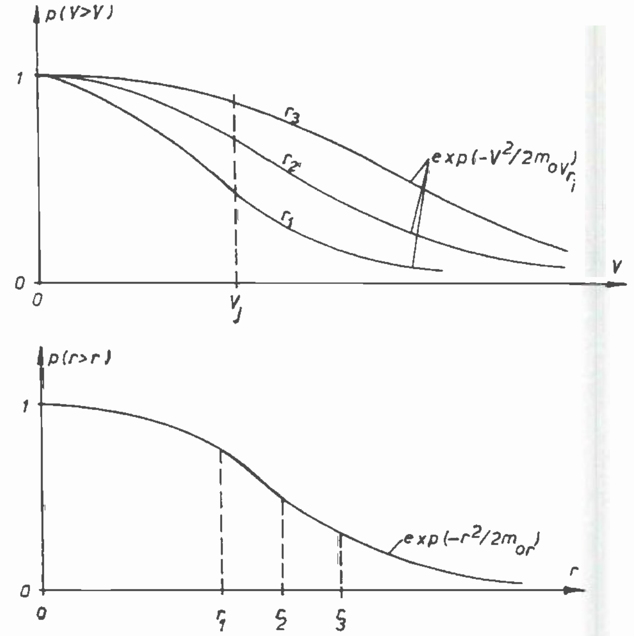

Fig. 18. Distribution functions of r and V.

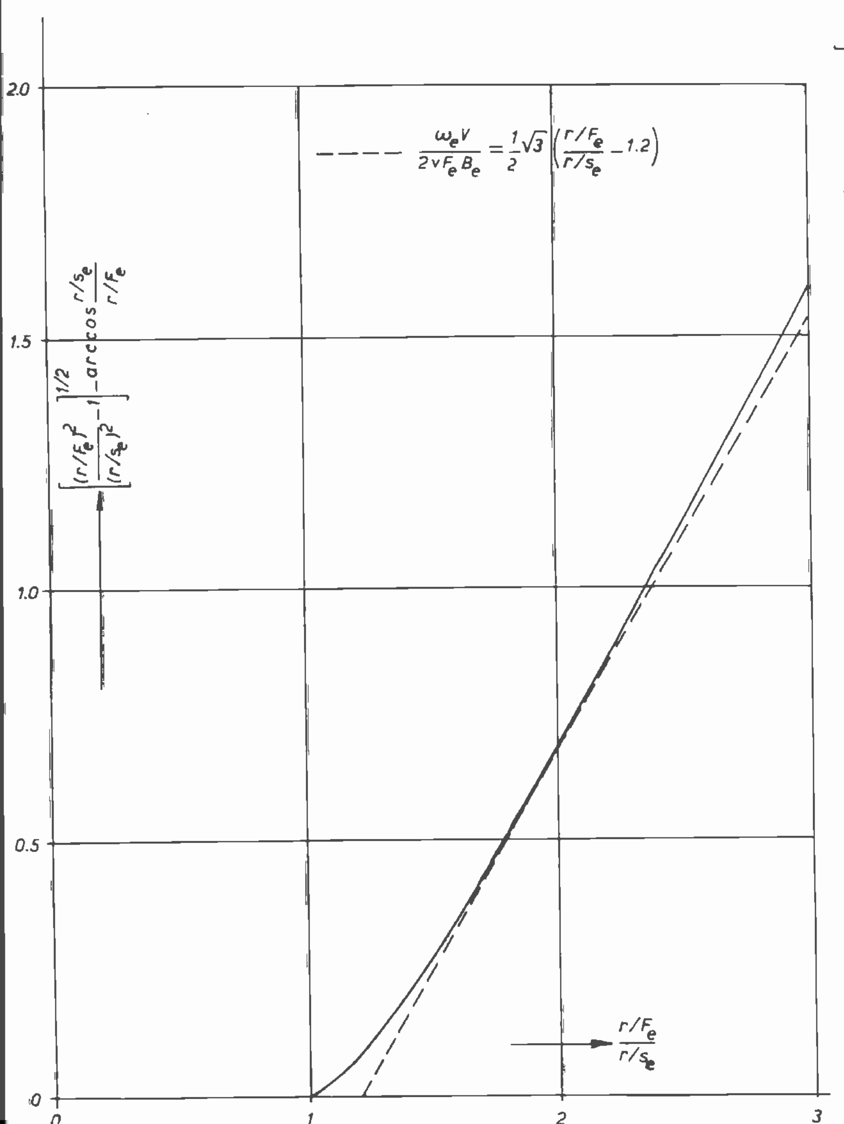

Fig. 19. Non-linear behaviour of the non-dimensional ship speed dependent term of the amount of shipping of water.

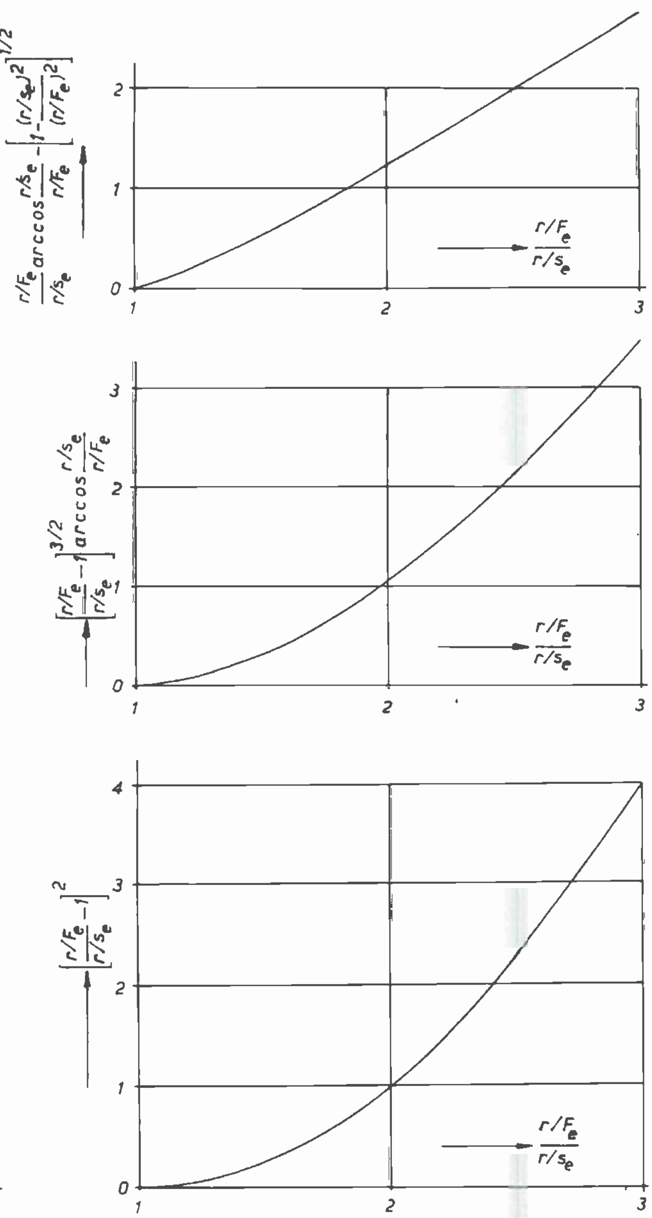

Fig. 20. Relationship between V-contributions and wave height.

