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Studium der Bewegung der Seeschiffe unter dem Einfluss von Seegang und Wind

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Section II

OCEAN NAVIGATION

NAVIGATION MARITIME

Subject 2 : Sujet 2

Study of the motion of sea-going vessels under the influence of waves, wind and currents, in order to determine the minimum depth required in port approaches and along off-shore berthing structures for tankers and ore carriers.

Étude des mouvements des navires de mer sous l'influence des lames, du vent, des courants, dans le but de déterminer la profondeur minimum dans les accès des ports et celle à prévoir le long des accostages pour pétroliers et minéraliers au large de la côte.

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PAPER

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I. NATURE OF PROBLEM.

The dimensions selected in the case of technical structures which are subjected to the influence of natural forces such as wind, swell, currents, etc., always present a problem, seeing that there are no exact limits for assessing stresses and strains. Complete safety in operation or, alternatively, safety in step with physico-technical knowledge, with potential incidences, cannot make for full security. This axiomatic appreciation is implicit in all requirements affecting safety. When, for instance, allowances for stresses must be made above the normal in the construction of technical installations by incorporation of additional security measures, this indicates solely that an incidental combination of a series of particularly unfavourable factors have arisen. The importance of the additional safety measures for meeting the extent of the incidental stresses is purely a matter of opinion. Logically, it can therefore be stated that according to " human judgement " nothing can happen where such security measures have been adopted. Regard for any remaining risk would be that coming within the scope of force majeure. From the scientific concept this approach is unsatisfactory; rather should one seek to clarify the factual connections, e.g. by determining a safety factor, which is in line with the probability of a given function, or corresponding to a probable degree of risk or peril during the occurrence of dangerous peak stresses. The approach was first adopted by Wendel in certain studies connected with the safety of ships in the surmounting of inflicted damage, and also in the handling of other security problems at the Institute for the design of vessels and ship's theory at the Technical High School in Hannover. (Technische Hochschule in Hannover.) It is assumed that by this method it is always possible to acquire a knowledge of frequency and consequently of the probability and spread of the stresses. Regrettably, theoretical assessments in the determination of distributory functions at the limits are very unreliable and statistical data, although adequate in scope and rendering apposite conclusions, but where it is a question of the realisation of new technical concepts in particular, generally fail to lend themselves to interpretation. As measurements for the collection of statistical data in connection with experimental structures in nature are mostly given up owing to expense, it is possible, however, to conduct these on a small scale model. This method was successfully utilized in latter years at the Institute in question, for the purpose of establishing the degree of risk in the capsizing of vessels in agitated seas and consequently to determine the appropriate degrees of safety, having regard to the minimum values of stability. The experience and knowledge acquired and which are embodied in the present report are the result of these measurements; they are, moreover, valid in respect of similar problems, as for instance, in the matter of research of minima depths at berthing structures or artificial islands. In the case of the model, natural conditions were created, such as obtain on inland lakes under appropriate wind conditions.

2. SIMILITUDE OF A NATURAL MODEL.

The intention to reproduce a complex range of subjects : wind and water — artificial islands — a vessel, on a small scale model, gives rise in the first instance to the question bearing on the field applicable to the laws governing models. There is no doubt that gravity waves are the main influence in the movement processes of the water's surface, its dynamic therefore determines the conditions of similitude, which must be realized in order to produce a working model. Should one choose the wavelengths as the characteristic values (in the case of realization in nature λ, in model size λ'), the conditions of similitude according to Froude are as follows :

Lengths $$\frac{a}{a'} = \frac{b}{b'} = \dots \frac{\lambda}{\lambda'} \qquad (1)$$

Speeds $$\frac{v}{v'} = \frac{w}{w'} = \dots \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}} \qquad (2)$$

Angle	$\frac{\alpha}{\alpha'}$	$\frac{\beta}{\beta'}$	 1	(3)
Angular Velocities	$\frac{\dot{\alpha}}{\dot{\alpha}'}$	$\frac{\dot{\beta}}{\dot{\beta}'}$	. . . . . $\left(\frac{\lambda}{\lambda'}\right)^{-\frac{1}{2}}$	(4)

