# GENERATION OF IRREGULAR WAVES ON MODEL SCALES

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## SUMMARY

Wind-wave flumes have been added to the laboratory facilities since a long time, in order to simulate natural wind waves. Most wind-wave flumes have been equipped in addition with mechanical (regular) wave generators to avoid extreme small model scales. For some time past a programmed (irregular) wave generator has been installed in one of the existing wind flumes of the Delft Hydraulics Laboratory.

After a historical review of the development of wave generating facilities a comparison has been made of the various kinds of wave generation. Moreover, some records of North Sea wave conditions have been added to the comparison.

## 1. INTRODUCTION

Wind-wave flumes have been applied since a long time in model experiments for several purposes. Regarding the investigations, three subjects of particular interest with respect to problems in marine engineering can be distinguished:

1. Properties of wind profiles.
2. Wave generation by wind.
3. Wave attack on maritime structures exposed to irregular waves.

Originally small flumes were used in which waves were generated by wind blowing over the water surface. The investigations mentioned sub 1 and to a less extent those sub 2 did not require a substantial development of the model facilities.
Fetch and depth in these flumes limit wave heights to a few centimetres and wave periods to far less than 1 sec. However, valuable investigations have been and still are being produced in these relatively short and shallow flumes, which have grown in number only.

For investigations of the third type, waves of considerably greater height and period are indispensable to perform the investigations on suitable scales with respect to Reynolds and Weber number.

This study deals mainly with wave generation for the purpose of investigations of the third type, though the same considerations are of importance to investigations into the the wind-wave interaction.

Three methods of generating irregular waves, namely,
wind,
wind + monochromatic-wave generator, and
wind + programmed wave generator
have been subjected to a critical analysis and results have been compared with prototype data in Section 4 of this study, while the methods of analysis are discussed in Section 3.

## 2. HISTORICAL REVIEW

The first experiments with irregular waves in the Netherlands date back as far as 1920 when in a wind-tunnel a provisional arrangement was made to study wave run-up. After similar investigations in 1933, the construction of a special wind-wave flume was started at the Delft Hydraulics Laboratory and put into use in 1936.

The dimensions of this flume (length 25 m; width 4 m; maximum water depth 0.45 m) were unique at that time. However, as the length was not sufficient to meet the requirements of wave height and period, it was extended to a length of 50 m in 1941 and equipped with a monochromatic-wave generator.

Investigations into wave run-up, wave overtopping, stability of rubble-mound breakwaters, wave impact forces and stability of floating structures have been successfully performed in this flume (Ref. 1, 2 and 3). Similar investigations in other Institutes confirmed the importance of the application of irregular waves (Ref. 4, 5 and 6).

It is interesting to notice that model investigations into wave generation, carried out during World War II, yielded good agreement with prototype data collected by Sverdrup and Munk (Ref. 7 and 8).

The interest in model experiments applying irregular waves was growing so fast that the Delft Hydraulics Laboratory decided to establish another wind flume in 1957 at "De Voorst". The length of this flume was 100 m, the width 4 m, and the maximum water depth 0.8 m. This flume was also equipped with facilities to generate waves, either by wind only or by a combination of wind and a mechanical (regular) wave generator.

The growing interest in irregular wave phenomena also resulted in an increasing number of observations in nature, and simultaniously forced the evaluation of elaborate statistical analysis conceiving the wave motion as a stochastical process. Application of the mathematical techniques to both model waves and prototype data have shown unacceptable discrepancies. Since 1962, therefore, the Delft Hydraulics Laboratory has been working on a system of wave generation which yields still a more realistic reproduction of natural wave conditions. A prototype of the installation has been installed in the existing wind flume at Delft. The installation comprises a wave board driven by a hydraulic servo system and generating waves according to an arbitrary programme. A similar installation, based upon this concept, has been realized at the River and Harbour Research Laboratory at Trondheim (Norway).

The new wind flumes, recently completed at Delft have also been equipped with programmed wave generators.

## 3. STATISTICAL ANALYSIS OF THE WAVE RECORDS

Descriptions and definitions will now be given of the different wave characteristics involded in the analysis of prototype as well as model records.

The characteristics applied in this study have by no means the pretension of giving a complete and satisfactory description. Moreover, the import of several of them is not clear in all respects. Their actual choice, however, is considered to be justified by the present state of research.

The individual wave heights and wave periods have been defined by the "zero-crossing method", in which each crossing of the surface elevation record $\eta(t)$ by the mean water level is termed a zero - crossing. Accordingly, the wave crest and wave trough are respectively the maximum (positive) and minimum (negative) value of $\eta(t)$ between two successive zero-crossings. The wave height H is termed the difference between the elevation of a wave trough and the next wave crest, and the wave period T: the time-lag between two zero - down crossings.

The zero - crossings method neglects the existence of positive minima or negative maxima. Also the Rayleigh distribution of wave heights (1) (presuming an energy spectrum with an infinitive small band width), similarly excludes the existence of negative maxima or positive minima (Ref. 9).

$$p(H) = H/4\sigma^2 . e^{-H^2/8\sigma^2} \qquad (1)$$

** $\sigma$ is the standard deviation of the wave record, and by definition also equal to the square root of the total (imaginary and real) area of the energy spectrum. From the cumulative frequency distributions of H and T the values have been determined, exceeded by 2,15 and 50 percent of the waves respectively. They have been demoted by the subscript 2, 15 or 50. Also the significant wave height Hs (average of the highest one-third waves of the record) has been calculated.

Apart from the statistical distributions of H and T, statistical distributions of the extreme values of $\frac{d\eta}{dt}$, separately for the lee-side and the windward-side of each wave, have been determined. $\frac{d\eta}{dt}$ has been approximated by $\frac{\eta(t) - \eta(t+\Delta t)}{\Delta t}$. Cumulative frequency distributions of $\frac{d\hat{\eta}}{dt}$, separately for the lee-side, $(\frac{d\hat{\eta}}{dt})^-$, and the windward-side, $(\frac{d\hat{\eta}}{dt})^+$, of the waves, give some information about the asymmetry. Accordingly the ratio of absolute $\frac{d\hat{\eta}}{dt}$ values at 15 % of exceedance

$$\frac{(\frac{d\hat{\eta}}{dt})_{+\,15}}{(\frac{d\hat{\eta}}{dt})_{-\,15}}$$

has been adopted as a "ratio of asymmetry" $\Delta$ of the waves.

Though very small, the correlation between H and T seems to be not always zero and consequently wave heights and wave periods may not be considered as stochastical uncorrelated variables.

The relation between wave heights and wave periods has been expressed in H - T correlation curves, indicating the mean height and the standard deviation of waves having periods within a distinct period interval.

Besides the statistical characteristics just described, the energy spectrum of the waves has been computed for all cases. In accordance with the more or less standardized procedure as proposed, for instance, by Blackman and Tukey (Ref. 10), the auto-correlation function $R(\tau)$ of the wave record and subsequently the Fourier transform of the correlation function have been computed, and conform to the expressions (2) and (3),

**

$$R(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{1}{2}T}^{\frac{1}{2}T} \eta(t) . \eta(t+\tau) . dt \tag{2}$$

$$S(f) = \int_{-\infty}^{+\infty} R(\tau) . e^{2\pi i f \tau} . d\tau = 2 \int_{0}^{+\infty} R(\tau) . \cos 2\pi f \tau . d\tau \tag{3}$$

$S(f)$ is the spectral density at the frequency $f$ (cps).