By repeating this calculation for other V_j values the $F(V)$ curve for the relevant F_e value can be found. However, this approach is scientifically not correct, because V being not linearly dependent on the wave amplitude r, the superposition principle cannot be applied.

This aspect has been further examined in Fig. 19, where the contribution to V resulting from the ship's speed has been determined as a function of the wave amplitude. The dimensionless value of $(\omega_e V)/(2vF_eB_e)$ has been plotted against $(r/F_e)/(r/s_e)$, it being assumed that r/s_e is constant. The graph shows clearly that on approximation there is a linear relation for higher values of S_e/F_e.

The indicated straight line touches the curve in the point corresponding to $S_e/F_e = 2$ and has a threshold value of $S_e = 1.2F_e$. A linear approximation, however, is of no practical value because it is inadequate in cases where $S_e/F_e \leqslant 1.5$.

Although of secondary importance, the other contributions to V have analogously been determined as a function of the wave amplitude and presented in Fig. 20. It shows that here too the above reasoning is to a greater or lesser degree valid.

An approximation which offers possibilities can be derived from reference [18].

The proposed method is based on a quasi-stationary consideration whilst assuming quasi-harmonic oscillations. By means of the spectral theory the following basic formula has been derived:

$$\bar{V} = \left(\frac{m_{2r}}{m_{0r}}\right)^{1/2} \int_{\omega=0}^{\omega=\infty} \mathrm{d}\omega \int_{r=0}^{r=\infty} V(r,\omega) \cdot p(r,\omega)\, \mathrm{d}r \quad (31)$$

$\bar{V}$ = average volume of water shipped per time unit (cu.m/sec)

$V(r,\omega)$ = to be determined according to formula (26)

$$p(r,\omega) = \frac{r^2}{(2\pi m_{0r} M)^{1/2}} \exp \left[-\frac{r^2}{2M}(m_{2r} - 2m_{1r}\omega + m_{0r}\omega^2) \right]$$

$$\text{with} \quad m_{nr} = \int_0^\infty \omega^n S(\omega)\, \mathrm{d}\omega \quad \text{and}$$

$$\text{and} \quad M = m_{0r} m_{2r} - m_{1r}^2 \quad (32)$$

Only in case $V(r,\omega)$ is linearly dependent upon the wave amplitude r there is an exact solution to the double integral of formule (31). Consequently, application in the context of shipping of water requires a numerical solution.

4 Presentation and analysis of model-test results and calculations

In order to obtain an idea of the degree of accuracy of the mathematical model, model tests have been carried out to a bulk carrier with an adapted bow in regular and irregular longitudinal waves as described in reference [19]. The model tests in regular waves have been carried out for 5 frequencies and 3 wave heights viz. $h = 3.50$ m, $h = 3.84$ m and $h = 4.25$ m.

The response functions show that the water-shipment phenomenon acts as a filter and that the frequency range is very limited namely $0.42 < \omega < 0.55$ in the case in question.

The tests have been carried out for a ship's speed of approximately 17 knots.

Based on the measured values of the effective relative motion S_e and freeboard F_e, supplemented with other necessary data, the response functions of V have also been calculated for the three measured wave heights. Subsequently, two alternatives have been elaborated, namely:

a. Based on F_{e1}, where F_{e1} respresents the effective freeboard as determined from the mean relative motion at the location concerned.

b. Based on F_{e2}, where F_{e2} represents the effective freeboard as determined from the bow wave in still water at the location concerned.

The number of locations where the relative motion was measured produced insufficient information on which to make an accurate calculation of the volume of shipped water per oscillation. Thus, only an approximate calculation had to be accepted. It should also be noted that the measuring points and consequently also the corresponding calculated points are limited in number. This means that curves connecting measuring points or calculated points are mainly serving for clearness and as a trend indication (the same goes for all figures relating to comparisons between experiment and calculation). The results presented in Fig. 21 show clearly that the calculated responses are 2 to 3 times higher than the measured values, although the trend does appear comparable. It should also be noted in this connection that the calculations only include contributions resulting from ship's speed and orbital speed in the wave. The term V_5, which allows for the effect of pressure height, has been neglected, because it only increased V by approximately 10%, whilst, moreover, the correctness of making any allowance for V_5 remains dubious.

Since the modified bow has perpendicular sides, the term V_4, which depends upon longitudinal and transverse flare, automatically comes to nil.

The term V_3, allowing for the effect of the surge motion, has also been neglected, the more so because during the model tests surge amplitude and associated phase difference were not measured.

To examine the sensitivity of the calculation with regard to the value of $[S_e - F_e]$, use has been made of the data in [19], where the transfer function of S_e/r has also been determined from irregular waves by means of the following relation:

$$s_a/r = [S_s(\omega)/S_r(\omega)]^{1/2} \qquad (33)$$

in which

$S_s(\omega)$ = spectrum of the relative motion
$S_r(\omega)$ = wave spectrum (as a function of ω)

From the data thus obtained the response curves for V have been calculated and presented in Fig. 22. It is clear that the agreement with the measured response, particularly in the case of F_{e1}, is appreciably closer. This leads to the conclusion that minor differences in S_e and/or F_e may have a considerable impact on the results. Fig. 23, in which the full line has been determined according to formula (33), shows clearly that it concerns a reduction in the S_e-value of approximately 10–15%. However, it is hardly to be expected that a greater degree of accuracy can be obtained in determining the S_e value than in the present case. The same reasoning applies, though perhaps to a less degree, when determining the F_e-value.

From this it would follow that it is not realistic to expect that an accurate prediction of the volume of shipped water should be within the range of possibilities.

Fig. 24 shows the effect of a variation of the ship's speed v whilst the other parameters remain constant.

