High-Frequency Components of Ocean Waves and Their Relation to the Aerodynamic Roughness

JUNSEI KONDO, YUKIO FUJINAWA AND GEN'ICHI NAITO

Institute of Coastal Oceanology, National Research Center for Disaster Prevention, Hiratsuka, Japan

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ABSTRACT

Ocean waves of high frequency (from about 10 to 200 rad sec⁻¹) were observed by means of a thin capacitance-type wave gage. The representative rms height, h_p , of the sea-surface irregularities associated with the high-frequency waves is less than the thickness of the laminar sub-layer under light winds, but increases with wind speed and exceeds the thickness of the laminar sublayer when the wind speed exceeds 3 m sec⁻¹. The values of the roughness Reynolds number, $h_p u^*/\nu$, which delineate the upper limit of the smooth surface regime and the lower limit of the fully rough regime are found to be about 6 and 67, respectively.

Power spectra vs frequency n from the present field observations indicate a significant departure from the n^{-5} saturation relation of Phillips at frequencies in the range 10–250 rad sec⁻¹. Moreover, the departure increases with wind speed indicating that a saturation limit does not seem to exist for the capillary range.

1. Introduction

Recent observations have shown that the drag coefficients of the sea surface at a height of 10 m under neutral or near-neutral conditions are of the order of magnitude of 10^{-3} to 2×10^{-3} . Deacon and Webb (1962), Kondo (1962), Phillips (1966), Hicks and Dyer (1970), and Kondo *et al.* (1972a) proposed that the drag coefficient in low wind speeds has the same coefficient as a smooth plate, but that in moderate and strong winds it increases with wind speed.

Similarly, Francis (1951), Hamada *et al.* (1963) and Kunishi (1963) have found the drag coefficient of a water surface in wind-tunnel experiments to increase with wind speed. When these authors extrapolated their 10-cm wind speeds to a height of 10 m, their drag coefficients had magnitudes very similar to those obtained over the sea surface. The energy-containing frequencies of waves in the wind tunnel fall in a range from about 2–10 Hz, but in ocean waves the corresponding range is from 0.1–0.5 Hz. Kondo *et al.* (1972b) showed a lack of significant dependency of the drag coefficient on the amplitude of sea-surface displacements having frequencies $\lesssim 0.5$ Hz. On the other hand, Toba and Kunishi (1970) show that the drag coefficient of a water surface in a wind-wave tunnel depends on a kind of roughness Reynolds number, and does not depend on the fetch.

Cox and Munk (1954) obtained a linear variation of the mean-square slope of the sea surface with wind speed, and discovered that the higher frequency wave components, which make large contributions to the mean-square slope, could be eliminated with artificial oil slicks. The effect on the stress of the ripples and

wavelets was shown by Van Dorn (1953) in his wind-stress measurements on an artificial pond, with and without a soap slick.

The above results strongly suggest that the mechanism of drag is controlled not by large waves but primarily by ripples and wavelets. In the present paper, observations of the high-frequency components of ocean waves are dealt with, and some analyses are made of the relation between the aerodynamic roughness parameter and the height of high-frequency wave components.

2. Observations and data analysis

Observations were made on the Marine Observation Tower of the Institute. The tower is located 1 km off the coast of Hiratsuka City in a water depth of 20 m. Details of the tower were described in a previous paper (Kondo *et al.*, 1972a). The sea-surface displacement and high-frequency wave components were measured by means of a capacitance wave-recording gage. The sensing element was made of insulated copper wire 0.3 mm diameter covered with a synthetic resinous paint. The response time of the sensing element was ~ 0.03 sec. This was obtained experimentally in a water tank filled with sea water.