It is known that it is impossible to expect that a strict detailed adherence to all these requirements can be achieved by the model. Everywhere where friction plays a role account must be taken of its physical laws. It is, therefore, a matter of analysis concerning the attainable similitude of the model. Wind and swell and the resultant vessel movements are stochastic in behaviour. Their consideration as a function of space and time is, therefore, not only involved but barren of result in certain circumstances, seeing that in actual fact individual phases of the process of movement are not characteristic, displaying, as it were, statistical gradations or divisions only. It can be safely assumed that the superimposition of various movements occur independently of the scale governed by the same laws of superimposition, given the same physical laws. This is the case, provided the model's scale is so chosen, that capillary waves are without noticeable influence. In the general sphere of gravity waves the superimposition will take place in accordance with a uniform law. Similar deviation from the theoretical linear assessments coming within the compass of the model will be encountered also in nature. In such circumstances, the proof of similitude of the statistical data is sufficient for the confirmation of like behaviour.

2.1. **Wind and Swell.**

It is both customary and appropriate to describe the swell by its spectrum of performance. A similitude corresponding to the equations (1)... (4) arises at the time when the relationship exists between the maritime spectrum and that of the model, as indicated hereafter :

$$\frac{r(\omega)}{r'(\omega')} = \left(\frac{\lambda}{\lambda'}\right)^{2,5} \tag{5}$$

$$\frac{\omega}{\omega'} = \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}}, \quad \frac{d\omega}{d\omega'} = \left(\frac{\lambda}{\lambda'}\right)^{-\frac{1}{2}} \tag{6}$$

Natural swell is produced by the wind. The relationship of wind and swell is described by Roll and Fischer with the spectral equation

$$\int_{\omega_1}^{\omega_2} d\,R = C\,.\,w^4\left[1+\left\{1+\frac{2g_2}{w^2\,\omega^2}\right\}-\exp\left(\frac{-2g^2}{w^2\,\omega^2}\right)\right]_{\omega_1}^{\omega_2} \tag{7}$$

The total performance of the spectrum is accordingly

$$R = C\,.\,w^4 \tag{8}$$

Postulating an analogous swell conforming to (5) and (6), with a relationship where the total performances are :

$$\frac{R}{R'} = \left(\frac{\lambda}{\lambda'}\right)^2, \tag{9}$$

it emerges according to (8) that the relationship of the speeds of the wind so generated must be :

$$\frac{w}{w'} = \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}} \tag{10}$$

Where an integration is made solely in the field of dR, where the limits in (7) corresponding to the requirement (4) $\frac{\omega}{\omega'} = \left(\frac{\lambda}{\lambda'}\right)^{-\frac{1}{2}}$ are

transformed, it follows that the same result is obtained. It should be pointed out, however, that the swell of the model both corresponds to and resembles the maritime swell in the sphere of validity of the afore mentioned (5) and (6) spectral equation, subject to the fulfilment of the condition of similitude (10) of the wind.

In whatever manner the particular mechanism of movement may behave in a given air space, it can nevertheless be regarded as proved, that the measurable wind speeds and their directions at a given point are, more or less, normally spread. The actual average values and dispersals depend on the meteorological conditions. The ratio between the average value and dispersal rests largely within the same order of importance. It is, therefore, possible for wind in nature to find a natural model wind, which corresponds, as regards average value and dispersal, to the requirements of similitude. The following equations are consequently valid :

$$\frac{w_m}{w'_m} = \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}} \tag{11}$$

$$\frac{S^2(w)}{S'^2(w')} = \frac{\lambda}{\lambda'} \tag{12}$$

A decisive element of importance in the reproduction of swell consists of the fetch. According to requirement (1) for lengths, the fetch should be in the ratio of

$$\frac{F}{F'} = \frac{\lambda}{\lambda'} \tag{13}$$

It remains to be proved that over corresponding distances similar masses of energy are transferred by the wind to sea swell.