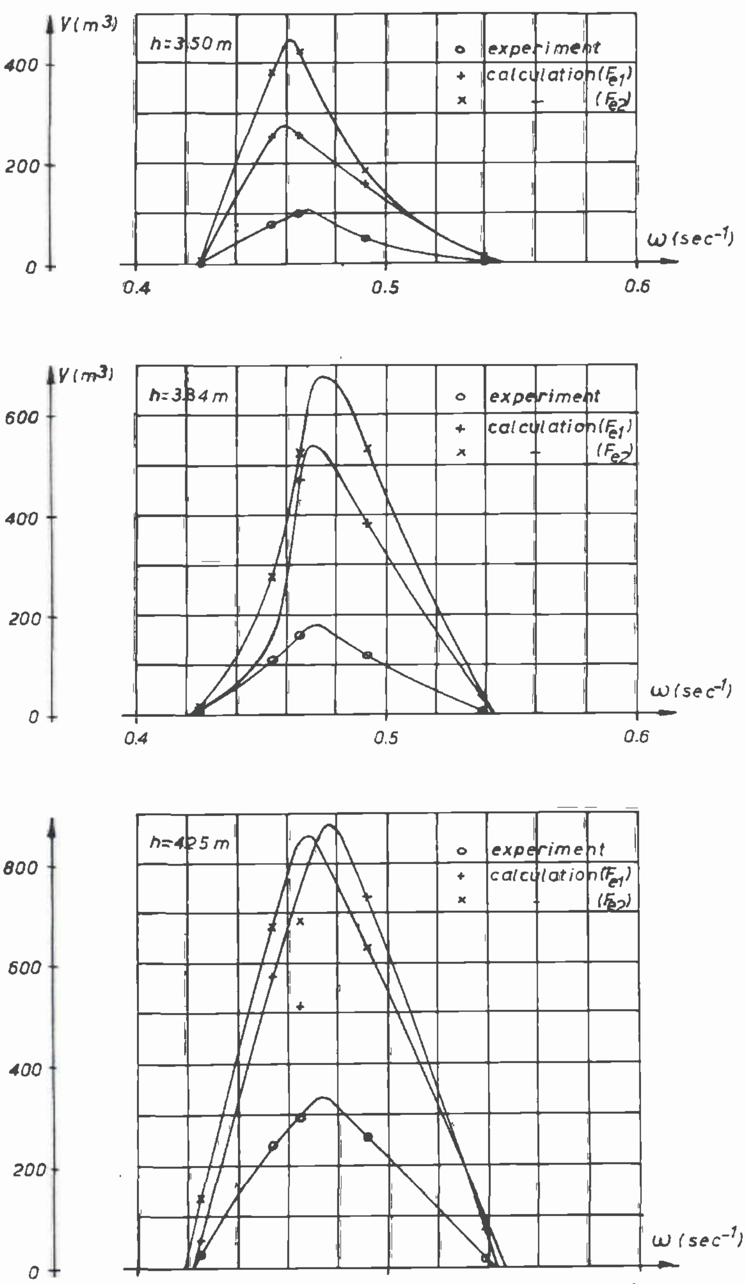

Fig. 21. Response curves of V.

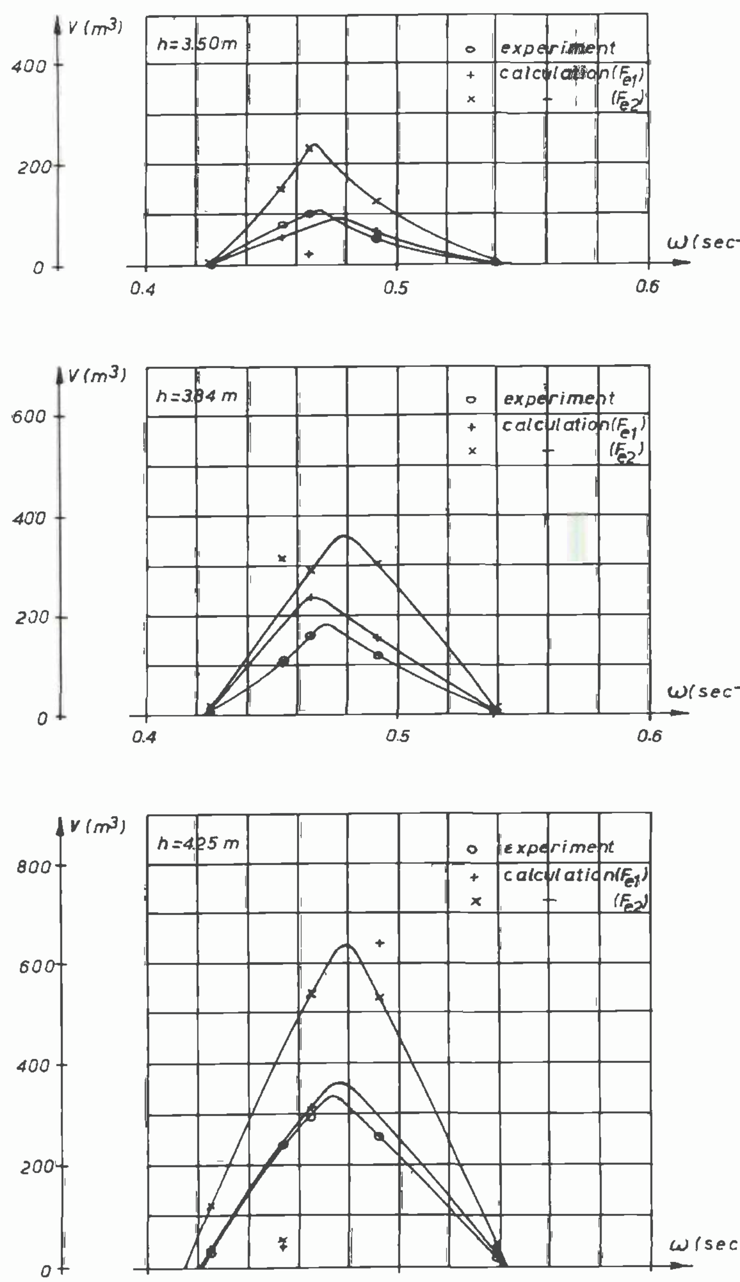

Fig. 22. Response curves of V.

In a wave height of $h = 3.50$ m ($v = 17$ knots, $\omega = 0.455$ rad/sec) a test has also been carried out with a reduced freeboard (height of forecastle above the water) notably with a freeboard of 8.36 m instead of 9.57 m applied in the other tests. The approximated calculated value of V amounts to 660 cu.m (based on F_{e2}) as against a measured value of 277 cu.m.

The case of $v = 0$ has been examined in a wave height of $h = 10.26$ m and a wave frequency near to the natural pitch period ($\omega = 0.644$ rad/sec). The approximated calculated values of V amount to 259 cu.m (based on F_{e1}) and to 148 cu.m (based on F_{e2}) as against a measured value of 455 cu.m. It is noteworthy that in this special case the calculated value is 2 to 3 times less than the measured value.