The width of the spectrum is expressed by the parameter $\varepsilon$

$$\varepsilon^2 = \frac{m_o m_4 - m_2^2}{m_o m_4} \tag{4}$$

in which $m_n = \int_{0}^{+\infty} S(f) . f^n . df$ (5)

For $n = 0$ one obtains the total (imaginary and real) area of the spectrum $m_o$ which follows by definition also from (2) for $\tau = 0$.
(Though the real area of the spectrum is only $\frac{1}{2} m_o$, as can be derived from (2) and (3), this factor $\frac{1}{2}$ is usually neglected in practice).

Though in principle not a statistical parameter, in practical computations the wave spectrum has a statistical nature too, because under the assumption of stationarity and ergodicity a finite record of the wave motion is taken, which yields an estimate of the spectral density distribution only.

All computations have been performed on a digital computer, for which the continuous wave records have been converted to digitized punch - tape records. The sampling frequency of the prototype records was 5 cps and of the model records 32 cps (in conformity with the adapted length scale 1 : 45 and time scale 1 : $\sqrt{45}$). The length of each "time series" was at least 15.000 samples for the records of the model wind waves, and at least 30.000 samples for all other records.

The statistical distributions of wave heights, periods and slopes $(\frac{d\hat{\eta}}{dt})$ as well as the H - T correlations have been determined directly from the obtained time series. Regarding the spectral analysis, only one of every six samples in the series has been taken in order to get a sufficiently high frequency resolution. As a result the Nyquist frequency $(\frac{1}{2\Delta t})$ became 2.666 cps and the frequency lag between two adjacent spectral estimates $(\frac{1}{2\ m\ \Delta t})$ 0.0444 cps. In order to "smooth" the spectrum, the correlation function has been filtered by a triangular-screen filter.

** Inherent to the definition of $\varepsilon$, the higher frequencies have an disproportionately large influence on the calculated value of $\varepsilon$, whereas both the accuracy and the practical interest of the spectrum in this frequency range is small. Therefore, the part of the spectrum at the high frequency side, which contributes 2% to the total area of the spectrum, has been discarded in the calculation of $\varepsilon$, and $\varepsilon$ calculated in this way has been denoted $\varepsilon_2$.

## 4. METHODS OF GENERATION

Three methods of wave generation have been compared on the basis of the parameters indicated in Section 3, and the results for each of the methods will be discussed separately. They have been compared with actually measured North Sea records and theoretical work of Cartwright and Longuet - Higgens (Ref. 9) as a reference.

### 4.1 Prototype records

Prototype records from the North Sea have been made availably by the Rijkswaterstaat. They have been recorded at the platform Triton, situated approximately 4 km off the Netherlands coast near Kijkduin, at a depth of 18 metres below M.S.L.

The wave height distributions, spectra and H - T correlations are shown in Fig. 6. Other parameters have been compiled in Table 1, together with data based upon Ref. 9.

### 4.2 Model records, wind only

Special measurements have been made in the wind-wave flume of the Delft Hydraulics Laboratory at "De Voorst". The fetch during these tests was 100 m, and water depths were 0.4 and 0.67 m. The average wind speeds $\bar{w}$ ranged from 6.6 to 22.5 m/sec. Wind profiles have been measured and related to the average wind speed (Figs. 1 a and b).
Note: $\bar{w} = w_{0.3}$ to $w_{0.4}$. (Wind speed measured at a height of 0.3 to 0.4 m above M.S.L.). Additionally, measurements of Colonell and Prins have been used. (Ref. 3 and 11).

It appears that the significant wave height Hs is increasing only slowly with the fetch for fetches greater than circa 100 m (Fig. 2). The same holds for the wave period (Fig. 3).

Apart from the absolute magnitude of height and period, the statistical distributions of these quantities show a rather limited variation, especially for higher wind speeds (See Table 2). Hence the spectra (Fig. 4 a) are very narrow, which is also illustrated by the small values of $\varepsilon$ ($\varepsilon_2 \approx 0.5$) and of T peak/T 50 in Table 2.
As the wind speeds in these tests have been exaggerated-in this sense that $\frac{gF}{w^2}$ is very small-to attain reasonable wave heights, the asymmetry of the waves can be expected to be high. This is confirmed by the tests, where $\Delta$ is found to be 1.15 to 1.77, whereas the prototype values varied from 0.99 to 1.15.

The H - T relation is given in Fig. 4 c, which shows both the average H - T relation of the six test runs and the average standard deviation with respect to the mean values.

## 4.3 Model records, wind strengthened swell

Measurements have been made in the same wind-wave flume as the tests mentioned in 4.2. The regular swell has been generated by a wave board situated at the beginning of the flume, and the period and height of the swell has been kept constant during each test run. Water depths were 0.4 and 0.67 m, and the periods of the swell 1.5 and 1.8 sec. respectively. Wave heights of the swell ranged from 5 to 15 cm. The average wind speeds varied between 6.6 and 12.8 m/sec. Wind profiles have not been measured separately.

The results of the tests have been summarized in Table 3 and Figure 5. It is evident that the spectra show a sharp and dominating peak at the frequency of the swell. The $\varepsilon$-values, however, do not indicate the narrow band width of the main part of the spectrum due to the second (wind) peak. Wave height distribution and period distribution are still less satisfactory then those of wind-generated waves. It is interesting to notice that also in this case the ratio of asymmetry $\Delta$, for the higher wind speeds, is considerably larger than the average value of the prototype waves.

The H - T relation shown in Fig. 5 c again presents the average wave height and average standard deviation in the corresponding period intervals, of all five tests. The regular character of this type of wave motion is accentuated by the very small standard deviation for periods exceeding 0.8 $T_{15}$.

## 4.4 Programmed wave generator

The purpose of the wave generator is to reproduce wide spectrum ocean waves as closely as possible. To achieve this, the wave board is driven by two separate hydraulic actuators so as to permit both translatory and rotational movements. Each actuator is controlled by two servo valves. The most attractive way to simulate ocean waves is to have an actual prototype record reproduced. The surface elevation record, however, has to be transferred into a command signal for the actuators, i.e., the horizontal movement of the wave board. Such a transfer function has been calculated by Biesel (Ref. 12) for monochromatic waves. The transfer function is shown in Figure 11, and presents the required stroke of the wave board at the water surface and near the bottom as a function of wave height, wave period and water depth. Though the theory of Biesel has been derived for monochromatic waves only, test results show that the method is also applicable for irregular waves.

Actual wave records can be used as an input signal to the programmed wave generator by means of a punch-tape. An electric network reproduces the transfer function of Fig. 11 and supplies separate command signals for both actuators.

If no prototype record is available, a wave record is simulated by using a random-noise generator, the random noise being filtered by a set of analogue second order filters. As both the resonance frequency and the damping of these filters are variable, the noise can be transformed into a signal having any arbitrary spectrum.
The output signal of the filter unit is fed into the transfer network in the same way as the puch-tape record. An outline of this system is presented in Fig. 12.

The tests referred to in this paragraph have been carried out in the old wind flume of the Laboratory at Delft. The length of this flume is 50 m and the water depth was 0.4 m. The prototype records mentioned in 4.1 have been reproduced on a length scale of 1 : 45.

The time and velocity scales were consequently $1:\sqrt{45}$. Average wind speeds during the tests ranged from 0 to 5.2 m/s; Wind profiles were not measured separately.

The results of the tests have been tabulated in Table 4 and are presented in Figs. 7, 8, 9 and 10.

It is clear that wave height and period distributions as well as the Δ-values are in very good agreement with the corresponding prototype data, both for the "punch-tape method" and the "random-noise method". The wave energy spectra also show satisfactory agreement with prototype data, though the energy density in the model is slightly lower in the high frequency range. In the meantime, this has been corrected by a modification of the electronic design.