By adopting the appropriate concept in the first instance, that the transfer of energy arises from the development of dynamic pressure potential, the energy emerges as proportional viz. :

$$E(T) \backsim (w-c)^2 \lambda \frac{T^2}{2} \tag{14}$$

due to the condition

$$\frac{E\,(T)}{E\,(T')} = \left(\frac{\lambda}{\lambda'}\right)^{3} \tag{15}$$

must be in proportion to

$$\frac{T}{T'} = \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}} \tag{16}$$

The equation

$$\frac{F}{F'} \qquad \frac{T\,.\,c}{T'\,.\,c'} = \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}} . \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}} = \frac{\lambda}{\lambda'} \tag{17}$$

is the ratio of lengths along which similar waves have travelled after being fed with similar amounts of energy i.e. the ratio of the similar fetches. There is no doubt that the influences of friction play a role in the transmission of energy, and it is necessary to allow for deviations from the ideal conditions of similitude, as outlined. According to measurements made up to the present, such deviations would, however, appear to be unimportant. The similitude is valid for deep waters, i.e. approximately for $Z < \lambda$; it may, however, be extended to include shallow waters. On the assumption that the density of the air ρL is so low as to be disregarded, as opposed to the density of water ρw and that capillary waves are without influence, the correlation, generally speaking, applicable to gravity waves is :

$$c^2 = \frac{g\,.\,\lambda}{2\,\pi}\ .\ \tan h \left(2\,\pi\ .\ \frac{Z}{\lambda}\right) \tag{18}$$

It follows that it is easy for $Z > \lambda$ which is included in the (17) similitude equation to read off " c " representing the speed of the wave.

This relation is applicable likewise to shallow waters, therefore, $Z < \lambda$ is valid, when care is exercised for the ratio of depth of water to length of wave to remain constant, when we have :

$$\frac{Z}{\lambda} = \frac{Z'}{\lambda'} \tag{19}$$

The conclusion may be reached, by virtue of the fact, that the equation $\frac{c}{c'} \quad \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}}$ is retained, that the deformations of the spectrums due to variations in the speeds of the waves are similar in shallow waters.

2.2. Vessels and other Structures.

As a first approximation the conditions (1), (3) and (4) of a ship's model are met, when next to the exterior shape the resultant positions of the centre of gravity and the radiuses of inertia are in the ratio of $\frac{\lambda}{\lambda'}$

The reduced pendulum lengths then behave in the same manner as $\frac{\lambda}{\lambda'}$ and the respective angular velocities and the frequencies behave similarly, as in the case of $\left(\frac{\lambda}{\lambda'}\right)^{-\frac{1}{2}}$; divergent conditions of similitude, due to the influence of friction, can generally be compensated by changing the damping properties of the superstructures. It is of decisive importance that the corresponding equations of movement (equations of momentum) display the same limb by limb relation one to another, therefore in the case of a general statement

$$f(\ddot{\varphi}) + d(\dot{\varphi}) + h(\varphi) + k(w) = 0 \tag{20}$$

an endeavour should be made :

$$\frac{f}{f'} = \frac{d}{d'} = \frac{h}{h'} = \frac{k}{k'} = \left(\frac{\lambda}{\lambda'}\right)^{4} \tag{21}$$

This requirement can be met with a satisfactory approximation, subject to checks and appropriate corrections. The condition (2) can be satisfied by an appropriate design of the propulsion unit. In addition, motions at the model, which themselves produce motions of the model, must of course fulfil condition (4), e.g. putting the helm of model or ship. In the case of other model structures, it follows of course, that the same principles as for ships' models apply.