Apart from tests in regular waves, the theory has also been verified by means of model tests in irregular waves with the same speed of approximately 17 knots. The wave spectrum corresponded to 9 Beaufort (see Fig. 26). The mean volume of water actually shipped per oscillation amounted to 116 cu.m. Based on the measured response curves for V (see Fig. 25) the water-shipment spectra have been calculated for the relative wave heights (see Fig. 27), from which subsequently the corresponding m_{0v} values were determined (see Table 1).

Table 1.

r_i (m)	$m_{0v_{r_i}}$ (m^6)	m_{0r} (m^2)
1.75	760	2.592
1.92	2224	2.592
2.125	7300	2.592

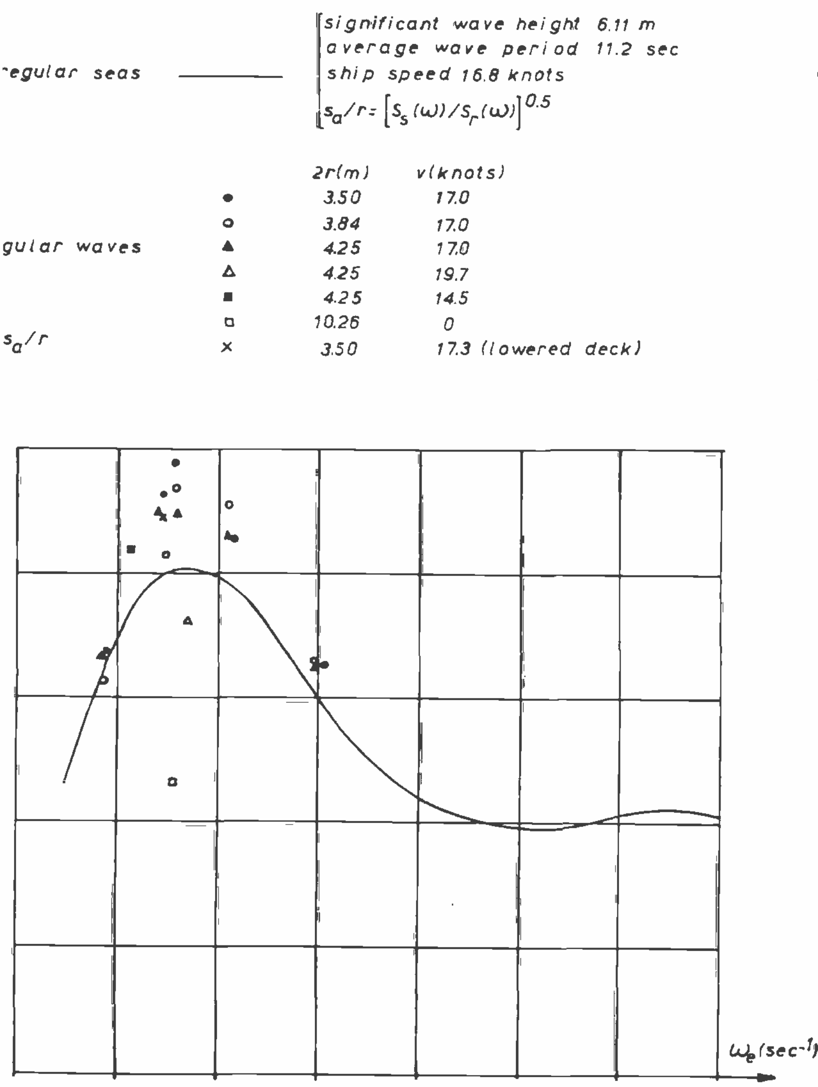

Fig. 23. (from ref. [19]): Response of relative motion at the stem.

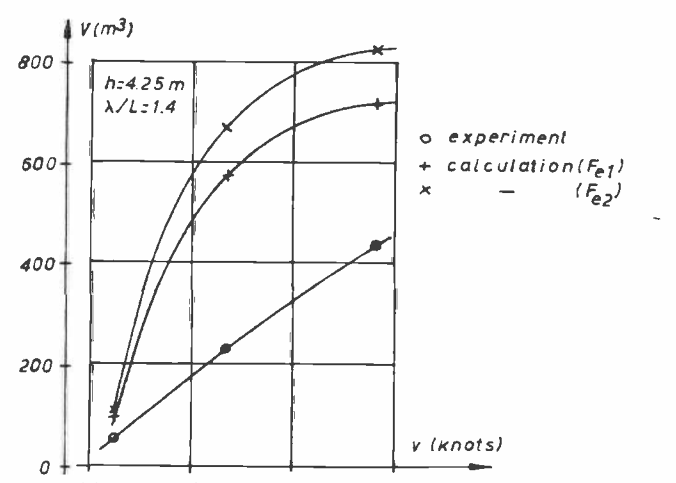

Fig. 24. Shipment of water as function of ship speed.

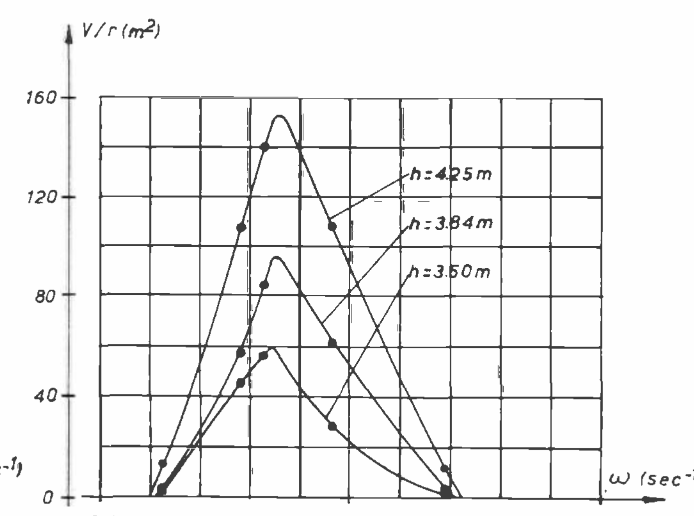

Fig. 25. Experimental response curves of V.

