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Forced Convection Accompanying Wind Waves*

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Abstract: Wind-wave tunnel experiments reveal, by use of techniques of the flow visualization, that wind waves are accompanied by the wind drift surface current with large velocity shear and with horizontal variation of velocity relative to the wave profile. The surface current converges from the crest to a little leeward face of the crest, making a downward flow there, even though the wave is not breaking. Namely, wind waves are accompanied by forced convections relative to the crests of the waves. Since the location of the convergence and the downward flow travels on the water surface as the crest of the wave propagates, the motion as a whole is characterized by turbulent structure as well as by the nature of water-surface waves. In this meaning, the term of real wind waves is proposed in contrast with ordinary water waves. The study of real wind waves will be essential in future development of the study of wind waves.

1. Basic concepts

Theories of water-surface waves have formed one of the oldest and the most successful branches of classical fluid dynamics. The Lagrangian vortex theorem, which assures the persistence of the irrotational motion, made the waves occurring at the still surface of water an appropriate object of the potential theory. In fact, concerning water waves that are generated by mechanical wave generators, theories agree in many aspects with actual phenomena, from the classical dispersive relation to the more recent resonant wave-wave interaction of waves of different frequencies (*e.g.* PHILLIPS, 1966). The irregular motion generated on the water surface by the action of the wind has been called "wind *waves*", and has so far generally been treated as the water-surface *waves*. Wind waves are, however, quite different from water waves generated by mechanical wave generators.

The characteristics of wind waves are, first of all, that the configuration of the water surface is irregular, and the variation of water level is at random. The first way of idealizing the irregular wind waves is to express them by some characteristic waves. The significant wave introduced by SVERDRUP and MUNK (1947) is one in this direction. The second way is to express the random variation of water level as the superposition of component waves of various frequencies of small amplitudes. Since PIERSON (1952), many workers contributed in this aspect of energy spectrum.

In the case of wind waves generated under simple conditions, the energy spectrum has a kind of similarity with a conspicuous peak. From the point of view of the energy spectrum, the significant wave corresponds conceptionally to the wave with the frequency at the spectral peak, although quantitatively there is a slight difference between them. As to the significant waves, there is a universal relation between the dimensionless wave height and the dimensionless wave period, as proposed by TOBA (1972, 1974) as the three-seconds power law.

Although the significant wave period and the significant wave height are two variables representative of the irregular wave field, it does not mean that the waves having the specific period and the specific height exist conservatively in the sea. At the same time, it should be noticed, as will be discussed in the following, that the expression by the superposition of component waves is just a mathematical idealization, and wind waves as physical phenomena are different from the waves realized as a superposition of infinite numbers of component waves.

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In the present article is demonstrated the existence of non-uniform wind drift surface current relative to the wave crest, and of a forced convection accompanying wind waves. In this meaning it is stressed that the form of the undulation of water surface under the wind, at any instance, has a great significance in the local structure of motion, and presumably in the growth of the wind waves, in contrast with the idea of regarding the undulation at any instance as the superposition of various component waves, or as an incidental undulation of water surface.

In the direction of the study of real wind waves, KUNISHI (1957, 1963) investigated the shearing flow in the subsurface boundary layer caused by wind stress, and noted the occurrence of turbulence in water. There have been some observations of wind-induced drift currents in a horizontally averaged conditions (*e.g.*, KONDO *et al.*, 1974; WU, 1975). BANNER and PHILLIPS (1974) and PHILLIPS and BANNER (1974) introduced the local vorticity in the study of waves under the influence of the wind. However, vorticity has not so far been considered as an essential factor for the growth of wind waves.