3. CONTROL OF THE MODEL'S FIELD.

The utilization of data in nature affecting model tests indicates that individual influential elements are not produceable on all occasions, as for instance, in an experimental tank, without having to wait until the desirable conditions are present. Fortunately, the most appropriate model wind adapted to model dimensions is quite frequently encountered; consequently, such experiments can be conducted at the proper seasons of the year without great delays. In order to make use of every opportunity for carrying out measurements it is, however, necessary to exercise a continuous supervision of the practical field of application offered for the conduct of model tests. A series of characteristic statistical measurement figures should always be available. This assumes the continuous study of a large number of measurement figures. The usual procedure — register first, then analyze — is not advisable on account of the loss of time involved. Moreover, this would give rise to an excess of figures for the trials consisting mostly of recordings proved to be valueless, and which would be hard to maintain in good order. New methods of technical measurements must be evolved, in order to conduct a statistical series of tests. Data must, therefore, undergo statistical selection of their value on the spot. This requirement entirely disposes of measurement dependent on the time factor, which can be justified only as a result of experience, seeing that, most times statistically speaking, stationary conditions obtain for an adequate period of time, and that within relatively short time intervals sufficiently accurate data can be established. The reduction in time imposed by the scale in the ratio $\left(\frac{\lambda}{\lambda'}\right)^{-\frac{1}{2}}$ is hereby shown to be highly favourable.

3.1. Swell.

In order to acquire a technical method for measuring swell, it is sufficient to measure the ordinate variations over a period of time from a fixed point inside the waters of the model, which is known as the swell function z (t). In this manner, by using stationary random and ergodic processes, it is possible to obtain an accurate appreciation of swell, provided that measurements extend over a sufficiently long period.

At times, however, the directions of propagation of individual waves, represented by β, play a role. This is, moreover, a cause of very considerable difficulty in the measurement of the directional spectrum $r'(\omega', \beta')$ of a so-called two-dimensional swell. Our purpose will be served in most cases by confining ourselves to a single dimensional spectrum $r'(\omega')$.

The quadratic mean value $\overline{z^2}$ of the swell function z (t) should be regarded as complementary. In order to achieve a correlation of measurable dimensions with the frequency of waves of varying amplitude these must be measured, failing which, one has to rely on scant theoretical assessments.

The measurement of the swell function can be obtained by recourse to the known principle that when plunging two wires under tension the currents differ dependent on the depth under water. It is then possible to obtain a variation in the water level at a given point, proportionate to the tension. Such a contrivance for measurement consists of a transistor circuit; it has been developed at the afore mentioned Institute.

According to the nature of the problem posed all statistical data should be immediately available at the place of measurement. This calls for the set-up of an appropriate installation for the production of the data.

In order to obtain the spectrum the Institute developed a special analogue computer for the relatively low frequencies of the model swell. Its function is based on the electro-mechanical creation of Fourier coefficients, which are expressible in terms of the following integral :

$$a_n = \int_0^T z(t) \cos(\omega_n t)\, dt \qquad (22)$$

$$b_n = \int_0^T z(t) \sin(\omega_n t)\, dt \qquad (23)$$

in consequence of which it is easy to obtain the spectrum :

$$r(\omega_n) = \frac{1}{T} \cdot \left(a_n^2 + b_n^2\right) \qquad (24)$$

The plan of the block diagram of figure 1 shows the principle of the

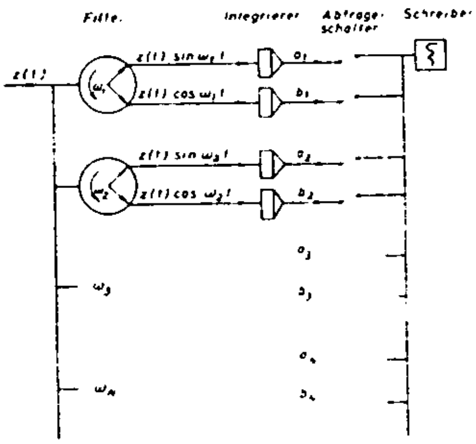

Fig. 1.
Principle of a switchboard of an electrical computer for a natural model swell.

LEGENDS.

Filter	=	filter.
Integrierer	=	integrator.
Abfrageschalter	=	switch.
Schreiber	=	writer.

analyser. The modulated direct current corresponding to the function of the swell is directly subjected to further electrical development. The product in the integrand is formed by the sin-cos-potentiometers which revolve at a speed corresponding to the frequency in question; integration is obtained by condensers. On account of a parallel disposition of all necessary filters of varying frequency, needed for the satisfactory decomposition of the spectrum, it is possible to dispense with the storage of z (t). The accumulated values of the Fourier coefficients are successively read out by a rotating switch (*).