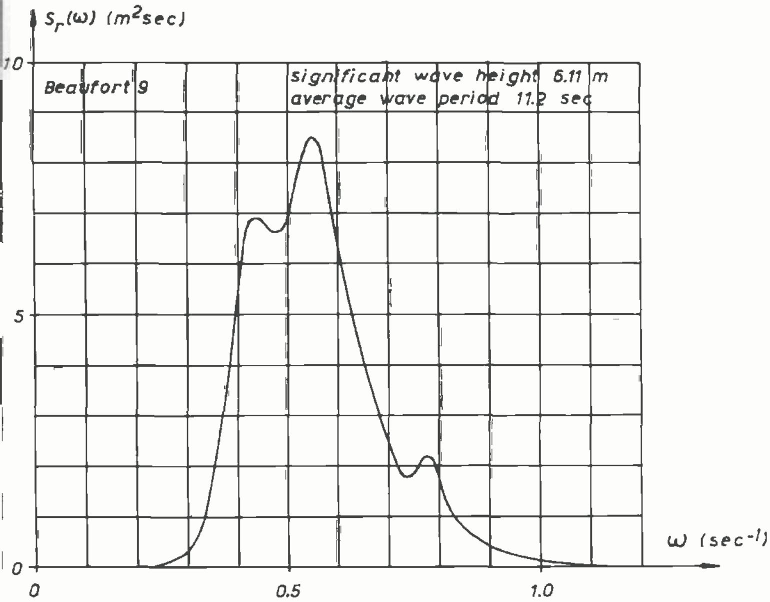

Fig. 26. (from ref. [19]): Measured wave spectrum.

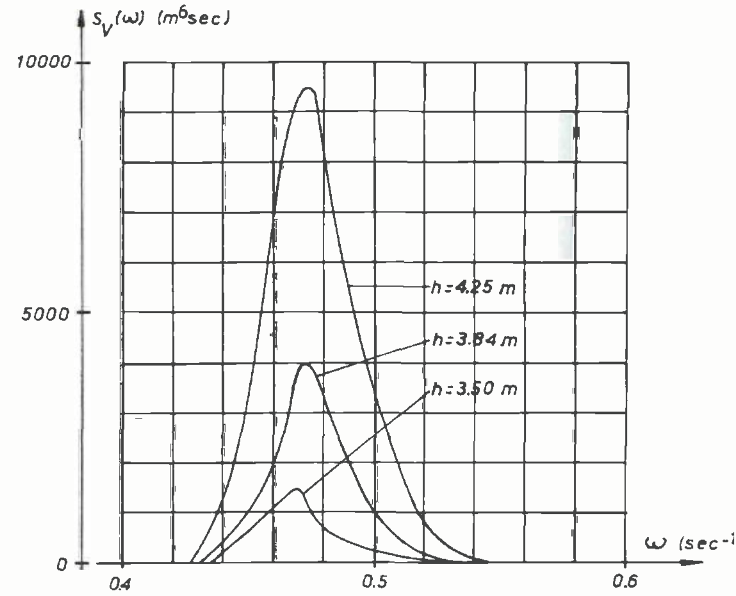

Fig. 27. Calculated spectra of shipment of water.

The m_{0_v} values for wave heights upwards of ~ 5 m have been obtained by extrapolation (see Fig. 28). The frequency distribution of V has been assessed on basis of formula (30) and with $m_{0_r} = 2.592$ sq.m. From this $F(V)$ curve (see Fig. 29) it has been calculated that the mean volume of water shipped per oscillation amounts to 102 cu.m which shows a reasonable agreement with the measured value of 116 cu.m. As regards the probability of shipping water, however, there is a discrepancy between the tested value of 0.37 and the calculated value of 0.60.

The laborious calculating procedure based on formula (31) has for the present been left aside, but it will be verified at a later stage.

The value of Tasaki's formula for shipping of water in regular waves has finally been verified by means of calculations according to formula (11) based on F_{e1}. The results of these calculations are contained in Tables 2 and 3.

It should be noted in this connection that the S_e/F_e values were in the range of $1.1 < S_e/F_e < 1.8$ whereas Tasaki's proposed approximation formula was, in principle, valid for $1.0 < S_e/F_e < 1.1$ i.e. for very minor water shipments.

In order to obtain confirmation of some of the provisional conclusions and also to study certain aspects in more detail, additional model tests were made as reported in reference [20]. The model used is again a bulk car-

Table 2.

	$h = 3.50$ m	$h = 3.84$ m	$h = 4.25$ m	
$\lambda/L = 1.0$	$V = 3.6$ m^3 $V = 3.8$ m^3	$V = 7.0$ m^3 $V = 21.8$ m^3	$V = 17.5$ m^3 $V = 44.5$ m^3	experiment Tasaki
$\lambda/L = 1.2$	$V = 49.4$ m^3 $V = 145$ m^3	$V = 119$ m^3 $V = 358$ m^3	$V = 260$ m^3 $V = 1635$ m^3	experiment Tasaki
$\lambda/L = 1.34$	$V = 99.1$ m^3 $V = 83.1$ m^3	$V = 161$ m^3 $V = 706$ m^3	$V = 298$ m^3 $V = 630$ m^3	experiment Tasaki
$\lambda/L = 1.4$	$V = 78.5$ m^3 $V = 214$ m^3	$V = 110$ m^3 $V = 79.0$ m^3	$V = 230$ m^3 $V = 1201$ m^3	experiment Tasaki
$\lambda/L = 1.6$	$V = 4.0$ m^3 $V = 0$	$V = 7.2$ m^3 $V = 0$	$V = 26.7$ m^3 $V = 26.9$ m^3	experiment Tasaki

Table 3.

		$v = 14.5$ kn	$v = 16.9$ kn	$v = 19.63$ kn	
$h = 4.25$ m	$\lambda/L = 1.4$	$V = 54.1$ m^3	$V = 230$ m^3	$V = 435$ m^3	experiment
$h = 4.25$ m	$\lambda/L = 1.4$	$V = 37.0$ m^3	$V = 1201$ m^3	$V = 1611$ m^3	Tasaki

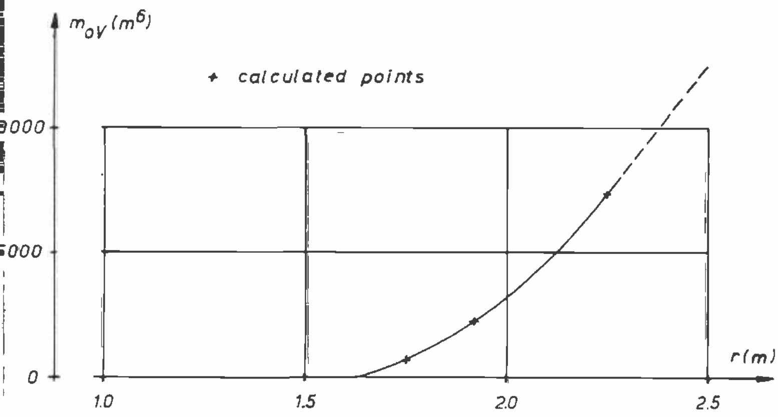

Fig. 28. Variance of shipment of water as function of wave amplitude.