The influence of wind speeds has been investigated extensively for run ST III. From Table 4 it appears that a variation of the average wind speed from 0 to 5.2 m/sec has no perceptible consequences for the statistical characteristics determined. As a result a small over- or underestimation of the wind speed in the model seems to have no consequences for the reproduction of the natural wave conditions. However, still insufficient information is available regarding the mechanism of the wind stress on the water surface and the shape of waves in exceptional conditions as to draw definite conclusions in respect to this.

The question might arise whether the application of programmed waves is worthwhile. In this respect attention is called to Refs. 6 and 13 where considerable influence of wave irregularity has been shown for wave run-up on smooth slopes and the stability of rubble-mound breakwaters.

## 5. SUMMARY AND CONCLUSIONS

Three methods of wave generation have been compared with prototype data on the basis of a number of statistical characteristics.

It has been shown that generating irregular waves by wind only has a serious drawback as flume lengths have to be very long. To limit the flume length, either wind speeds are increased and thus exaggerated with respect to the model scale, or swell is generated mechanically in addition.

Both methods affect the desired frequency distribution of wave heights and periods, and lead to relatively narrow energy spectra. The steepness of the wave fronts seems also to be rather high in comparison with prototype data.

An alternative method is found in the application of a hydraulic servo system, the programmed wave genrator. With this system it appears to be possible to reproduce actual prototype records or to simulate these records on the basis of their energy spectrum.

Also in the latter case it has been found that the frequency distributions of wave heights and periods are in good agreement with data obtained from prototype or theory. As to the shape of the wave, an attempt has been made to evaluate a parameter describing the asymmetry of the wave, and it appears that the application of wind is important in this respect.

During the evaluation of statistical parameters for the comparison of wave records it became clear that hardly any data are available on the detailed shape of prototype waves. Further research on this subject seems to be necessary as, for instance, the steepness of wave fronts is considered to be of great importance for the occurrence of impact forces. The use of the spectral width parameter $\varepsilon$ has proved to be hazardous in some case, especially when double-peaked spectra occur.

TABLE 1. Prototype Records.

| No. of record | ST III | 165 | 224 | Ref. |
|---|---|---|---|---|
| Date of record | 30 XI 65 | 4 XII 64 | 14 II 65 | |
| $H_{15}$ (m) | 3.85 | 3.95 | 3.15 | - |
| $H_{15}/H_{50}$ | 1.64 | 1.68 | 1.57 | 1.62 |
| $H_2/H_{50}$ | 2.30 | 2.34 | 2.23 | 2.37 |
| $T_{15}$ (sec) | 10.3 | 10.7 | 9.1 | - |
| $T_{15}/T_{50}$ | 1.46 | 1.49 | 1.48 | - |
| $T_2/T_{50}$ | 1.67 | 1.94 | 1.98 | - |
| $T_{peak}/T_{50}$ | 1.31 | 1.50 | 1.39 | - |
| $m_o$ ($m^2$) | 1.03 | 1.06 | 0.73 | - |
| $Hs/\sqrt{m_o}$ | 3.89 | 3.91 | 3.80 | 4.0 |
| $\varepsilon_2$ | 0.64 | 0.65 | 0.64 | - |
| $\Delta$ | 1.135 | 0.99 | 1.15 | - |

TABLE 2. Wind-generated Waves, Fetch 100 m.

| Test Run | T2 w | T3 w | T5 w | T6 w | T7 w | T8 w |
|---|---|---|---|---|---|---|
| $\bar{w}$ (m/sec) | 6.6 | 12.8 | 16.5 | 16.3 | 6.6 | 22.5 |
| d (m) | 0.4 | 0.4 | 0.67 | 0.67 | 0.67 | 0.67 |
| $H_{15}$(cm) | 4.6 | 13.4 | 18.1 | 16.4 | 6.2 | 20.6 |
| $H_{15}/H_{50}$ | 1.64 | 1.36 | 1.35 | 1.35 | 1.44 | 1.35 |
| $H_2/H_{50}$ | 2.13 | 1.65 | 1.59 | 1.79 | 1.80 | 1.65 |
| $T_{15}$(sec) | 0.86 | 1.30 | 1.28 | 1.27 | 1.13 | 1.45 |
| $T_{15}/T_{50}$ | 1.16 | 1.12 | 1.13 | 1.14 | 1.11 | 1.13 |
| $T_2/T_{50}$ | 1.32 | 1.31 | 1.24 | 1.30 | 1.29 | 1.28 |
| $T_{peak}/T_{50}$ | 1.05 | 1.01 | 0.98 | 1.03 | 0.99 | 1.00 |
| $m_o$ ($cm^2$) | 1.39 | 12.9 | 22.8 | 19.6 | 2.5 | 30.0 |
| $Hs/\sqrt{m_o}$ | 4.01 | 3.79 | 3.80 | 3.83 | 3.90 | 3.81 |
| $\varepsilon_2$ | 0.50 | 0.51 | 0.49 | 0.50 | 0.43 | 0.56 |
| $\Delta$ | 1.15 | 1.22 | 1.38 | 1.28 | 1.23 | 1.77 |

TABLE 3. Wind-strengthened Swell, Fetch 100 m.

| Test run | T.4 | T.8 | T.12 | T.14 | T.18 |
|---|---|---|---|---|---|
| $H_{swell}$ (cm) | 5.0 | 10.0 | 7.5 | 7.5 | 15.0 |
| $T_{swell}$ (sec) | 1.5 | 1.5 | 1.8 | 1.8 | 1.8 |
| $\overline{w}$ (m/sec) | 12.8 | 6.5 | 6.6 | 11.4 | 11.4 |
| d (m) | 0.4 | 0.4 | 0.67 | 0.67 | 0.67 |
| $H_{15}$(cm) | 13.4 | 13.4 | 10.2 | 17.3 | 21.2 |
| $H_{15}/H_{50}$ | 1.31 | 1.08 | 1.16 | 1.34 | 1.10 |
| $H_2/H_{50}$ | 1.67 | 1.16 | 1.27 | 1.61 | 1.22 |
| $T_{15}$ (sec) | 1.78 | 1.70 | 1.94 | 1.89 | 1.96 |
| $T_{15}/T_{50}$ | 1.25 | 1.07 | 1.04 | 1.66 | 1.04 |
| $T_2/T_{50}$ | 1.37 | 1.10 | 1.08 | 1.80 | 1.11 |
| $T_{peak}/T_{50}$ | 1.06 | 0.95 | 0.97 | 1.70 | 0.96 |
| $m_o$ ($cm^2$) | 12.2 | 17.5 | 8.1 | 19.8 | 37.5 |
| $Hs/\sqrt{m_o}$ | 3.92 | 3.24 | 3.58 | 3.95 | 3.55 |
| $\varepsilon_2$ | 0.61 | 0.56 | 0.75 | 0.62 | 0.60 |
| $\Delta$ | 1.11 | 1.00 | 1.01 | 1.19 | 1.28 |

TABLE 4. Programmed Wave Generator.

