Observations on long waves sweeping through short waves

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ABSTRACT

Glitter photographs illustrate an important phenomenon on interactions between short and long waves: long waves sweep through short waves, causing the short waves to break on the forward face of the long wave crests.

Introduction

Wind waves are seen with ripples covering the profile of long waves. The horizontal contraction of the surface near the crest of the long wave was described by Longuet-Higgins & Stewart (1960) to shorten the length and increase the amplitude of short waves (ripples). In addition, the ripples are further steepened by receiving more energy through the work done by the long waves against the radiation stress of the short waves. These short waves may be the surface roughness (Wu, 1970*b*), which easily reaches the saturated state. Consequently, any further steepening is very likely to force their breaking. It has been suggested by Phillips (1963), Longuet-Higgins (1969) and Hasselmann (1970) that since the long waves travel faster than the short waves, the long waves sweep through the latter, and the breaking should most frequently occur on the forward face of the long wave crests.

In the open sea, two types of wave breaking were described by Phillips (1963); one type occurs when the crests of two long waves intersect and the other takes place when short waves are overtaken by long waves. For the latter type Phillips showed analytically that the energy loss by short waves near the crests of long waves is partially supplied by the long wave because of the second-order radiation–stress interaction. The dynamical consequence is the attenuation of long gravity waves by short breaking waves.

Realizing that linear mechanisms (Miles, 1957, 1962; Phillips, 1957) for the generation of sea waves fail to describe the most rapid stage of waves growth, Longuet-Higgins (1969) proposed a nonlinear "maser mechanism". In this latest model, the slow-moving short waves are considered to lose their energy when they are swept through by the fast-moving long waves, and at the same time the short waves give up their momentum to the long waves. Longuet-Higgins then argued that the short waves contributed energy to the long waves at a rate proportional to the orbital velocity in the long waves. Since the orbital motion is forward at the forward face of the long wave crest, the short wave therefore supplies a positive amount of energy to the long waves. The energy loss by long waves discussed in the previous paragraph is considered by Longuet-Higgins (1969) to be small compared with the energy gain through "maser mechanism".

Shortly after publication of "maser mechanism" Hasselmann (1970) presented his study on the mass and momentum transfer between short and long gravity waves. His results indicate that the work done on the long waves by the "maser mechanism" is balanced by the loss of potential energy arising from the mass transport. The loss is due to taking mass of high potential energy from the crests of long waves and returning at a lower potential level in the troughs.

There is no doubt that further studies are required to settle these various arguments vitally important to the dynamics of ocean waves. However, all these models are based on one common phenomenon: long waves sweeping through short waves, causing short waves to break on the forward face of the long wave crests. Unfortunately, no physical evidence to substantiate this basic phenomenon has yet been