A preliminary evaluation indicates that the breaking waves observed in these experiments were composed of wave components with frequencies $\gtrsim 2$ Hz and with amplitudes of a few millimeters to a few centimeters. Fig. 1 shows some example wave records which were obtained when a breaking wave passed through the sensing element of the wave gage. In our analysis attention was confined to such high-frequency wave

FIG. 1. Examples of wave recordings illustrating breaking waves.

components by processing the record through an electronic band-pass filter circuit, the frequency response function of which is presented in Fig. 2. This was obtained in the laboratory by making the capacitance of the calibration apparatus change sinusoidally with a frequency f . The variable condenser of the apparatus is electrically connected in parallel to the sensing element of the wave gage.

The sampling interval was 0.0125 sec for the high-frequency wave components and the recording time for each run was 150–250 sec. The output from the instrument was digitized and transmitted to an SDS-M92 computer. On the other hand, passage of a whitecap through the wave gage was marked on the recorder by an observer who was watching through a telescope mounted at a height of 20 m above the sea surface.

Examination of breaking waves as shown in Fig. 1 suggests that the variance of fluctuations may be a suitable parameter for representing high-frequency waves. Owing to the inadequacy of the filter at the low-frequency end, the variance is dependent on the sampling duration due to the influence of low-frequency wave components which remain in the filtered record. In order to suppress the influence of the residual low frequencies, the variance v is calculated for durations of 0.2 sec (16 samples) at intervals of 0.1 sec over the record, rather than evaluating a variance for the whole record from the overall mean level. The following two quantities are defined:

$$h = 2(v)^{1/2}, \quad (1)$$

$$\bar{h} = \frac{1}{N_0} \sum h, \quad (2)$$

where N_0 is the total number of calculations of h in a run. Since h is based on samples of only 0.2 sec duration, we will refer to it as a “local” scale height, which is related to frequencies exceeding a few cycles per second. The values of h are distributed over a range from 10^{-2} cm to a few centimeters.

Photographs of whitecaps were taken with an 8-mm automatic movie camera. The camera was mounted on the tower at 20 m above the sea surface and was tilted so that its field of view might cover a distance range of 32 to 150 m from the tower. Photographs were taken from a line of sight parallel to the wave crests, thus avoiding hidden areas. Analysis of the whitecaps was made for each frame, over a trapezoidal region of the sea surface (of 2730 m² area) bounded by two parallel lines, 35 m and 100 m from the tower, and two lateral lines forming an angle of 31° at the tower. The fraction of sea surface covered by whitecaps was determined by projecting each photographic transparency onto a graduated sheet of frosted glass 29 cm long and 21 cm wide. One hundred to several hundred photographs were analyzed for each run, using whitecaps larger than 20 cm × 20 cm. Details of the instrumentation and observational data are described elsewhere (Kondo *et al.*, 1973).

Observations were confined to nearly neutral stability conditions in this study.

3. Power spectra of sea-surface displacement

For *gravity* waves under the influence of local wind, an equilibrium range presumably exists in the spectral density, $P(n)$, of surface displacements having the form

$$P(n) = \beta g^2 n^{-5}, \quad (3)$$

where g is the gravitational acceleration, n angular frequency ($2\pi f$), and β a nondimensional constant. Phillips (1966, pp. 113–114) has summarized results of previous measurements in the equilibrium range and suggests a mean value of β of 1.17×10^{-2} . It is noteworthy that these previous measurements are confined to frequencies < 16 rad sec⁻¹ (Fig. 4.8 of Phillips).

The present measurements indicate an upper limit of n for the applicability of (3). Examples of the spectral density vs n obtained for two different values of wind speed at 10 m elevation are presented in Fig. 3. The open circles and squares were obtained from the un-

FIG. 2. The frequency response function of the band-pass filter.

filtered records; the solid symbols were obtained from the filtered records in which the low frequencies are suppressed, taking into account the correction for the filter response (Fig. 2). The Nyquist frequency in the present experiments is 40 Hz or about 250 rad sec⁻¹, which is well into the capillary range in which surface tension dominates over gravity. Thus, it should not be surprising that the spectra depart significantly from (3) at frequencies greatly in excess of 10 rad sec⁻¹.