3.2. Wind.

According to the relationships mentioned in the first part between wind and swell, the effective speed of the wind conveys the earliest indication of the swell which can be expected. It is, therefore, most important to select an appropriate time constant for the measuring apparatus. On the one hand, it may not be too short, in order that the indications obtained are sufficiently stable, on the other hand, it should not be too long, so that changes can be noticed in good time. It would be reasonable to select about 1/10 of the duration of influence of the wind on characteristic waves. If, for instance, the characteristic wavelength of the model is 2 m and the length of the wind track 2.000 m, it would be 1.120 sec and a time constant of about 120 sec may be selected. It is, moreover, desirable to determine the linear average and the dispersal of the speed of the wind and of its direction. This can be achieved either by classification of these values, according to relative periodicity or by integration in an analogue computer. The latter method is preferable as it is less work, although somewhat larger mistakes may arise thereby.

3.3. Vessel.

The realisation of similitude of a ship's model and the corresponding control measurements are fundamentally simple, they call, however, for a certain exercise of care. According to a preparatory rough calculation, the following experiments are conducted on a ship's model respectively in smooth waters and in the wind tunnel :

(a) Heal over test, in order to determine the position of the resulting centre of gravity.

(b) Experiments in rolling, pitching and plunging, in order to determine the proper periods and consequently the proper frequencies.

(c) Test by free oscillations of the determination of the damping factors.

(d) Measurement of wind forces at a superstructure model in a wind tunnel.

By this means it is possible to check the requisite similitude in (21)

$$\frac{f}{f'} \quad \frac{d}{d'} = \frac{h}{h'} = \frac{k}{k'} = \left(\frac{\lambda}{\lambda'}\right)^4$$

(*) Attention is drawn to the fact that this computer is also suitable for the study of maritime swell when the latter's variation of tension is in step. In this connection, the frequencies, which are even smaller in comparison with those of the model's swell, are easily overcome, owing to the dependence of the filter on the speed of rotation of the potentiometer in question.

and to achieve adequate accuracy by making appropriate corrections to the model.

A similar speed, according to requirement (3)

$$\frac{v}{v'} = \left(\frac{\lambda}{\lambda'}\right)^{\frac{1}{2}}$$

is obtained by an appropriate design of the propulsion unit following the results measured during mile trips of the model. In order to develop similar movements of the model's rudder special measures are needed.

Owing to (4)

$$\frac{\alpha}{\alpha'} = \left(\frac{\lambda}{\lambda'}\right)^{-\frac{1}{2}}$$

the angle of velocity of deflection of the rudder of a model is always greater than on a corresponding ship in nature. This cannot, however, be carried out perfectly by direct human control of the rudder on account of the physiological reactive delay. It is, therefore, necessary to incorporate a self-steering contrivance, which independently exercises the necessary control of the rudder in its movements for the proper steering over a given course. A straight course can be relatively easily maintained by a model fitted with a gyroscopical control loop.

4. EXPERIMENTAL INQUIRY INTO STATISTICAL DATA.

There is no doubt that the survey of the model's similitude calls for the necessary pre-suppositions on broad lines; it is, however, obvious that, as far as the most important influences between corresponding complex systems are concerned, uniform relations of similitude can be achieved. In addition to influences of scale resulting from the phenomena of friction, where there is always a possibility of an experimental check and compensation, there is a considerable simplification in the derivations, i.e. those consisting of the linear superimposition of the components of a spectrum. We are aware that in the field of very great amplitudes, at any rate, this law no longer applies. It may, however, be assumed with certainty that in the field of gravity waves the superimposition conforms to a uniform law, and in consequence, similar deflections in the model as in nature can be expected in regard to the theoretical linear assessments. It follows that relations of similitude, as described, continue valid and furnish justification for the collection of statistical data of the model for their extrapolation in nature. The method described calls also for a grasp of the statistical approach in the values sought, in precisely the same manner when the question arose of considering the values of exciting quantities in the statistical field.