Since the location of the forced convection travels as the crest of the wave propagates on the water surface, wind waves substantially produce turbulence in the surface layer of water. Nonlinearities in water waves of finite amplitudes, and in the interactions among waves of different wave numbers, are well known. In addition to these nonlinearities of ordinary sence, it is stressed in the present paper that wind waves are characterized by an even stronger nonlinearity. In this meaning, wind waves have an aspect of turbulence on the one hand. On the other hand, since the undulations of water surface propagate under the restoring forces of the gravitational force and the surface tension, they should have a character of the water waves. Thus there is duality of turbulence and wave in wind waves, and it was from this basis that the previously mentioned three-seconds power law was derived also by the combination of the properties of water waves and turbulence (TOBA, 1974a).

2. Flow visualization study of wind waves

2.1. Initial stage of the wind-wave generation

When the wind begins to blow on a still water surface, a thin skin flow with large velocity shear first occurs at the water surface. This is apparently due to the existence of viscosity of air and water. When the laminar skin flow attains to some critical state, some undulations arise nearly suddenly on the water surface as KUNISHI (1957, 1963) first observed in a wind-wave tunnel (70 cm wide and 21.6 m long) at Kyoto University.

We have re-observed, in different methods from Kunishi's, the initial stage of the generation of wind waves by use of our smaller wind-wave tunnel (15 cm wide and 4.55 m long) at Tohoku University. In Photo. 1 is shown the flow visualization of the laminar skin flow near the water surface by use of the technique of hydrogen-bubble lines. There was a slow uniform flow of about 2.5 cm/sec in water from the left to the right, and the hydrogen-bubble line was produced at the left hand part of the photographs at 0.04-second intervals. The water surface plays the role of a mirror, and the mirror image is seen at the upper part. The wind was blowing from the left to the right, and the mean wind speed in the tunnel section of 17 cm high was 6.2 m/sec corresponding to the extraporated wind speed at 10-m level of 12.8 m/sec, and the fetch was 2.85 m. The surface velocity of from 10 to 13 cm/sec is seen in the photographs. The time measured from the start of the wind is indicated, although the three photographs were not taken in one sequence. In the top photograph is shown the stage of no undulation, in the middle and the bottom photographs are shown the initial regular undulations at the surface, and in the latter the occurrence of some turbulence. By the time of occurrence of the surface undulation and turbulence, the laminar shear flow reached only 2.2 mm depth in scale thickness. In the case of the observation by KUNISHI (1957, 1963), however, the experiment was carried out at much lower wind speed, and consequently, the velocity shear was much smaller and the laminar skin flow reached 2 cm depth before the commencement of some turbulence.

We also used artificial, neutrally floating particles, of about 1.8 mm in diameter, in order to trace the movement of water particles. They were made of polystyrene*. The specific gravity was adjusted to be 0.99. In Photo. 2 is shown some frames of sequential photographs taken after the onset of the wind. The mean wind speed in the tunnel section was 8.6 m/sec, and the fetch was 2.85 m. The time measured from the start of the wind is shown at the side of each photograph. The experiment was started after most of the particles rose by the slight buoyancy force up to the water surface. When the skin flow was laminar, most of the particles were just beneath the water surface, as seen in the first two photographs. Only after 0.44 sec from the second photograph, the third photograph shows apparent undulations of the interface, and as soon as the undulations occur, the neutral particles begin to disperse downwards into the water as seen in the photographs. It is considered that this provides an evidence that wind waves produce turbulence substantially.

2.2. Case of developed wind waves

In Photo. 3 is shown typical cases of developed wind waves in the same wind-wave tunnel, with the hydrogen-bubble lines. The mean wind speed was 6.2 m/sec, and the fetch 2.85 m. In spite that there was no breaking of the waves, some conspicuous turbulent structure is seen in the photographs.

A skin flow with a strong shear is seen at the top of the second hydrogen-bubble line of *a* of Photo. 3. Also, some surface current, or a skin flow in a macroscopic sense, that reaches even to 1 or 2 cm in depth, is seen throughout the wind-ward (rear) face of the wave crest. The macroscopic skin flow converges at the lee (forward) face of the wave crest, making some downward flow there, together with some compensating upward flow to the left of the downward flow, as seen in *b* and *c*. Thus, wind wave is accompanied by a forced convection relative to the wave profile.