| Test run | ST III A | ST III B | ST III C | ST III R | 224 P | 165 P | 165 R |
|---|---|---|---|---|---|---|---|
| Origin Input signal | punch-tape | punch-tape | punch-tape | random-noise | punch-tape | punch-tape | random-noise |
| $\overline{w}$ (m/sec) | 3.0 | 0 | 5.2 | 3.0 | 3.0 | 3.0 | 3.0 |
| $H_{15}$ (cm) | 8.6 | 8.4 | 8.9 | 8.5 | 7.3 | 8.3 | 8.5 |
| $H_{15}/H_{50}$ | 1.62 | 1.64 | 1.59 | 1.63 | 1.62 | 1.57 | 1.54 |
| $H_2/H_{50}$ | 2.17 | 2.18 | 2.14 | 2.30 | 2.16 | 2.15 | 2.00 |
| $T_{15}$ (sec) | 1.57 | 1.56 | 1.52 | 1.60 | 1.47 | 1.76 | 1.81 |
| $T_{15}/T_{50}$ | 1.27 | 1.27 | 1.32 | 1.28 | 1.36 | 1.46 | 1.39 |
| $T_2/T_{50}$ | 1.52 | 1.55 | 1.56 | 1.61 | 1.80 | 1.87 | 1.78 |
| $T_{peak}/T_{50}$ | 1.16 | 1.17 | 1.25 | 1.17 | 1.18 | 1.81 | 1.27 |
| $m_o$($cm^2$) | 4.9 | 4.7 | 5.6 | 5.0 | 3.7 | 5.1 | 4.9 |
| $Hs/\sqrt{m_o}$ | 3.92 | 3.91 | 3.88 | 3.89 | 3.86 | 3.80 | 3.90 |
| $\varepsilon_2$ | 0.52 | 0.52 | 0.54 | 0.54 | 0.54 | 0.59 | 0.61 |
| $\Delta$ | 1.04 | 1.015 | 1.04 | 1.10 | 1.05 | 1.075 | 1.09 |