Fig. 4 shows $P(n)$ vs u_{10m} for $n=26, 47, 79, 126$ and 209 rad sec⁻¹. The plotted points are classified according to the heights of significant ocean waves, $H_{1/3}$. The open circles and triangles pertain to strong waves, and the crosses and solid circles to light waves. The dependency of $P(n)$ on $H_{1/3}$ is clear in the figure. What is somewhat unexpected is the significant dependency of $P(n)$ on wind speed in the capillary range, since Phillips (1966) suggests that a saturation limit should also exist for this range. There is some evidence to substantiate Phillips' hypothesis from the laboratory measurements by Cox (1958) of wave slopes in the capillary range. However, our field results do not indicate a capillary saturation limit, at least within the range of winds encountered (about 1–16 m sec⁻¹ at 10 m). Moreover, the results of Cox indicate a high-frequency cutoff, dependent on wind speed, beyond which the spectrum drops off drastically; since this occurred at frequencies well above 200 rad sec⁻¹, a similar feature could not be detected in our results.

4. Whitecaps

Fig. 5 shows the percentage of the water surface covered by whitecaps as a function of u_{10m} . The figure

FIG. 3. Frequency spectra of sea-surface displacement. For run 37, $u_{10m} = 12.4$ m sec⁻¹ while for run 74, $u_{10m} = 6.1$ m sec⁻¹. The heavy line represents Eq. (3) with $\beta = 1.17 \times 10^{-2}$.

FIG. 4. Spectral density vs u_{10m} . The points are classified according to the significant ocean wave height ($H_{1/3}$).

indicates that there is an onset of whitecaps when the wind speed exceeds 5 m sec⁻¹. On the other hand,

FIG. 5. Percent of the sea surface covered by whitecaps as a function of wind speed. The observations are classified according to the water temperature at the sea surface (T_w).

FIG. 6. The frequency distribution of the local scale h of sea surface irregularity for runs 71-76. The open squares indicate all observations. The solid and open circles indicate the small-scale and the medium-scale whitecaps, respectively, which pass through the wave gage.

Blanchard (1963) shows that there are no whitecaps when the wind speed $< 3 \text{ m sec}^{-1}$, Monahan (1971) when the wind speed $< 4 \text{ m sec}^{-1}$, and Munk (1947) when the wind speed $< 6 \text{ m sec}^{-1}$.

The figure also indicates that the whitecap coverage is invariably $< 0.1\%$ when $u_{10m} < 8 \text{ m sec}^{-1}$, and is about 1% when $u_{10m} = 15 \text{ m sec}^{-1}$. Comparison of the present results with the works mentioned above shows that the whitecap coverage derived from the present observations is much less than existing published values at corresponding wind speeds. One of the reasons for this discrepancy may be found in the different methods of photography. In the present case the photographs were taken normal to the direction of wave propagation and at a short distance, thus minimizing any over-estimation effects. On the other hand, the other published results derive from photographs obtained at large horizontal distances and taken from the windward side.

The lifetime of an individual whitecap was measured by continuous photographs. Values of the lifetime of most whitecaps are distributed in the range between 0.3 and 3 sec. The mean lifetime is about 1.3 sec when $u_{10m} = 5-11 \text{ m sec}^{-1}$ and 1.6 sec when $u_{10m} = 11-14 \text{ m sec}^{-1}$. The dependency of lifetime on water temperature is obscure.

The area of an individual whitecap tends to be smaller than 20 m^2 when $u_{10m} < 10 \text{ m sec}^{-1}$, with the area increasing with increasing wind speed. The largest area, 40 m^2 , was observed at the greatest wind speed, $u_{10m} = 14 \text{ m sec}^{-1}$. The mean area of individual whitecaps was 1.4 m^2 for $u_{10m} = 5-11 \text{ m sec}^{-1}$, and 2.2 m^2 for $u_{10m} = 11-14 \text{ m sec}^{-1}$.

