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SHORT CONTRIBUTION

A note on minimum wind stress for wave inception

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1. Introduction

Many experiments have been conducted to evaluate the rate of energy transfer from wind to waves through the measurement of fetch-wise wave growth under a steady wind. There has been little systematic study, however, of local inception of waves by the wind. Earlier experiments on wave initiation were performed with conventional wave height gauges (Ursell, 1956) which are inaccurate for such purpose, while optical wave-slope gauges were used in recent experiments (Cox, 1958; Scott, 1974; Long & Huang, 1976) where the wind stress was not measured. Both macro- and microscopic structures of the disturbed water surface were measured in the present study along with the wind profiles. There is no minimum wind velocity found for the inception, but there is a critical wind-friction velocity for effective wave growth. The conditions of this effective growth are compared favorably with both resonance (Phillips, 1957) and viscous interaction (Miles, 1962) mechanisms.

2. Experiment

The wind-wave tank is 1.5 m wide, 1.55 m deep and 11 m long. An axial flow fan is mounted at the upwind end of the tank. The air passage is 0.35 m high and the normal water depth is 1.2 m. The fetch at the test section is 5.5 m.

The wind-velocity profiles in the tunnel were determined by vertical traverses of a pitot-static tube. A conductivity probe was used for recording wave heights and an optical instrument for measuring surface slopes. The optical instrument, described in detail elsewhere (Wu et al., 1969), is arranged to have its angular sensitivity in the cross-wind direction about 20 times less than that in the wind direction. The angular resolution of the instrument to the water surface slope in the wind direction, slightly modified for the inception measurement, is about $\frac{3}{4}°$. The signals of the instrument are light pulses representing the occurrences of a given surface slope. The distribution of the surface slopes is represented by their relative frequencies of occurrence.

3. Results

3.1. *Wind conditions*

The friction velocities (u_*) obtained from the logarithmic wind profiles are presented in Fig. 1.

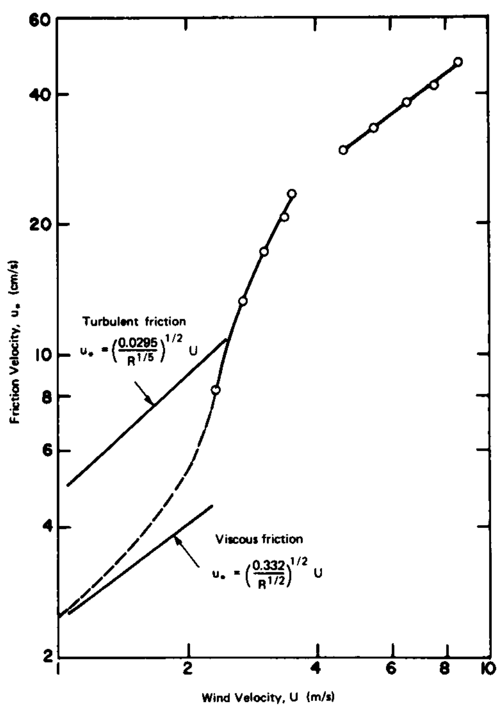

Fig. 1. Development of airflow boundary layer along water surface.

Lines also shown in the figure are the friction velocities for a viscous and a turbulent boundary layer in the aerodynamically smooth regime (Schlichting, 1968); the Reynolds number ($R = UL/\nu$) shown in Fig. 1 is defined with the free stream wind velocity (U), the distance between the fan and the test sections (L), and the kinematic viscosity of air (ν). Two other lines, one straight and one curved, were faired to the data for the aerodynamically smooth and rough regimes, respectively (Wu, 1968).

The airflow boundary layer was considered (Wu, 1968) in the pre-transition region at very low wind velocities, as the air was sucked by the fan, through guiding vanes only, into the tank. The guiding vanes were arranged to straighten the flow but not to diminish the high turbulence level, for the purpose of increasing the effective length of wind fetch. The effective transition of the boundary layer to fully turbulent occurred at $U = 2.5$ m/s, where, as shown in Fig. 1, the turbulent-friction line intersects the present data. The friction velocity at very low wind velocities $U < 2.3$ m/s, however, should be lower than that indicated by the turbulent-friction line, and should approach asymptotically the viscous-friction line as the wind velocity decreases. Accepting this argument and following the trend of the present data, a dashed line is faired in Fig. 1 to approximate the friction velocities for very light winds.

3.2. *Slope distributions and root-mean-square slopes of wind waves*

For each wind velocity, the optical instrument was set successively at various angles of inclination to count occurrences of the water surface slope. The data follow essentially a Gaussian distribution. Few sample sets of the data are shown in Fig. 2a, where the windward slope is considered negative, the leeward slope is considered positive, and the continuous line is the Gaussian curve fitted to the data according to the least squares.