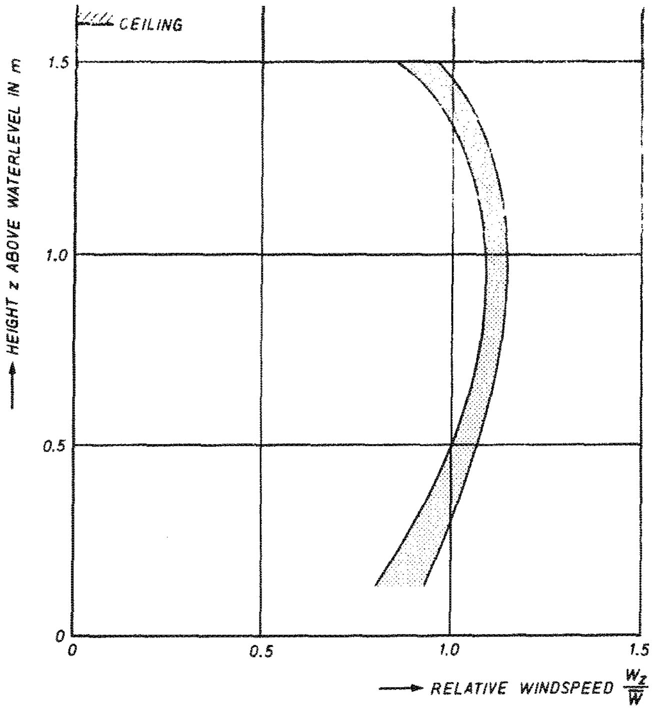

FIG. 1a RELATIVE WINDSPEED, WATERDEPTH 0.4 m

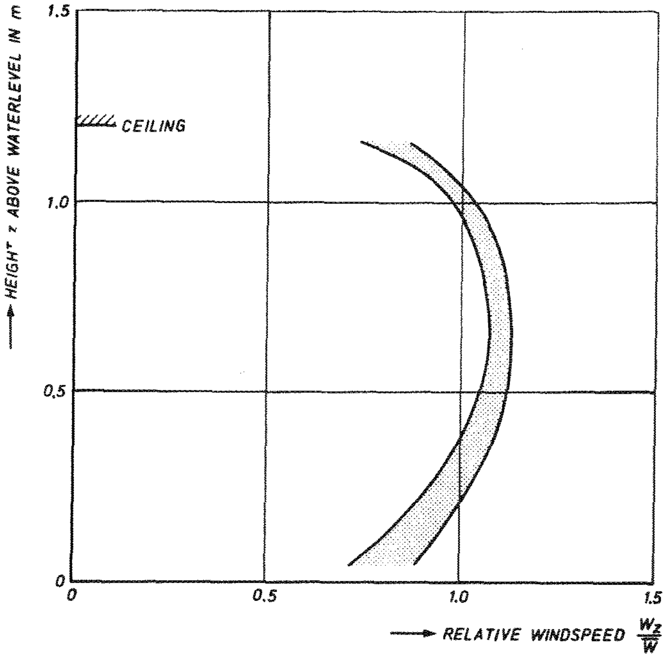

FIG. 1b RELATIVE WINDSPEED, WATERDEPTH 0.8 m

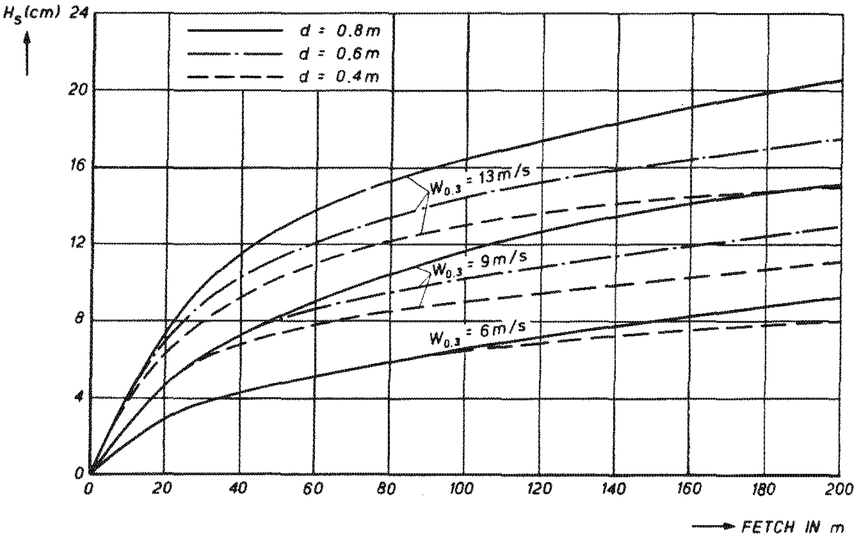

FIG. 2 SIGNIFICANT WAVE HEIGHT VERSUS FETCH

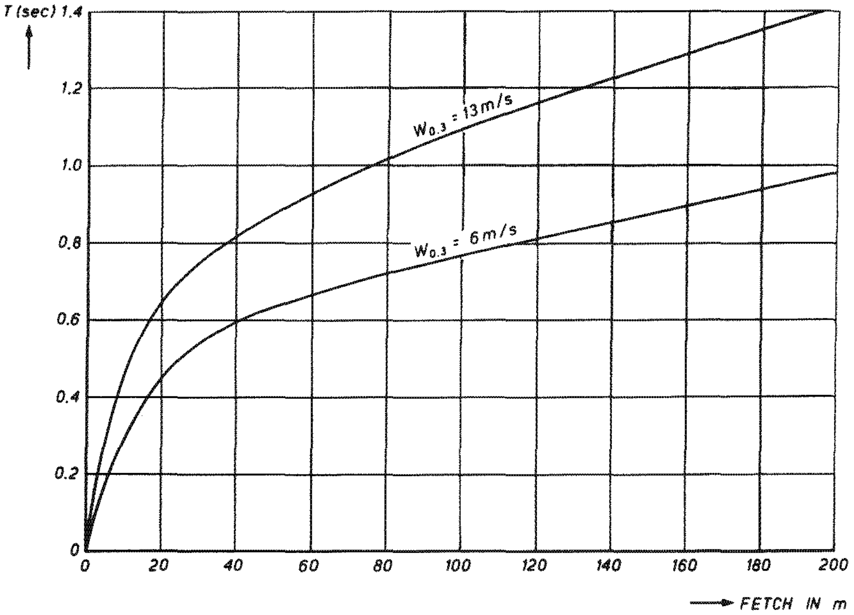

FIG. 3 WAVE PERIOD VERSUS FETCH

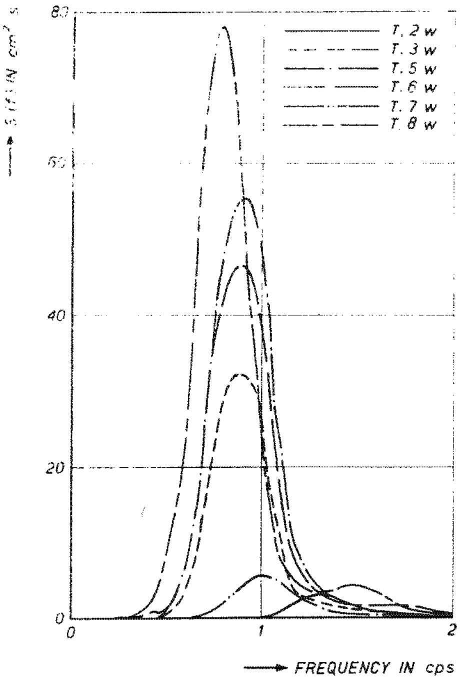

FIG. 4a WAVE-ENERGY SPECTRA, WIND GENERATED WAVES

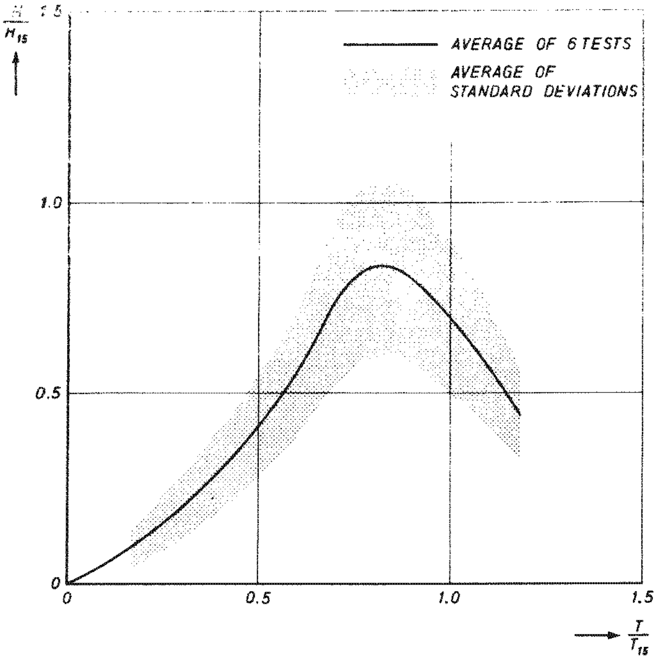

FIG. 4c H-T RELATION, WIND GENERATED WAVES

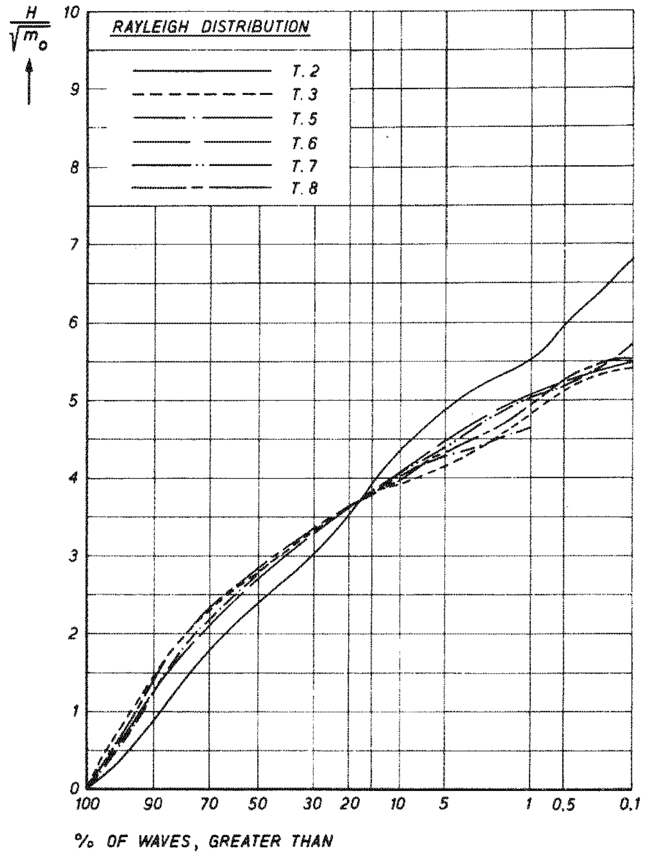

FIG. 4b WAVE HEIGHT DISTRIBUTIONS WIND GENERATED WAVES

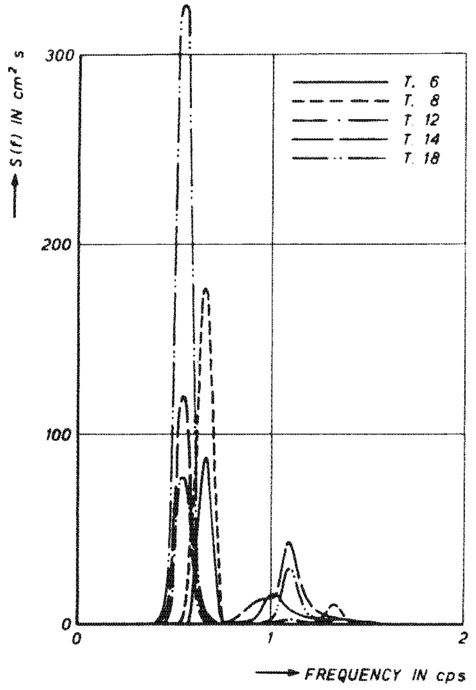

FIG. 5a WAVE-ENERGY SPECTRA, WIND STRENGTHENED SWELL

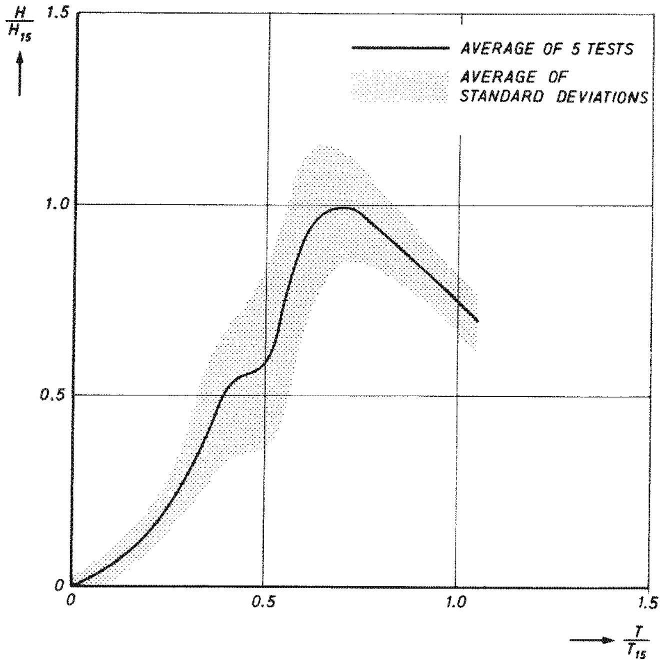

FIG. 5c H-T RELATION, WIND STRENGTHENED SWELL

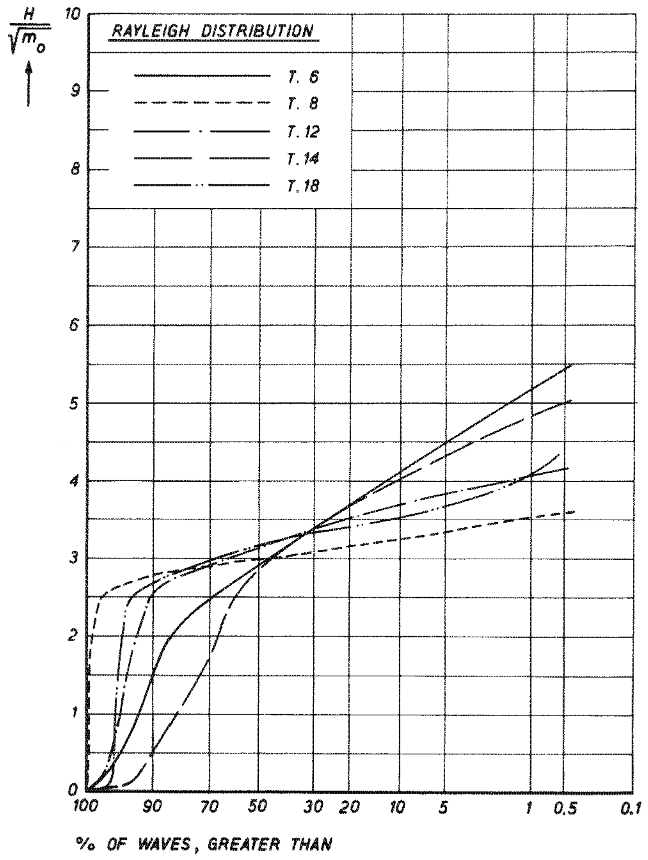