Particularly in the field of extremely large amplitudes, whose exclusive importance is confined to the considerations of security, provide results by these means which are noticeably better than those which can be furnished from known theoretical assessments. This is not only valid for the exciting forces of wind and swell, as also for the ship's movements produced thereby. In this connection, the tests on the model offer the special advantage of developing actions, which must be avoided in nature, such as result in capsizing or running aground.

Theoretical functions of amplitude frequencies usually throw up results with digits running into infinity. Practically speaking, however, there is always a limit, although it cannot be stated with accuracy, but it must be regarded as certain that where such a limit is reached, its value is such that it can be visualized. Indeed, the field of larger and extremely large maxima play but a very small part in the sum of frequencies; in such cases a general description of processes of movement, theoretical and measured frequency functions are of equal value, but such is not the case where considerations of safety are concerned, as then this field only can be of interest. As will be readily appreciated in such cases differences of the orders of magnitude occur, so that measured values must necessarily be accorded priority as against those ascertained theoretically, which, though expressed with care, can be highly inaccurate. Measured values are certainly preferable, when a reasonable compromise between economy and safety can be found. It should be observed that, in most cases, the frequency of extreme amplitudes is equivalent to the degree of risk; on the basis of theoretical frequencies it would appear, therefore, that safety is considerably increased to the detriment of the economy. A further advantage of the model method is that, in a relatively short period of time, the same volume of information becomes available as by observations extending over several decades. It can be stated that "extreme swell" in a model is met with much more frequently than extreme maritime swell, and besides the higher state of frequency in the model acts as an economy in time.

$$T' = T \left(\frac{\lambda}{\lambda'}\right)^{-\frac{1}{2}} \qquad (25)$$

The time saved thus results in a more expeditious performance of the experiment providing, at the same time, a greater opportunity of obtaining information and affording an improved overall view of the phenomenon.

4.1. Measurements made of the Stability of Vessels in Swell.

The methods of measurement, described in Part 3, serve in the first instance for the supervision of the model, i.e. in regard to the testing of the similitude which is essential for the problem posed. They are much concerned with the devices for measurement and calculation, which are utilised in order that the experimental requirements may remain subject to permanent control. On the other hand, the actual object of the measurement, the determination of statistical data of the limit conditions for the ascertainment of safety factors and the fixing of safety limits presents no difficulty. This will be clarified by the example of the investigation conducted on the immunity to capsizing in swell. The stability of a ship, i.e. the ability to right herself again after listing is dependent on the position of the centre of gravity of the ship and on the centre of buoyancy of the displaced volume of water. The horizontal projection of the distance of these two centres of gravity, the arm of the lever of the rising moment is a measure of the stability. When a ship travels through waves the ship's longitudinal axis and the wave crests are perpendicular one to another, it is especially then that the shape of the displaced volume of water varies materially from the shape in smooth water. It follows, therefore, that the centre of buoyancy is not the same.

and consequently the arm of the lever of the rising moment changes as well. Should the ship be riding on the crest of the wave the arm of the lever is generally much smaller, in the trough of the wave it is, however, greater than in smooth water. The reduction at the crest, the cause of a number of ship losses, is dependent on the form of the wave, therefore, in the main on the wavelength and amplitude. Where length is concerned the maximum of this deviation is given by a wavelength approximately equal to the ship's length, the dependence of the amplitude being linear in the first order of approximation. In such circumstances, a ship capsizes on the meeting of waves whose amplitude is equal to or greater than a given limit of amplitude. Where this limit lies is thoroughly defined by the stability in smooth water. The danger limit is identical with the probability of the appearance of amplitude above this limit.

Such are the broad lines of the subject from which the developments have evolved. It now remains to define the stability in smooth water, which according to a given swell determines a given degree of security or a corresponding degree of danger for a ship.