As the crest of waves propagates on the water surface, the location of the forced convection should travel together with the crest. Now the motion as a whole becomes complicated. It seems that there is no deterministic solution expressing this kind of motion. It will substantially have the character of turbulence.

The skin flow seen near the source of the hydrogen bubbles in *a* and *d* is apparently controlled by the molecular viscosity. Since there are many small scale undulations on the surface of wind waves, the skin flows will converge at the crest of each small scale undulation, making smaller scale convections, and in turn, smaller scale turbulence there. It is considered that the macroscopic skin flow is produced through the smaller scale turbulence due to the smaller scale undulations at the water surface. It seems that the turbulence shown in Photo. 2 originates in this way from the forced convections of various scales.

3. Movement of water particles in wind waves

3.1. Case of breaking wind waves

In Photo. 4 is shown an example of the breaking wind waves. It was taken by use of the wind-wave tunnel of Kyoto Univ. (TOBA, 1961). The mean wind speed in the tunnel section was 10.8 m/sec, the fetch was 13.6 m, in this case. Air bubbles were entrained in water at the lee face of the wave crest, carried down to the depth of from 2.5 to 3 times the wave height, and then rose up to the water surface at the rear side of the wave.

Typical movement of this kind of bubbles has been traced by the use of 16-mm cinefilms. In Fig. 1 is shown the path line of a bubble together with the movement of the water surface. The wind speed in the tunnel section was 12.1 m/sec, the fetch 10.0 m and the wave length about 42 cm in this case. In Fig. 2 is shown the movement of the bubble relative to the wave profile. The line at the bottom indicates the movement of the coordinate system. The estimated naturally rising velocity

* Eslen Beads, available from Sekisui Plastics Co., Ltd., Tokyo, were thermally treated. The detailed description of the preparation including further studies, will be reported by K. OKUDA, S. KAWAI, M. TOKUDA and Y. TOBA: A detailed observation of the wind exerted surface flow by use of flow visualization methods.

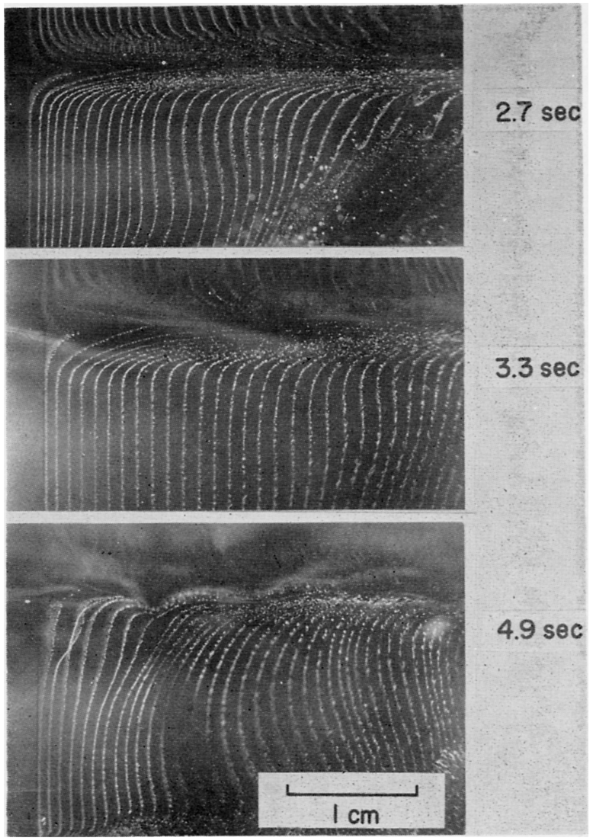

Photo. 1. Flow visualization of the wind-induced skin flow at the water surface by use of hydrogen-bubble lines. The wind was from the left to the right and the mean wind speed in the tunnel section was 6.2 m/sec. The time measured from the start of the wind is indicated.