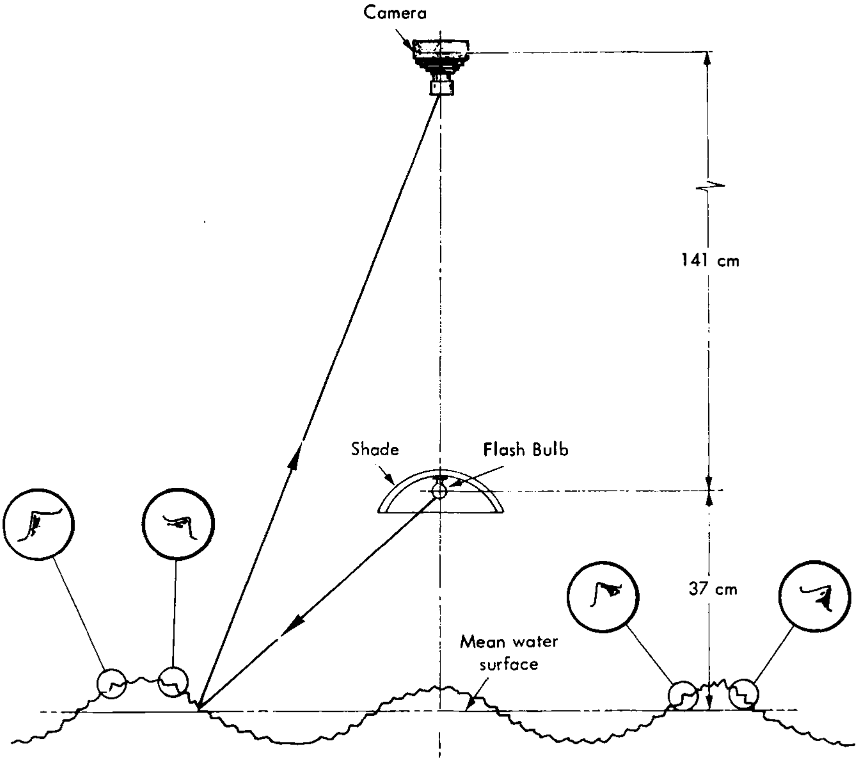


Fig. 1. Experimental arrangement for glitter photography.

reported. An attempt is made here to illustrate this phenomenon visually through photographs of glitter patterns.

Experiment

The experiment conducted here is attempted by visual observation of a wind-disturbed water surface, to verify the critical conditions assumed in the dynamical process of energy exchange between short and long waves. The experiment has been performed in a wind–wave tank 14 m long, 1.5 m wide, and 1.55 m deep. The maximum obtainable wind velocity with a 0.35 m deep air passage above a normal 1.2 m water depth is 14 m/sec.

The air was sucked by an axial fan and through guiding vanes into the wind-wave tank. The guiding vanes were spaced in such a way so as to straighten the flow but not to diminish the high turbulence level, which is helpful to increase the effective length of the wind fetch. The airflow at very low wind velocity $U < 1.9$ m/sec, is therefore not laminar but in the pre-transition region. The wind boundary layer becomes fully turbulent at $U = 2.4$ m/sec. The transition from the hydrodynamically smooth regime to rough is completed at $U = 3.5$ m/sec. Rhombic wave cells are observed before the wind boundary layer becomes fully rough. Parasitic capillaries are formed in front of the gravity wave crests immediately following transition; the water surface is generally smooth elsewhere. This is the surface-tension governing regime of wind–wave interactions. As the wind velocity increases, $U > 9$ m/sec, ripples are seen covering the water surface and wave breaking is visually observed *near* the crest of gravity waves. Gravity then replaces surface tension as the governing parameter (Wu, 1968).

Observations were made by photographing the glitter pattern on the water surface. As shown in Fig. 1, a flash bulb and a camera are supported on the same vertical axis at 0.37 and

Table 1. *Glitter pattern related to ripple position.*

<table>
<tr><td colspan="3" rowspan="2">Glitter (highlight) Location</td><td colspan="2">Left (upwind)</td><td colspan="2">Right (downwind)</td></tr>
<tr><td colspan="4">half of the picture</td></tr>
<tr><td colspan="3" rowspan="2">Ripple (short wave) Location</td><td>Front</td><td>Rear</td><td>Front</td><td>Rear</td></tr>
<tr><td colspan="4">face of the long wave</td></tr>
<tr><td rowspan="4">Glitter pattern related to ripple position</td><td rowspan="2">Front</td><td rowspan="4">face of ripple</td><td>Steeper</td><td>Flatter</td><td>Steeper</td><td>Flatter</td></tr>
<tr><td>Shown as highlight further from the axis</td><td>Shown as highlight closer to the axis</td><td colspan="2">Reflecting light away from the camera</td></tr>
<tr><td rowspan="2">Rear</td><td>Flatter</td><td>Steeper</td><td>Flatter</td><td>Steeper</td></tr>
<tr><td colspan="2">Reflecting light away from the camera</td><td>Shown as highlight closer to the axis</td><td>Shown as highlight further from the axis</td></tr>
</table>

It is clear from Table 1 that the portions of the wind-disturbed water surface involved in the present discussion are the front face of the ripple on the left half of the picture and the rear face of the ripple on the right half. For other cases, the light is reflected away from the camera by the ripple.