It should now be possible, in principle, to continue varying the stability of a model until the limit of security is reached and the task would thereby have been completed. As however this value must lie very close to 1 — this indicates, that the average period of risk of capsizing is very long — it would appear that this would undoubtedly take up too much time.

The following modus operandi appears appropriate : the smooth water stability is measured in such a manner that the ship capsizes after a relatively short time. The periods of time of a great number of cases of capsizing are ascertained and averaged. This average of the time period for capsizing is identical with the average time interval of dangerous amplitudes and is inversely proportional to the existing danger limit.

It is possible to determine by appropriate wave measurements the valid repartition of amplitude and thereby ascertain the limit of amplitude of the point of danger in this condition of the model. It is, in like manner, possible to determine the limit of amplitude of the permissible degree of risk. As regards the connexity between amplitude and the reduction in stability, it is now definitely possible to lay down the measure of security needed for smooth water stability.

Experiments conducted in the manner described were made with a variety of ships' models on an inland lake (Grosser Plöner See in Schleswig-Holstein) and these yielded good results.

4.2. Minimum Draft at Berthing Structures.

Similar methods can be adopted for determining the necessary minimum depths in the construction of discharging berths. A model of the projected installation is made in natural surroundings. According to a depth where contacts with the bottom still occur their relative frequency is determined. As in this case too, there is a direct relationship between the wave amplitudes and the amplitudes of movement of the ship, the requisite depth for the desirable margin of safety can be ascertained. In the circumstances, the actual question of measurement amounts to a computation.

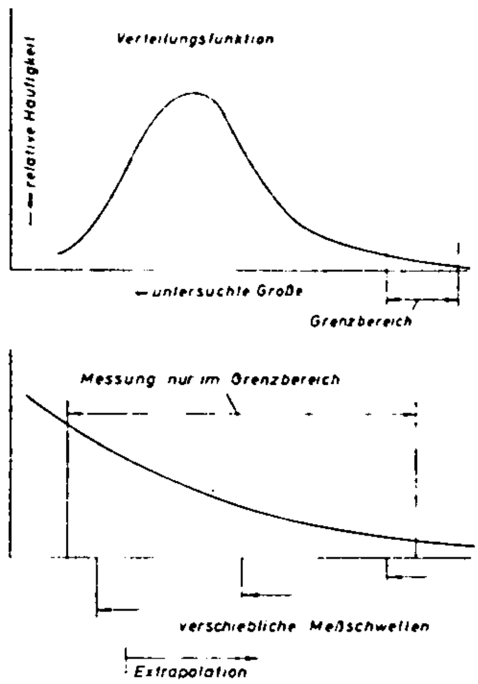

Fig. 2.

Representation of any repartition function and of its boundary range.

LEGENDS.

Verteilungsfunktion	=	divisory function.
relative Häufigkeit	=	relative frequency.
untersuchte Grósse	=	tested quantity.
Grenzbereich	=	boundary range.
Messung nur im Grenzbereich	=	measurement within the boundary range only.
verschiebliche Messschwellen		movable measuring devices.
Extrapolation		Extrapolation.

The procedure may be refined yet further if for a number of varying depths the frequency of ground contact is ascertained. The result then gives directly the curve of the amplitude function within the range covered, from which conclusions may be drawn towards the necessary depths for higher safety coefficients (fig. 2). It will be appreciated, that the frequency distribution curve of any other quantity may as well be determined in the same model system by using suitable gauges according to the problem posed, e.g. that consisting of the forces resulting from the bumping of a ship's keel on the bottom, etc.

5. CONCLUSION.

The description of the model method shows the means of ascertaining reliable, i.e. practical relevant statistical data regarding the behaviour of ships in swell. In particular, where theoretical assessments yield only a qualitative elucidation — this happens to be the case in the field of extremely large amplitudes, which are solely of importance in regard to considerations of safety — it is a valuable source for obtaining direct means for the appropriate dimensions of structures, and further to broaden our general knowledge of behaviour under extreme conditions. Critical loads, in particular, constitute factors determining the appropriate dimensions of structures and for attaining a desirable or necessary degree of safety; therefore, a compromise must be struck allowing for the necessary expenditure for meeting particular requirements without losing sight of the limits of stress. The actual question of costs is one that can be easily solved in the light of technical and economic data. The other aspect, for purposes of comparison, is conditioned by the experiments as described.