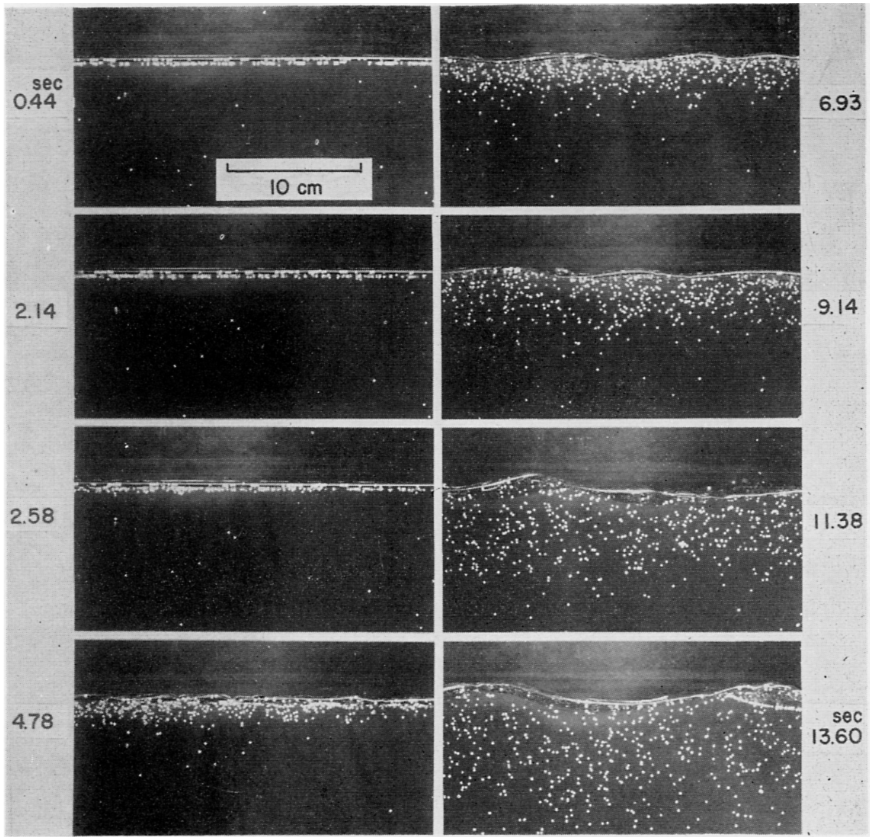

Photo. 2. A sequence of photographs taken after the onset of the wind. Neutral particles of the specific gravity of 0.99 quickly disperse into water by the generation of wind waves. The mean wind speed in the tunnel section was 8.6 m/sec, and the fetch was 2.85 m. The time measured from the start of the wind is shown by seconds. Except the second photograph, they are shown at about 2.2-sec intervals.