5. Frequency distribution of h

Fig. 6 presents the frequency distribution of the local scale h characterizing the sea surface irregularity. In

this figure $N(h)$ is defined by

$$N(h) = \frac{\Delta N(h_i)}{2\Delta h}, \quad (4)$$

where $\Delta N(h_i)$ represents the numbers of occurrence of h between $h_i + \Delta h$ and $h_i - \Delta h$, h_i is the abscissa of the points of Fig. 6, and Δh is a small interval of h , proportional to h_i . The distribution has been normalized by N_0 such that

$$\int_0^\infty [N(h)/N_0] dh = 1. \quad (5)$$

The data in Fig. 6 were obtained from the contiguous observational runs 71 to 76, for which $u_{10m} = 7.6 \text{ m sec}^{-1}$, $\bar{h} = 0.6 \text{ cm}$ and $N_0 = 24,000$. The open squares express the frequency distribution for all observations with and without whitecaps. Values of $h \geq 5 \text{ cm}$ are indicated as having non-zero probability, i.e., $6/24,000$. These extreme values of h were observed on occasions involving the breaking of the crest of significant waves. In general, for the cases of light winds the values of h at the crest are nearly the same as those at the trough; for $u_{10m} > 5 \text{ m sec}^{-1}$, however, the values of h at the crest tend to be larger than those at the trough.

In the distribution curve of $N(h)/N_0$ a peak is seen at $h = 0.3 \text{ cm}$. Hereafter, we define h_p to be the value at which $N(h)/N_0$ takes its maximum value. From the observational data we obtain the empirical relation $\bar{h} \approx 2.0h_p$.

In runs 71-76, 41 small-scale whitecaps (those with areas $< 1 \text{ m}^2$) and 21 medium-scale whitecaps (those with areas from $1-3 \text{ m}^2$) are included. An important feature shown in the figure is that although whitecaps are accompanied by h values invariably larger than 0.5 cm , values of $h > 0.5 \text{ cm}$ occur quite frequently without accompanying whitecaps. In other words, the high-frequency components of ocean waves are not

FIG. 7. The frequency distribution of the local scale h of sea surface irregularity for runs 32, 37, 44 and 74.

often composed of whitecaps, but rather of ripples and breaking waves unaccompanied by whitecaps. It was only in runs 71–76 that simultaneous observations were made of the size of the whitecaps and the frequency distribution of h in them.

Fig. 7 presents the frequency distributions for runs 32, 37, 44 and 74, and the associated meteorological and oceanographic data are given in Table 1. The crosses indicate run 32 ($u_{10\text{ m}}=0.7\text{ m sec}^{-1}$), the open squares run 74 ($u_{10\text{ m}}=6.1\text{ m sec}^{-1}$), the solid circles run 44 ($u_{10\text{ m}}=12.3\text{ m sec}^{-1}$ with short fetch), and the open circles run 37 ($u_{10\text{ m}}=12.4\text{ m sec}^{-1}$ with long fetch). We can see that although h_p increases with wind speed, the shape of the distribution function for h is found to be nearly independent of wind speed.

6. Sea-surface irregularity and thickness of the laminar sub-layer

Representative scales for the sea-surface irregularities, h_p , were estimated for all observational runs. These are plotted as a function of wind speed in Fig. 8, the data being classified according to the heights of significant ocean waves, $H_{1/3}$. The open circles and triangles indicate strong waves, and the crosses and solid circles light waves. The weak dependency of h_p on $H_{1/3}$ is clear, and h_p is found to increase with wind speed.

For aerodynamically smooth flow, it is well-known that there is a laminar sub-layer above the surface, whose thickness is given by (Schlichting, 1968)

$$\delta \approx 11.5\nu/u^*, \quad (6)$$

where ν is the kinematic viscosity of air and u^* the friction velocity. The value of u^* for smooth flow is determined by the well-known formula:

$$u_z = u^* \left[\frac{1}{k} \ln \left(\frac{zu^*}{\nu} \right) + 5.5 \right], \quad (7)$$

where k ($=0.4$) is von Kármán's constant and u_z the wind velocity at the height z . The broken line in Fig. 8 indicates the value of δ as a function of wind speed at 10 m.