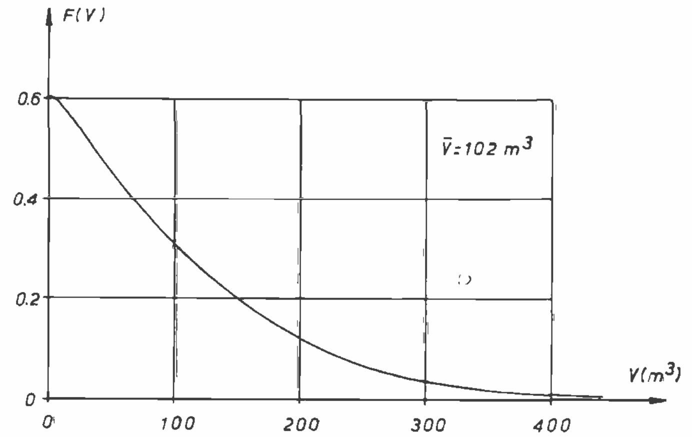

Fig. 29. Calculated distribution function of V.

rier but with a modified bow shape, instead of the fairly full rounded form of earlier tests, it now had a fairly sharp wedge shape, with maintenance of the perpendicular sides. The tests have been carried out for a ship's speed of approximately 12 knots. The model tests in regular waves have been made for 5 frequencies and 3 waves heights viz. $h=3.95$ m, $h=4.10$ m and $h=4.25$ m. Again the response functions of V were calculated, notably on basis of F_{e1} because this alternative probably produces the most accurate results. Furthermore, the number of locations where the relative motion was measured was sufficient for an accurate numerical integration over x to determine V. The results are presented in Fig. 30 in which the most striking aspect is the occurrence of two peaks in what is already a very limited frequency range of water shipments. The underlying cause is a dip in the response curves of the relative motion. In the V response this phenomenon is so much reinforced that it shows several discrete and pronounced peaks.

A comparison between calculation and measurement shows that the calculated V response is about 1.5 to 2 times the measured value. Contrary to the calculations made for the first series of model tests, the calculations for the second series include, in addition to the terms allowing for ship's speed and orbital speed in the wave, also the term V_5 representing the effect of the pressure height.

If in this case the term V_5 were neglected, the calculated V response would show a reduction in the order of 30%: approximately 40% at the peaks and 10–20% over the rest of the curve.

The case of $v=0$ has been further examined in a wave height of $h=8.50$ m and a wave frequency of $\omega=0.637$ rad/sec ($\lambda/L=0.7$). In this special case the approximated calculated value of $V=62.3$ cu.m as against a measured value of $V=36.2$ cu.m.

The effect of the surge motion on the volume of shipped water has been examined by duplicating a number of selected model tests in such a way that they yielded results of the model both free and fixed in surge motion.

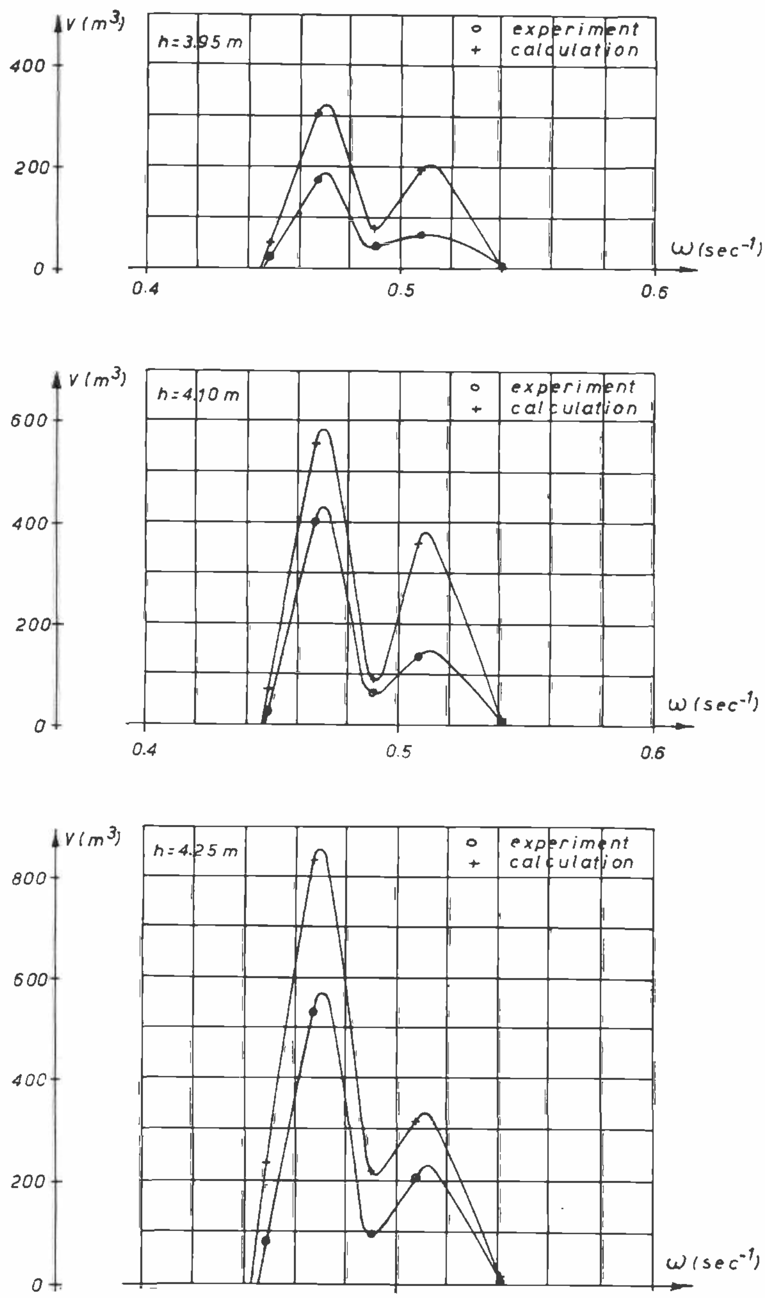

Fig. 30. Response curves of V.

These results are given in Table 4. From this Table it emerges that in this case the measured experimental values of V can increase by as much as 50% if the model is fixed in the surge motion.

Consequently, this effect cannot be left out of account. As the apparent cause can be mentioned the effect of the coupling of the surge motion on the relative motion as shown in Fig. 32, where the measured value of the relative motion increases by about 10% in the case of the model not being freely surging. Figure 32 also allows the concluson that there is a definite linear dependence between relative motion and wave motion.