In the matter, for instance, of safety against capsizing in swell, it should be possible to refer to this experimental process, that very simplified quasi-stationary calculations of the stability of ships in swell produce quite reliable results, pointing to safety from capsizing, a proof which, theoretically, had so far not been realised.

At all events, measurements for every project are unnecessary. The results obtained in connection with a series of measurements should enable operations of relatively broad scope to be undertaken by means of simple theoretical assessments. It is precisely this possibility of restricting the scope of validity of theoretical assessments by measurement within a complex system, which constitutes the outstanding merit of the method described in this paper.

MEANING OF THE SIGNS IN THE FORMULAE AND ON FIGURE 1.

- l = Any track.
- L' = Length of Vessel.
- V' = Speed of Vessel.
- w = Speed of Wind.
- w_m = Average Speed of Wind.
- c = Speed of Waves.
- α = Angle of Rudder.
- β = Direction of Movement of Single Waves. —
- ω = Wave frequency. —
- λ = Length of Wave.
- s = Dispersal.
- r = Spectral power density of the seaway. —
- R Cumulative power density for the full spectral range. —

- C = Constant.
- E = Energy.
- F = Fetch.
- t Time.
- T = Period of Time.
- τ = Wave Period.
- Z = Depth of Water.
- g = Gravitational Acceleration.
- φ = Angle of Inclination.
- f = Term of Inertia in the Equation of Motion. —
- d = "Damping Moment". —
- h = "Restoring Moment". —
- k = Moment of Wind Pressure.
- z = Function of the Seaway.
- a_n , b_n = Fourier Coefficients.

The legends without a dash apply to nature.

The legends with a dash apply to the model.

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RESUME

Il est généralement d'usage, lors de la fixation des dimensions des ouvrages, d'avoir recours aux données statistiques relatives aux causes des sollicitations. Celles-ci, la plupart du temps des forces naturelles, répondent à des lois immuables et elles ont été observées et notées. Elles ne peuvent cependant être judicieusement utilisées que lorsqu'on peut en déduire d'avance des données relatives aux effets. Lorsqu'il existe des relations simples et visibles, la chose est possible par voie théorique, il n'en est pas de même lorsque les causes produisent des mouvements compliqués par exemple ceux d'un navire sous l'effet de la houle et du vent. Dans ce cas des données relatives aux effets et basées sur des observations sont indispensables lorsqu'il s'agit de trouver un compromis satisfaisant

entre la sécurité et l'économie. Dans le cas d'un développement lent et continu de telles données peuvent être recueillies par des observations permanentes à des ouvrages exécutés et être utilisées pour des nouveaux ouvrages à construire. Il est certain que la plupart des prescriptions pour la sécurité sont nées de cette manière.

Mais lorsque le développement est rapide et a lieu par bonds, ou qu'il s'agit de réaliser des conceptions complètement nouvelles, ce procédé est en défaut; les données relatives aux effets manquent et des échecs sont possibles. Le rapport décrit comment, à l'aide de données naturelles relatives aux mouvements des navires, des renseignements extrapolables a la nature peuvent être obtenus sur des modèles réduits. Un grand avantage réside dans le fait qu'il est possible de produire dans le modèle des phénomènes, qui doivent être évités dans la réalité et que d'autre part un grand nombre de renseignements peuvent être obtenus dans un temps relativement court, par des conditions extrêmes de l'état de la mer. Des éclaircissements au sujet de la méthode en modèle sont fournis à l'aide d'un exemple, notamment celui du chavirement des navires par gros temps; cette méthode peut également être utile pour la détermination des profondeurs minima nécessaires le long des ouvrages de déchargement.

Les résultats sont des degrés de sécurité ou de risque qui, combinés avec des considérations d'économie, permettent de fixer les dimensions voulues