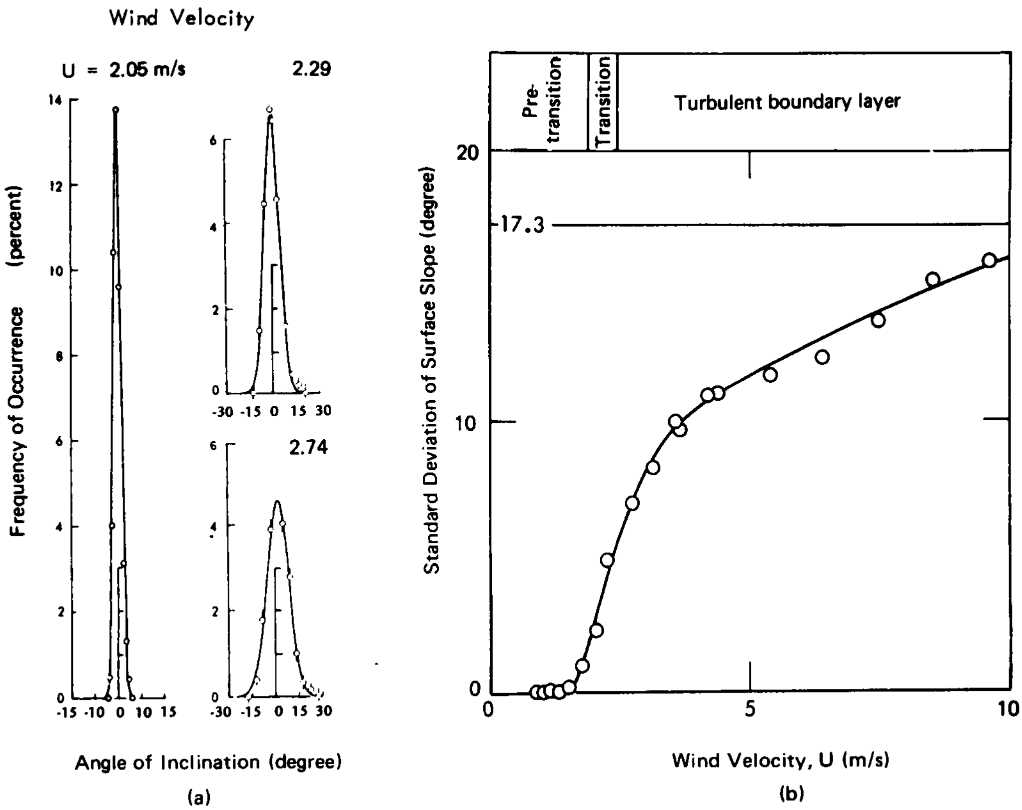

Fig. 2. Inception of high-frequency components of wind waves. (a) Slope distributions and (b) root-mean-square slopes.

The root-mean-square water surface slopes, obtained from the slope distributions, are plotted versus the wind velocities in Fig. 2b. At very low wind velocities, $U < 1.6$ m/s, the root-mean-square slope is only a fraction of a degree. A sudden rise of the slope is observed in the wind-velocity range from 1.6 to about 2.6 m/s; this is also the velocity range where the wind boundary layer makes its transition to turbulence. The mean-square slope increases almost linearly with the wind velocity within this range, and shows a more gradual increase beyond this range. It is conceivable that to increase the slope resolution of the instrument, the lower end of the sudden slope rise (with slopes less than or near $\frac{3}{4}°$) will shift toward a lower wind velocity. However, the stem of this rise will stay in the same wind velocity range as shown in Fig. 2b.

3.3. *Minimum* (U_{min}) *and critical* (U_{crit}) *wind velocities*

As discussed above, the waves in the present tank start to grow very rapidly with the wind strength around $U = 1.6$ m/s; however, initial waves with infinitesimal amplitudes were detected by the optical instrument even below this wind velocity. The direction of propagation of these waves cannot be determined by the instrument, which only counted the number of waves with a slope change from one face to the other exceeding $\frac{3}{4}°$. The frequency of these waves was registered as 13.4 Hz, corresponding to a wavelength of 1.7 cm. These infinitesimal waves, however, fail to grow in either length or slope with the wind velocity in the pretransition region of the airflow boundary layer. The mechanism of generating these initial waves is unknown, except that these initial waves have the most unstable wavelength, 1.7 cm (Ursell, 1956).

The detection of the initial infinitesimal waves depends on the sensitivity of the sensor, which makes the determination of the minimum wind velocity U_{min} for wave generation rather arbitrary. As pointed out by Ursell (1956), both theoretical arguments and experimental results indicate $U_{min} = 0$ as the most probable value. The widely scattered values of U_{min} proposed by various investigators may be related to the wind velocity where the sudden growth of waves is observed. The wind velocity where this rapid growth starts can be defined approximately. This velocity is called here the critical wind velocity U_{crit}; it is determined to be 1.6 m/s in the present tank by extending the sudden growth portion of the curve shown in Fig. 2b to zero slope.

4. Discussion

The most effective growth of waves starts at $U = 1.6$ m/s, corresponding to which the wind-friction velocity can be found from either the viscous or the turbulent friction line shown in Fig. 1 as 3.5 and 7.3 cm/s respectively. The actual friction velocity falling between these two values is therefore very close to the minimum wind friction velocity for the wave growth, 4.4 cm/s, found analytically by Miles (1962).

It is interesting to note that the boundary-layer thickness at the lower end of this velocity range is about twice the wavelength (Wu, 1968). In other words, the length scale of the pressure fluctuations, about one-half the boundary-layer thickness (Phillips, 1958), is about the same as the wavelength. This is one of the conditions required for wave inception due to the resonance mechanism (Phillips, 1957). The other condition favoring the resonance mechanism is that at the low-wind velocity end of the most effective wave-growth range, waves of 1.7-cm length were observed. Unfortunately, as discussed earlier, no directionality of wave propagation was measured to indicate that these are indeed resonance waves.

In summary, a sudden increase of the water surface slope is observed at the wind velocity of 1.6 m/s; infinitesimal waves were generated even below this so-called critical velocity but these initial waves failed to grow. At the critical wind velocity, we have wind and wave conditions similar to those required by the resonance mechanism, and the friction velocity is compared favorably with that predicted by the viscous mechanism. The favorable conditions for both mechanisms can be explained by the viscous mechanism taking over as soon as waves are started by the resonance mechanism. The favorable aspect of both of these linear mechanisms also indicates that the nonlinear process is perhaps not important at the wave-inception stage.

5. Acknowledgement

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