FIG. 5b WAVE HEIGHT DISTRIBUTIONS WIND STRENGHTHENED SWELL

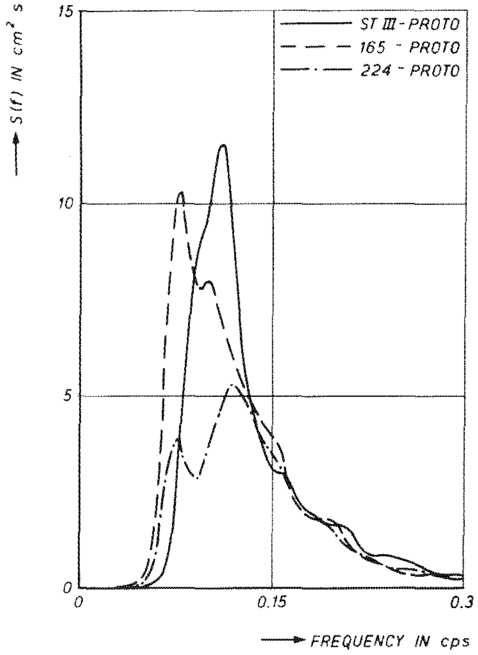

FIG. 6a WAVE-ENERGY SPECTRA PROTOTYPE WAVES

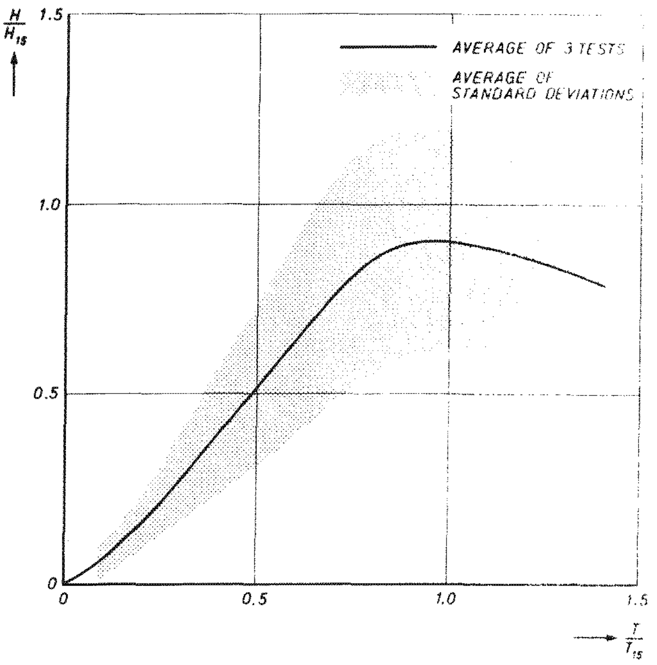

FIG. 6c H-T RELATION, PROTOTYPE RECORDS

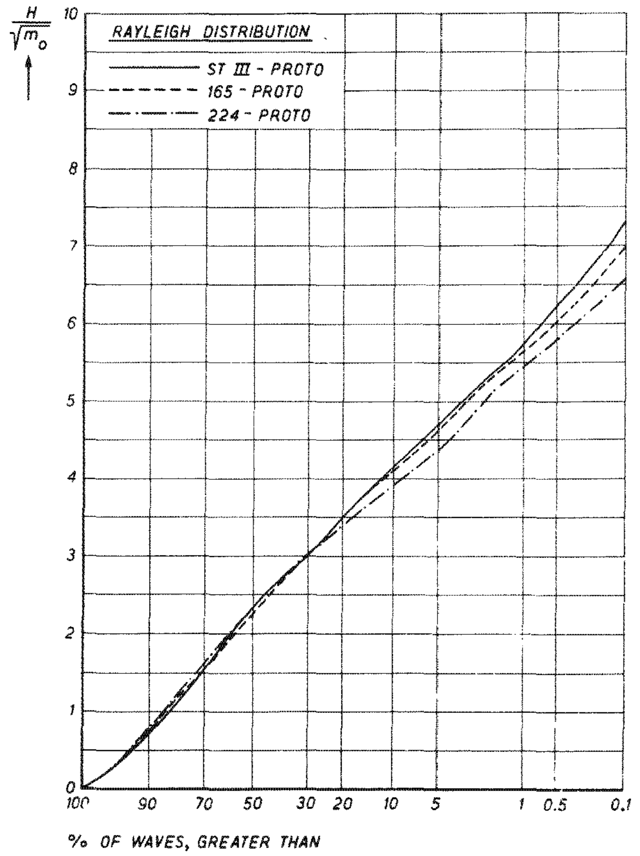

FIG. 6b WAVE HEIGHT DISTRIBUTIONS PROTOTYPE WAVES

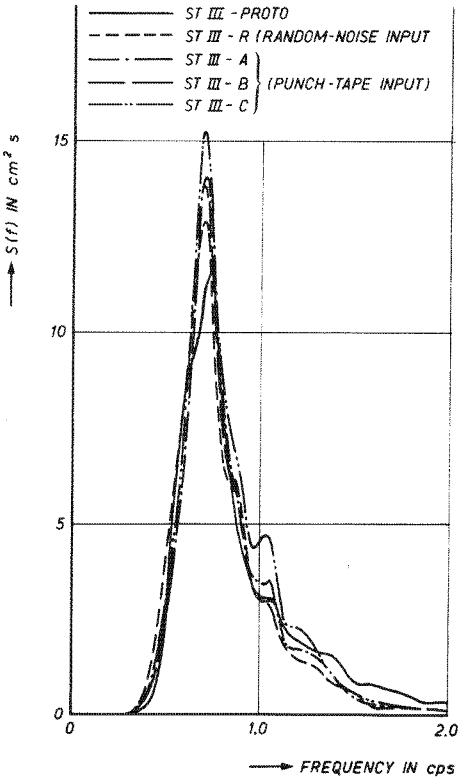

FIG. 7a WAVE – ENERGY SPECTRA, PROGRAMMED WAVES VERSUS PROTOTYPE WAVES

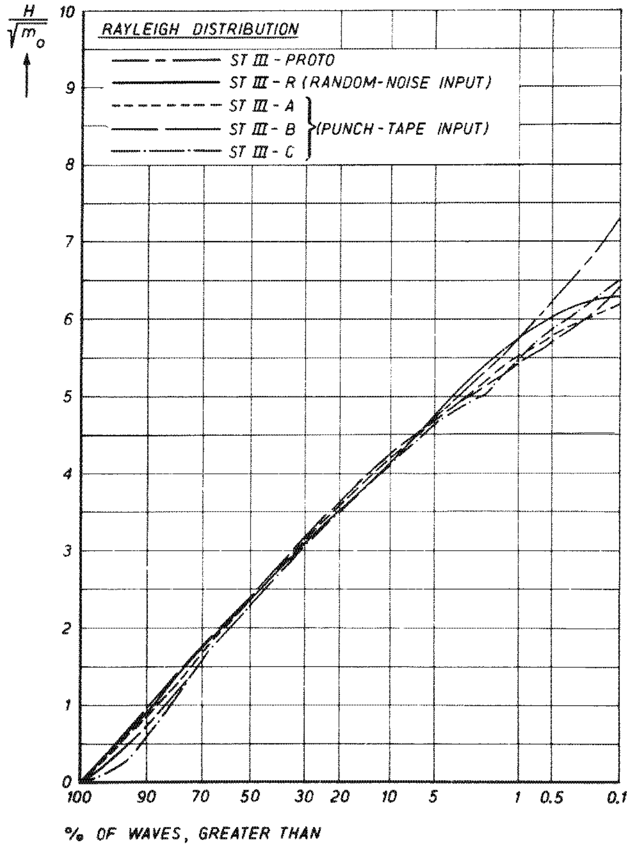

FIG. 7b WAVE HEIGHT DISTRIBUTIONS, PROGRAMMED WAVES VERSUS PROTOTYPE WAVES

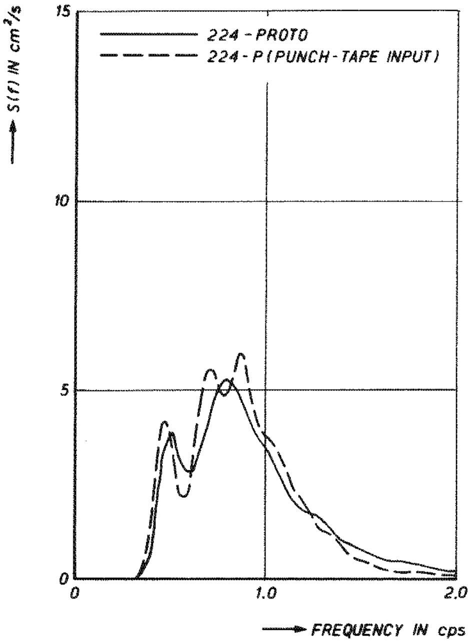

FIG. 8a WAVE – ENERGY SPECTRA, PROGRAMMED WAVES VERSUS PROTOTYPE WAVES

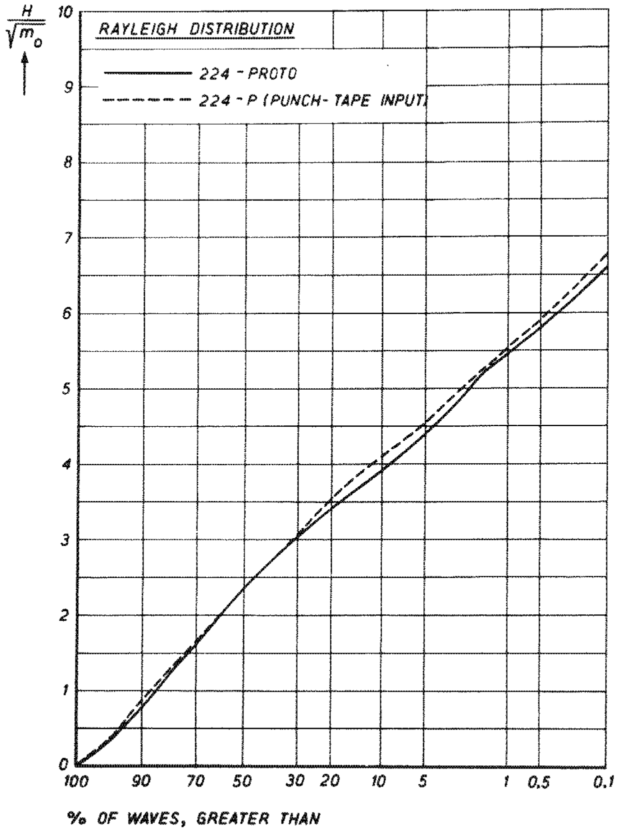

FIG. 8b WAVE HEIGHT DISTRIBUTIONS, PROGRAMMED WAVES VERSUS PROTOTYPE WAVES