1.78 m above the water surface, respectively. The light, shaded from the camera, is reflected by the ripples with a selective slope into the camera, and is shown as a highlight on the film; see Figs. 1 and 2. The selective slope of the ripple is steeper when the corresponding highlight is further away from the axis. The contour lines of these slopes, shown in Fig. 2, are circles with their origin at the vertical axis. It may be worthwhile to note that the rhombic wave cells are produced by scattered lights.

Discussion

The glitter patterns at various wind velocities are shown in Fig. 2. The wind, in all cases, blows from left to right. The dark disk shown at the center of the picture is the light shade, 15.8 cm in diameter. The rhombic cells are foggy and the highlight is seen as a streak, because the finite size and exposure time of the flash bulb. As discussed previously, the glitter patterns demonstrate that rhombic wave cells and parasitic capillaries are produced at low wind velocities and ripples cover long waves at high wind velocities.

It is clear that the highlights shown in Fig. 2 are the light reflected from the steep-faced short waves (ripples) riding on top of long waves. The relevant conditions involved here for interpreting those pictures are the position of the highlight on the left (upwind) or right (downwind) side of the picture and the distribution of the ripple on the front or rear face of the long wave. As illustrated in Fig. 1, some explanations can be made and are tabulated in Table 1.

The distribution of highlights shown in Fig. 2 is asymmetrical: highlights are seen to be more numerous and lie further from the axis in the left half compared with fewer and closer to the axis in the right half of the picture. As shown in Table 1, this pattern indicates that the front face of the ripple on the left (upwind) side is steeper than the rear face of the ripple on the right (downwind) side. This skewed glitter pattern is obviously the result of steepening the front face on the left and flattening the rear face on the right. According to Table 1, the outlook of