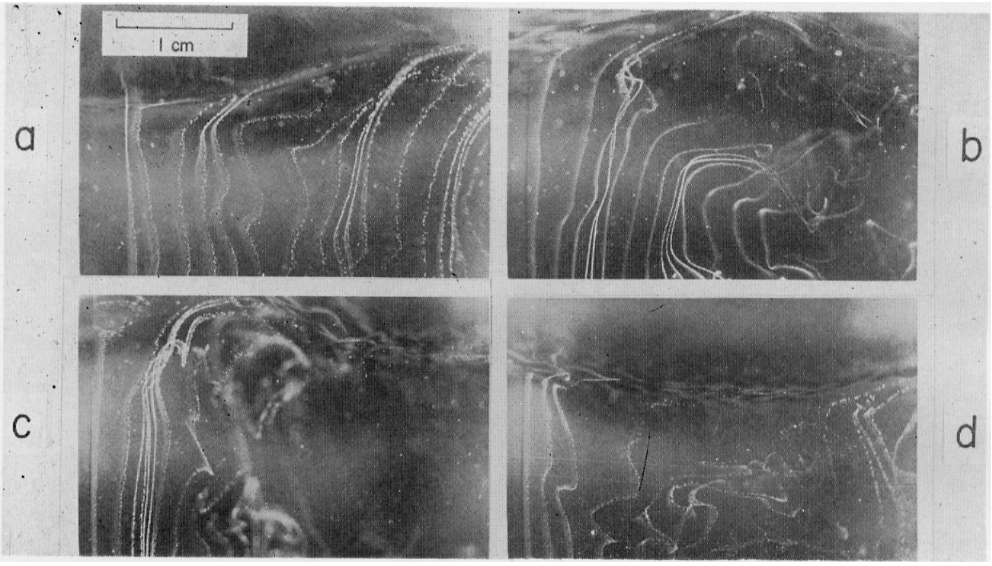

Photo. 3. Flow visualization in the wind waves. Surface currents, forced convections, and the resulting turbulent structure in wind waves are seen.

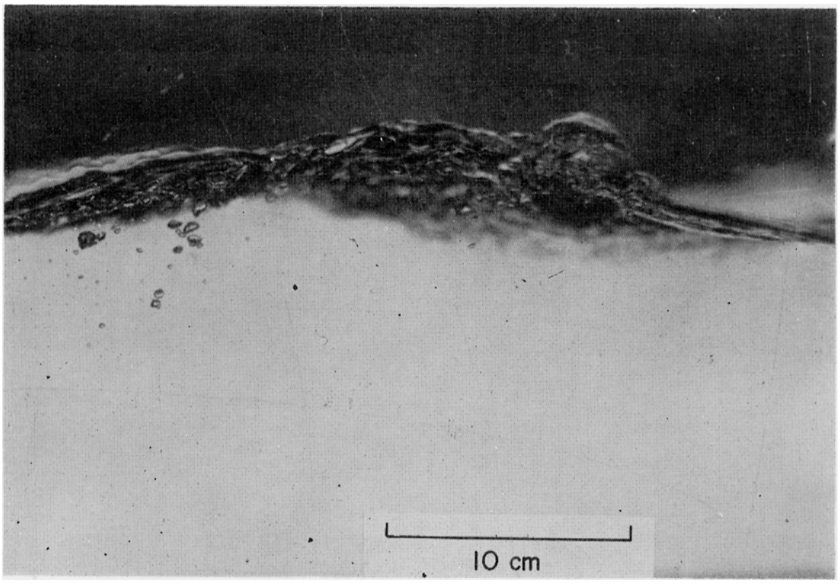

Photo. 4. Distribution of air bubbles entrained by the breaking of the interface at the lee face of a wind wave. The wind was blowing from the left to the right. (TOBA, 1961)

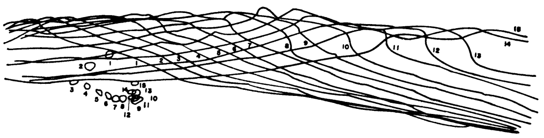

Fig. 1. Example of the path line of an entrained bubble and the movement of the interface.

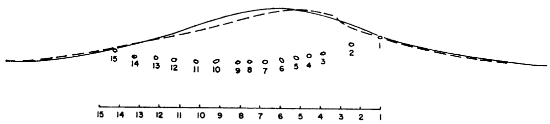

Fig. 2. Movement of the bubble relative to the wave profile, obtained from Fig. 1.

Fig. 3. Estimated forced convection in the breaking wind wave of Fig. 1.

of the bubble and the estimated orbital motion of Stokes wave are subtracted from the observed movement of the bubble, and in Fig. 3 are entered the vectors showing the non-wave component, or the forced convection in the wind wave other than the orbital motion of Stokes wave. The lengths of the arrows indicate the movement per 0.02 sec. Detailed description of the study, including more data, will be reported elsewhere.