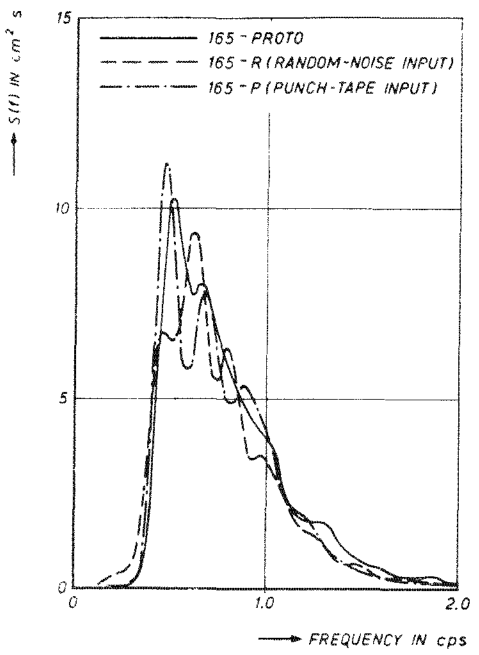

FIG 9a WAVE – ENERGY SPECTRA, PROGRAMMED WAVES VERSUS PROTOTYPE WAVES

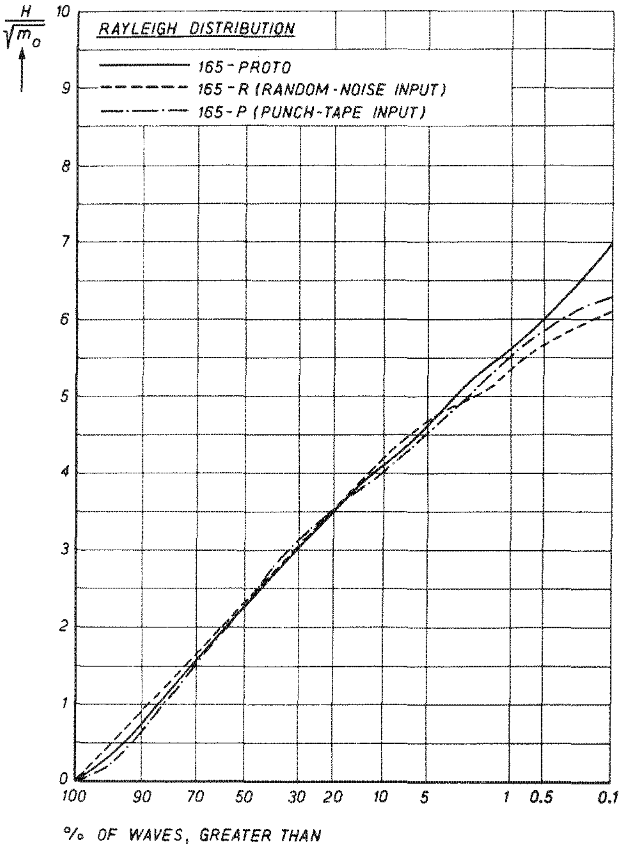

FIG. 9b WAVE HEIGHT DISTRIBUTIONS, PROGRAMMED WAVES VERSUS PROTOTYPE WAVES

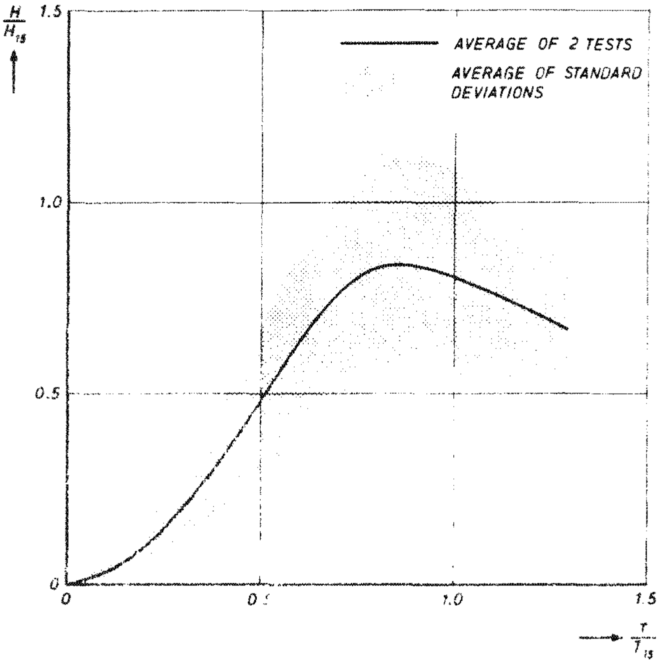

FIG 10a H-T RELATION, PROGRAMMED WAVES
[illegible]

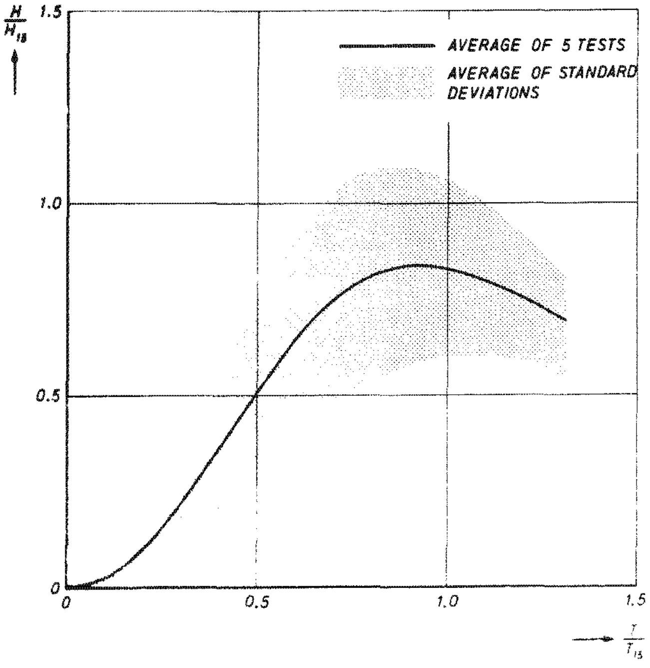

FIG 10b H-T RELATION, PROGRAMMED WAVES
PUNCH-TAPE INPUT

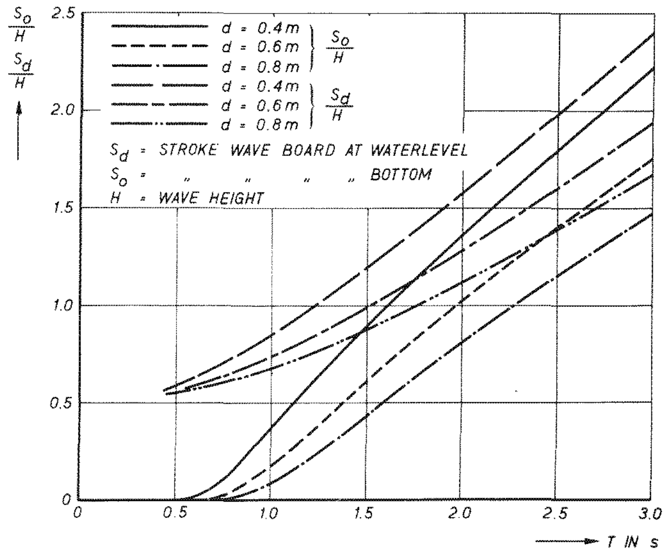

FIG. 11 TRANSFER FUNCTION WAVE HEIGHT TO WAVE BOARD

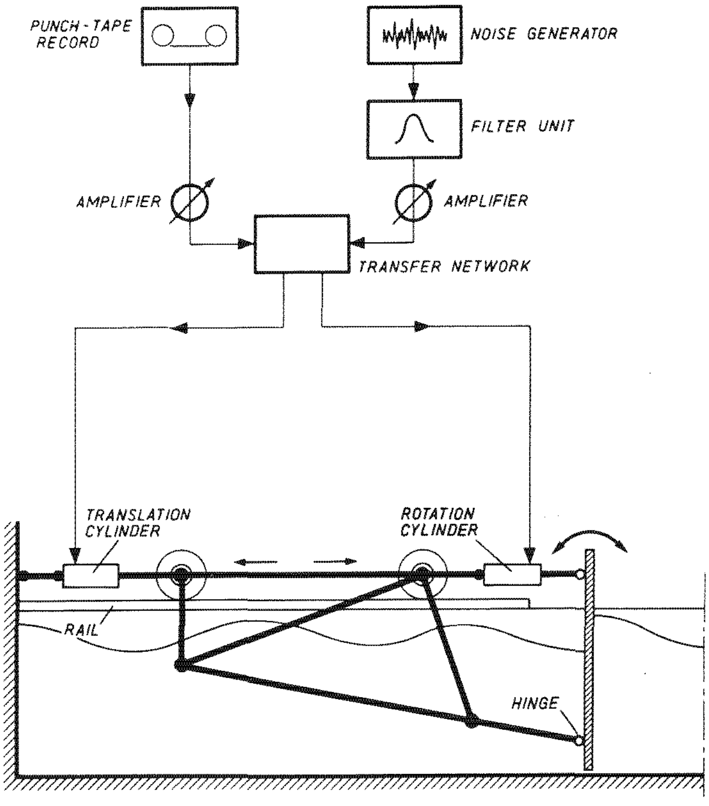

FIG. 12 SYSTEM SET-UP WAVE GENERATOR

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## LIST OF SYMBOLS

| | |
|---|---|
| $d$ | water depth |
| $\Delta$ | ratio of asymmetry of the waves |
| $\varepsilon$ | spectral width parameter |
| $f$ | frequency in cps |
| $H$ | wave height |
| Hs | significant wave height |
| $H_n$ | wave height with an percentage of exceedance n |
| $m$ | number of points of the auto-correlation function |
| $m_n$ | $n$ th moment of the energy spectrum |
| $p(H)$ | probability density function of wave heights |
| $S(f)$ | spectral density at frequency f |
| $T$ | wave period |
| $T_n$ | wave period with an percentage of exceedance n |
| $T_{peak}$ | period of the wave spectrum with maximum energy density |
| $t$ | time |
| $\eta(t)$ | surface elevation record |
| $\Delta t$ | time-lag between two samples in the time series |
| $\tau$ | time - shift |
| $R(\tau)$ | auto - correlation function |
| $w_z$ | wind speed measured at z metres above the mean still-water level |
| $\overline{w}$ | average wind speed |

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