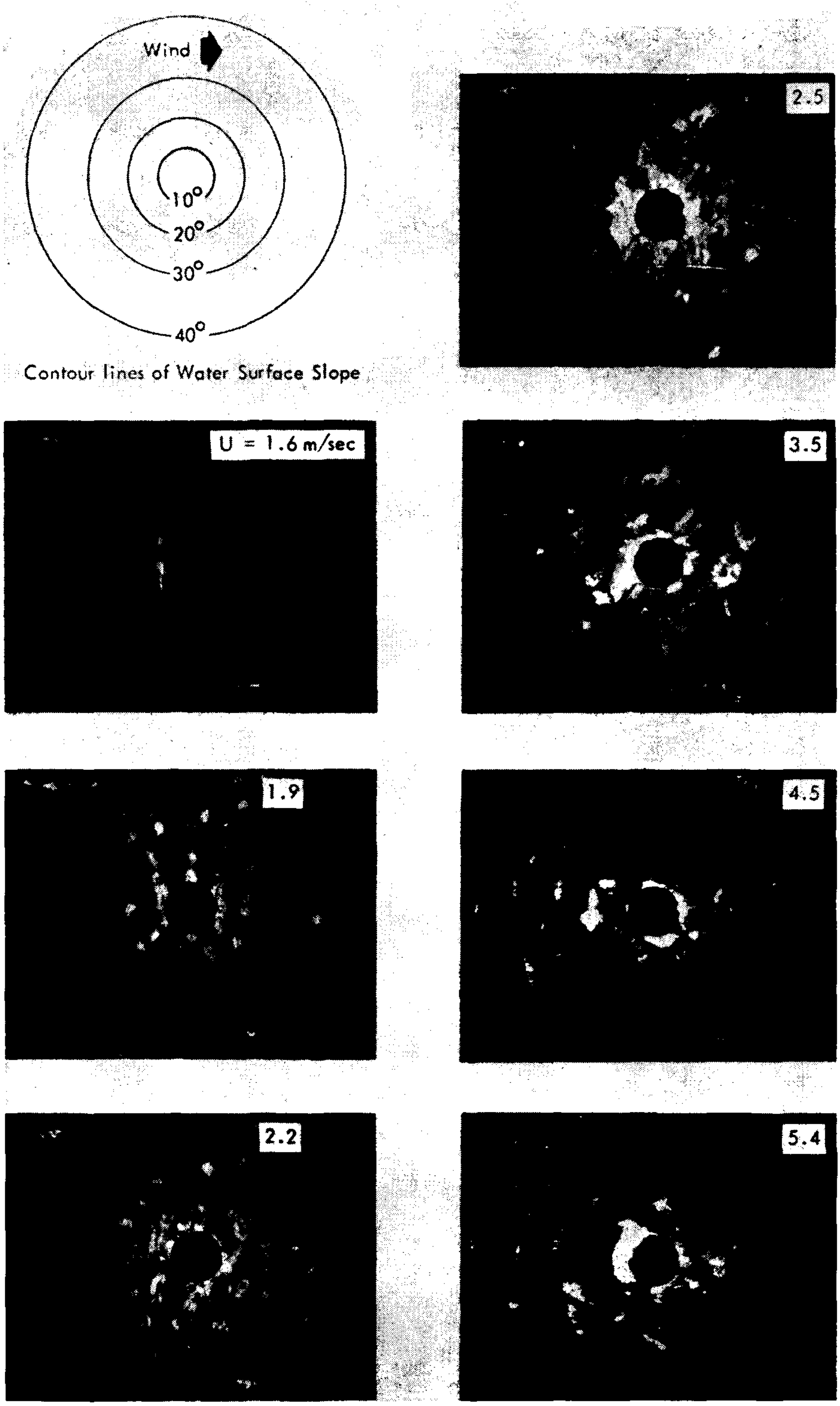
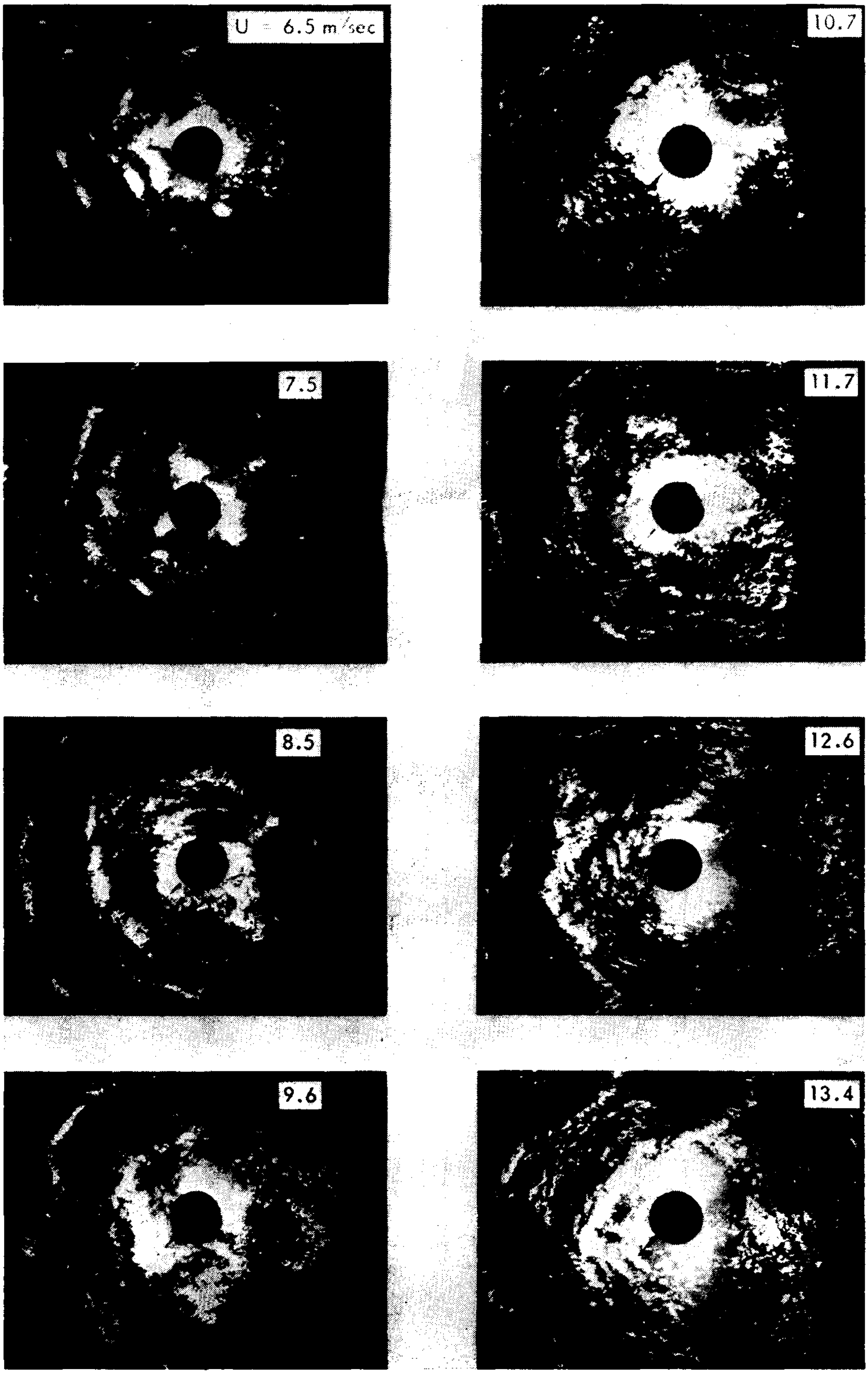