Assuming a complete sinusoidal motion, the time interval τ of an oscillation at which shipping of water occurs can be written as follows (see Fig. 31):

$$\tau = \frac{2}{\omega_e} \arccos \frac{F_e}{s_e} \tag{34}$$

The time lapse τ is an important measurement whereby to assess the degree to which the relative motion deviates from the assumed harmonious oscillation as a result of disturbances occurring in the wave motion and the ship's motions. Table 5 shows clearly that there is a reasonable measure of agreement between measurement and calculation as far as the duration of the water shipment is concerned.

It also allows the conclusion that τ, at any rate in this case, will slightly increase if the model is not free to surge.

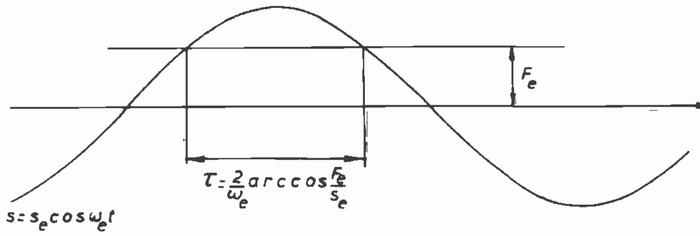

Fig. 31. Definition of time lapse τ.

As part of the additional model tests with the modified bow shape, the practical value of the approximation in formula (31) has been verified by a model test with a ship's speed of 12 knots in irregular waves. The main characteristics of the wave spectrum were a significant wave height of 5.7 m and an average wave period of 10.3 sec, which roughly corresponds to 9 Beaufort.

The basic data necessary for the calculation according to formula (31), notably the values of the coefficients as defined in (32), are contained in Table 6.

The model test showed an average water shipment of 280 cu.m per oscillation during which water shipment did indeed occur, which was the case for almost 30% of the oscillations.

Table 6.

m_{0r} (m^2)	2.0520
m_{1r} (m^2sec^{-1})	1.2375
m_{2r} (m^2sec^{-2})	0.7852
M (m^4sec^{-2})	0.0798

Table 4.

		free to surge		surge restrained	
		experiment	calculation	experiment	calculation
$h=3.95$ m	$\lambda/L=1.10$	$V=67$ m^3	$V=196$ m^3	$V=104$ m^3	$V=330$ m^3
$h=4.10$ m	$\lambda/L=1.18$	$V=65$ m^3	$V=90$ m^3	$V=83$ m^3	$V=306$ m^3
$h=4.10$ m	$\lambda/L=1.30$	$V=400$ m^3	$V=556$ m^3	$V=562$ m^3	$V=234$ m^3
$h=4.25$ m	$\lambda/L=1.41$	$V=83$ m^3	$V=234$ m^3	$V=94$ m^3	$V=251$ m^3

Table 5.

		free to surge		surge restrained	
		experiment	calculation	experiment	calculation
$h=3.95$ m	$\lambda/L=0.97$	$\tau=0.18$ sec	$\tau=0.48$ sec		
	$\lambda/L=1.10$	$\tau=1.98/2.03$ sec	$\tau=2.40$ sec	$\tau=2.53$ sec	$\tau=2.57$ sec
	$\lambda/L=1.18$	$\tau=1.79$ sec	$\tau=2.15$ sec		
	$\lambda/L=1.30$	$\tau=2.87$ sec	$\tau=2.94$ sec		
	$\lambda/L=1.41$	$\tau=2.42$ sec	$\tau=2.56$ sec		
$h=4.10$ m	$\lambda/L=0.97$	$\tau=0.42$ sec	$\tau=0.77$ sec		
	$\lambda/L=1.10$	$\tau=2.35/2.50$ sec	$\tau=2.57$ sec		
	$\lambda/L=1.18$	$\tau=2.14$ sec	$\tau=2.19$ sec	$\tau=2.50$ sec	$\tau=2.65$ sec
	$\lambda/L=1.30$	$\tau=3.20$ sec	$\tau=3.28$ sec	$\tau=3.74$ sec	$\tau=3.83$ sec
	$\lambda/L=1.41$	$\tau=2.86$ sec	$\tau=2.46$ sec		
$h=4.25$ m	$\lambda/L=0.97$	$\tau=0.53$ sec	$\tau=1.38$ sec		
	$\lambda/L=1.10$	$\tau=2.69$ sec	$\tau=2.45$ sec		
	$\lambda/L=1.18$	$\tau=2.31$ sec	$\tau=2.50$ sec		
	$\lambda/L=1.30$	$\tau=3.28$ sec	$\tau=3.50$ sec		
	$\lambda/L=1.41$	$\tau=2.96$ sec	$\tau=3.03$ sec	$\tau=3.08$ sec	$\tau=3.14$ sec

However, the calculation yielded a corresponding value of 0.24 cu.m per oscillation, so that there is a discrepancy in the order of a factor of 10^3. This is presumably attributable to a fundamental incorrectness in formula (31), which necessitates the consideration of a revised derivation.

5 Conclusions and final remarks

1. Assuming that the measurements were sufficiently accurate, the measurements were sufficiently accurate, the tentave finding is that the theoretical calculation model is not yet fully adequate, considering the fact that in the first series of model tests with $V = 17$ knots the calculation predicted a twice higher value than the measurement and in the second series with $V = 12$ knots (V_5 being neglected) the calculation was approximately 25% higher than the measurement.
On the other hand, it can be stated that the trend showed a fair measure of agreement and that the accuracy of the V response is very sensitive to fluctuations in the effective freeboard and the effective relative motion.

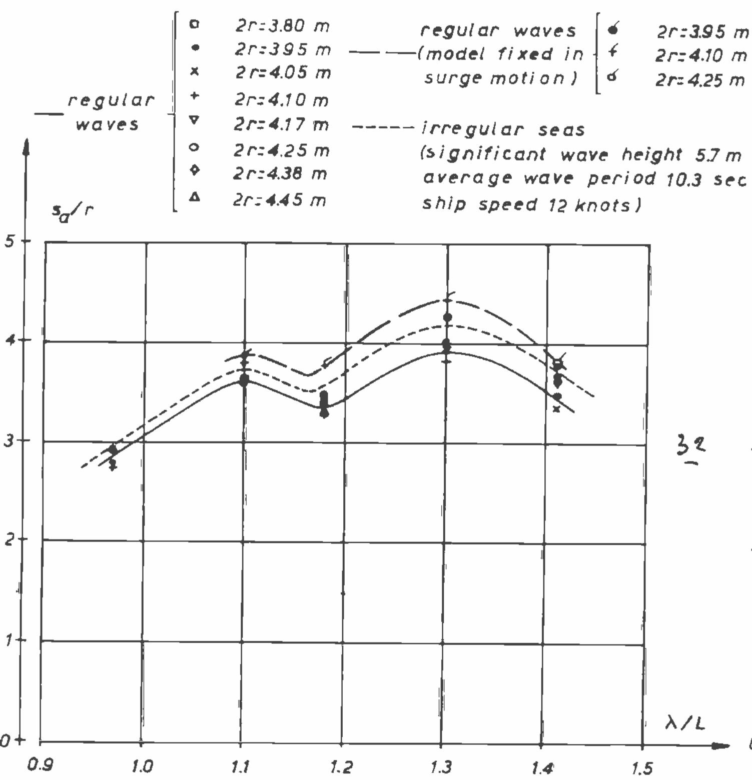

Fig. 32. (from ref. [20]): Response of relative motion at the stem.