7. Results and discussions

The ocean and wind-wave tunnel experiments mentioned in Section 1 show that the surface is invari-

TABLE 1. Meteorological and oceanographic data summaries for runs 32, 37, 44 and 74.

Run	$u_{10\text{ m}}$ (m sec ⁻¹)	Fetch (km)	Significant wave Height (cm)	Period (sec)	h_p (cm)
32	0.7	1	44	8.4	0.07
37	12.4	30	137	4.8	0.57
44	12.3	1	38	1.5	0.43
74	6.1	40	63	2.9	0.30

FIG. 8. The representative scale h_p of the sea-surface irregularity as a function of wind speed. The observations are classified according to the significant ocean wave height ($H_{1/3}$). The thickness of the laminar sub-layer is shown as a broken line.

bly smooth when $u_{10\text{ m}} < 2\text{ m sec}^{-1}$. For $u_{10\text{ m}} = 2\text{ m sec}^{-1}$ it is found from Fig. 8 that $h_p \approx 0.5\delta = 0.14\text{ cm}$. This implies that 30% of the surface protrusions extend outside the laminar sub-layer and 70% are contained within. This can be obtained from the function representing the shape of frequency distribution of h (Figs. 6 and 7). If the sea surface is smooth for $u_{10\text{ m}} = 2\text{ m sec}^{-1}$, the friction velocity is found to be $u^* = 6.2\text{ cm sec}^{-1}$ [from Eq. (7)], and the roughness Reynolds number to be $h_p u^* / \nu \approx 5.7$. This value is very similar to Nikuradse's (1933) critical Reynolds number for the upper limit of the smooth regimes.

Fig. 8 also shows that the value of h_p extends above the laminar sub-layer as the wind speed exceeds 3 m sec^{-1} , and that $h_p \approx 4.4\delta = 0.34\text{ cm}$ at $u_{10\text{ m}} = 8\text{ m sec}^{-1}$. The latter relation implies that almost all protrusions (99.9%) extend above the laminar sub-layer. According to the well-known rough flow criterion (Schlichting, 1968), when surface protrusions extend outside the laminar sub-layer, the flow becomes aerodynamically rough. Kunishi's (1963) experiment in the wind-wave tunnel shows that a completely rough regime exists when $u_{10\text{ m}} > 8\text{ m sec}^{-1}$. This particular value of wind velocity (8 m sec^{-1}) agrees closely with that obtained by Wu (1972), namely $u_{10\text{ m}} = 7\text{ m sec}^{-1}$.

The average 10 m drag coefficient, when $u_{10\text{ m}} = 8\text{ m sec}^{-1}$, was found to be $C_{10\text{ m}} = 1.4 \times 10^{-3}$ (equivalent to an aerodynamic roughness height of $z_0 = 0.023\text{ cm}$). This value is obtained from the published results of Deacon and Webb (1962), Kondo (1962), Phillips (1966), Hicks and Dyer (1970), Smith (1970), Kondo *et al.* (1972a), Francis (1951), Kunishi (1963), and Hamada *et al.* (1963). From the definition

$$u^{*2} = C_{10\text{ m}} u_{10\text{ m}}^2, \quad (8)$$

one obtains $u^* = 29.9\text{ cm sec}^{-1}$ for $u_{10\text{ m}} = 8\text{ m sec}^{-1}$. These values, together with the $z_0 = 0.023\text{ cm}$ mentioned

above, give $h_p u^* / \nu = 67$ and $h_p / z_0 = 15$ for $u_{10\text{ m}} = 8\text{ m sec}^{-1}$. The former value is very similar to Nikuradse's (1933) critical Reynolds number at which the flow achieves the fully rough regime, and the latter value is comparable with those obtained from the wind-wave tunnel experiments by Kunishi (1963), $H/z_0 = 10$, and Hamada *et al.* (1963), $H/z_0 = 20$, where H is the mean height of waves with frequencies of 2–10 Hz.

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