It is noted from Photo. 4 that bubbles at the left part of the photograph are distributed along several inclined lines, which indicate also existence of the surface current and the convergence near the crest of the wave. Bubbles constituting each inclined line were entrained as a mass of bubbles, and then their distribution was elongated aslant by the surface current. The several inclined lines of the bubbles represent a sequence of the entrainment of the masses of bubbles. The far left line was entrained first, and since the time from the entrainment is the longest of all the lines, the distribution of bubbles are most elongated aslant. From the inclination of the line and the location relative to the crest, the velocity of the surface current near the surface in this case may be estimated as about 40 cm/sec.

3.2. Case of non-breaking wind waves

It is considered that the convergence and the downward flow at the lee face near the crest are general phenomena in wind waves, and when they attain some critical conditions, the entrainment of air bubbles, or the breaking of wind waves occurs. In order to ascertain this idea, the neutral particles, as shown in Photo. 2, have been traced in the 16-mm cinefilms by the use of the smaller wind-wave tunnel of Tohoku University, in the case of non-breaking wind waves. In Fig. 4 is shown an example of overlapping of many vectors of the movement of particles in which the orbital motion of Stokes waves has been subtracted. In this case the mean wind speed was 8.5 m/sec, and

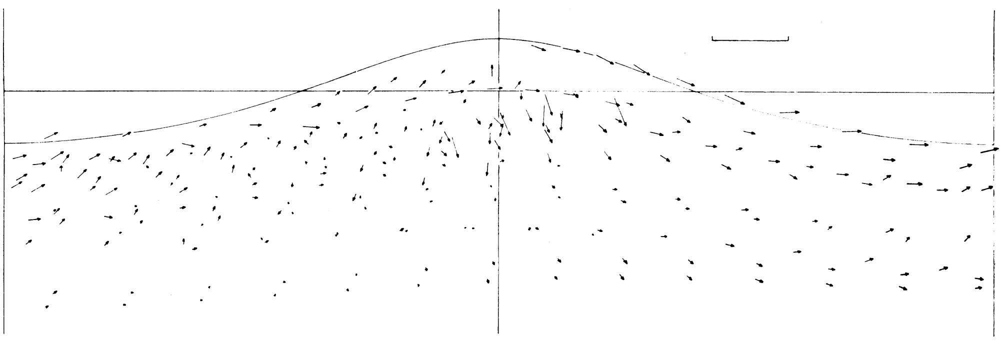

Fig. 4. Overlapping of vectors representing the forced convection in a non-breaking wind wave. The horizontal line at the top right part represents the distance of propagation of the wave crest in 0.024 sec, and the length of the arrows indicates the movement of convection in the same time interval.

the mean wave length was 17.1 cm. The arrows indicate the movement of particles per 0.024 sec, and the figure shows the result obtained from the trace of the neutral particles during about 0.36 sec at a fixed area. A pattern of the forced convection is seen here also.

Although the convective pattern is somewhat different for each of many cases, as will be reported elsewhere, it should be concluded that the forced convection relative to the wave profile really exists. It should be better that a term "real wind waves" is introduced, in order to descriminate actual conditions of wind waves from ordinary water waves, which are produced by mechanical wave generators and which may be expressed as a linear superposition of component waves of various frequencies. The term of real wind waves in contrast with water waves is somewhat analogous to the term of real fluid in contrast with ideal fluid. The study of the real wind waves will be crucial in the future development of the study of wind waves.

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風波に伴う強制対流

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要旨：流れの可視化法を用いた風洞水槽実験によって，風波は，大きな速度のシアーと波形に相対的な速度の水平変化のある表面吹送流を伴うことがわかった．この表面流は，波が必ずしも崩れていないときでも，波の峯からその少し風下側にかけて収束して，そこに下降流を作る．すなわち，風波は，波の峯に相対的な強制対流を伴っている．この収束と下降流の位置は波の峯の伝播につれて水面を動くので，全体としての運動は，水面波の性質とともに乱流的構造によって特徴づけられている．この意味において，通常の水の波に対照的に，現実の風波という言葉が提案される．現実の風波の研究は，風波の研究の今後の発展にとって本質的であろう．

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