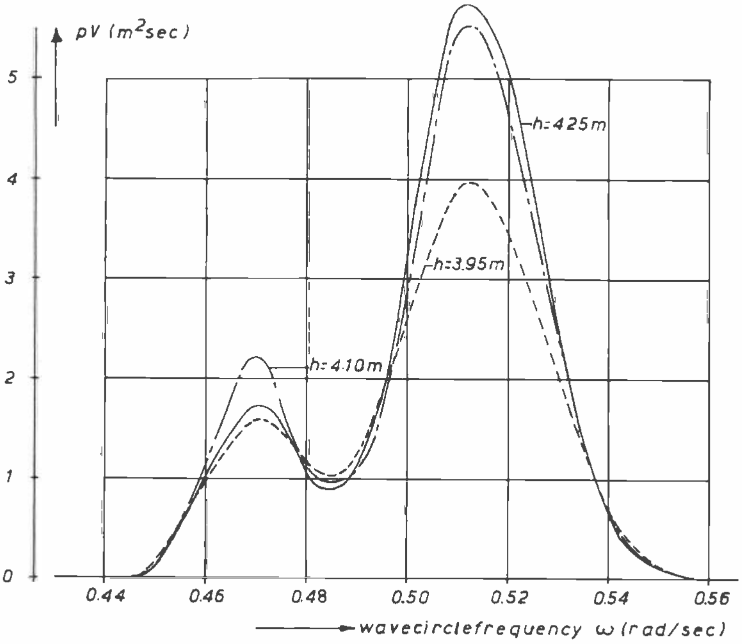

Fig. 33. pV as function of ω.

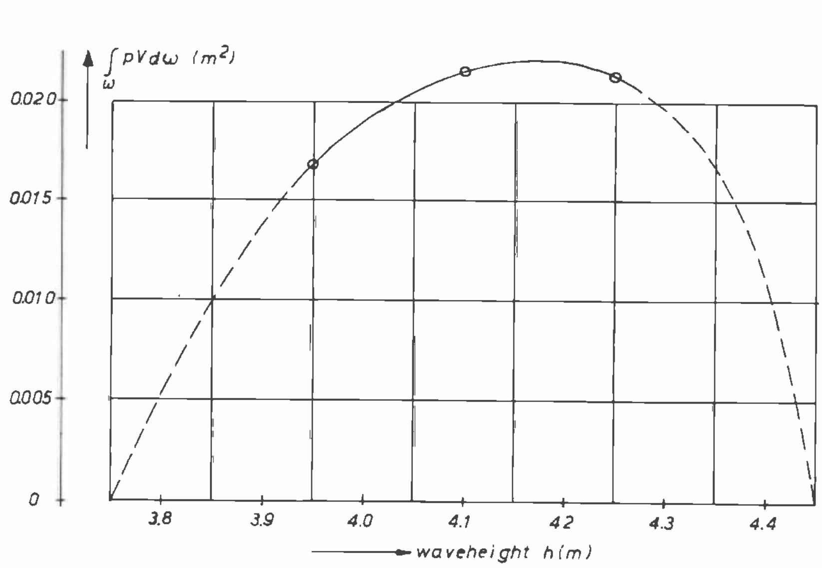

Fig. 34. $\int_\omega pV\,d\omega$ as function of h.

Since the degree of accuracy obtained in determining both the effective relative motion and the effective freeboard is such that it is practically incapable of further refinement, a prediction of the quantity of shipped water, as a secondary effect, remains perforce a rough approximation. The discrepancies between calculation and measurement for the two series of model tests are possibly attributable to diffraction phenomena occurring as a result of the differences in hull form.

If more model-test results become available, it will be possible on the basis of the experimental data to derive a correction coefficient as a function of the form parameters.

2. Although Tasaki's formula (11) is based on model tests carried out in practically identical conditions as the first series of tests made for the purpose of this study, its application shows little agreement where considerable water shipments are concerned. A further drawback of this approximation is that for the special case of the ship's speed being zero, the water shipment is also nil. It can, however, be established that for a sailing vessel her speed has a dominating effect on the incidence of water shipment.
3. Model tests aiming to study more closely the water-shipment phenomenon (as a quantity) are very well feasible, provided due attention is being given to the frequency-wave height range and the measurement of the relative motion.
4. The most reliable measurement of the static swell-up is probably the one based on the mean relative motion at the relevant location (F_{e1}), because it does not require superposition of the relative motion on the ship's own wave system. An element of mutual influence cannot be ruled out considering that various tests with the same speed show a considerable spread in the static swell-up.
5. From the model tests it emerged that in assessing water shipment the surge motion must not be neglected because there is apparently a strong coupling effect between relative motion and surge motion.
6. Considering the fact that the process of shipping water during an oscillation is of a continuous non-stationary character and also in view of the indication obtained from the model-test results, it can be stated that the mathematical model should probably not allow for the term dependent on the pressure height (V_5).
7. On basis of the measured response functions in the case of irregular waves, the agreement between the model test and the calculation according to formula (30) with respect to the average quantity of shipped water per oscillation can, by way of a tentative conclusion, be called reasonable. However, the alternative given in formula (31) requires further elaboration.
8. Although the mathematical model can relatively simply be extended to include a wave direction other than longitudinal, it is of little practical use as long as the mathematical model for longitudinal waves is not accurate.
9. It is advisable, particularly where the theoretical calculation model is concerned, to examine the possibility of obtaining a more accurate determination of the static and the dynamic swell-up than the approximation formulae currently available, which find only limited application.
10. It is recommendable that the effect of flare as indicated in the mathematical model (V_4) should be verified by means of model tests to be carried out with systematically varying bow shapes.

    The effect of flare on the shipment of water can be considerable as has been shown by Tasaki (see Fig. 10).

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