Fig. 2. Glitter pattern of wind-disturbed water surface.


U = 6.5 m/sec
7.5
8.5
9.6
10.7
11.7
12.6
13.4

the glitter pattern is dominated by such a combination when more steep-faced ripples ride on the front face of long waves than on the rear face. The asymmetrical glitter pattern may also result from skewed profiles of capillary waves. However, the skewness of the capillary wave profile, if there is any, should be rather small and cannot account for the large difference observed here.

The most interesting observation provided by the glitter pattern is the long transverse cluster of highlights formed *near* the wave crest. The cluster is produced by 'boiling' water surface accompanying wave breaking. The distance between the clusters is the length of long waves as compared with our wave measurements reported elsewhere (Wu, 1968). These *isolated* line concentrations of highlights are shown exclusively toward the left half of the picture. This clearly demonstrates that the breaking of small waves occurs at the forward face of the long wave, since, if the breaking of small waves had occurred on the rear face of the long wave, the long transverse cluster of highlights would also be seen *away* from the axis in the right half of the picture just like those shown in the left half. There is no doubt that the breaking water surface also gives cluster on the right half of the picture. However, according to Table 1, the breaking water at the forward face of long waves should give clusters closer to the axis. Mixed with other highlights close to the axis, these clusters cannot easily be identified as can the isolated line concentrations of highlights, shown on the left half of the picture.

Visual observations seem to indicate that whitecaps tend to form near the crest of long waves. The photographic evidence, a frozen visual observation, illustrates that the wave breaking occurs on the forward face of basic waves. These observations are essentially complementary. Taken together, they demonstrate that wave breaking tends to occur on the forward face of long waves crests. This is the *critical condition* on dynamic interactions between short and long waves. In other words, the observations verify a basic phenomenon important to mass, momentum and energy transfer between short and long waves, Needless to say that far more studies are needed in order to establish the dynamical consequences of these various types of interactions.

There may be some differences between the dynamic process of wind-wave interactions in the laboratory and that taking place in the field (Wu, 1970*a*). However, the present discussion does not have much concern in the detailed process of wave generation by wind but illustrates the sweeping action of long waves through ripples. These waves are already there and the sweeping action between waves is believed not to be influenced by fetch.

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НАБЛЮДЕНИЯ ПРОХОЖДЕНИЯ ДЛИННЫХ ВОЛН ЧЕРЕЗ КОРОТКИЕ ВОЛНЫ

Фотографии волн в отражённом свете иллюстрируют важное явление взаимодействия между короткими и длинными волнами: длинные волны, проходя через короткие, вызывают обрушение коротких волн на передней стороне гребней длинных.