

Measurement of Skin Friction Distribution along the Surface of Wind Waves*

Kuniaki OKUDA**, Sanshiro KAWAI** and Yoshiaki TOBA**

Abstract: Measurements of local values of the skin friction have been made at many points along the surface of representative wind wave crests in a wind wave tunnel, by use of the distortion of hydrogen-bubble lines. The results obtained at 2.85-m fetch under 6.2 m s^{-1} mean wind speed show that the intensity of the skin friction varies greatly along the surface of wind waves as a function of the phase angle. It increases rather continuously at the windward surface toward the crest, attains a value of about 12 dyn cm^{-2} near the crest, decreases suddenly just past the crest, and the value at the lee surface is substantially zero. Values of the skin friction thus determined along the representative wind waves give an average value of 3.6 dyn cm^{-2} , rather exceeding the overall stress value of 3.0 dyn cm^{-2} , which has been estimated from the wind profile. The results are interpreted as that the skin friction bears most of the shearing stress of wind, and that it exerts most intensively around the representative wave crests at their windward faces.

1. Introduction

In our recent papers (TOBA *et al.*, 1975 and OKUDA *et al.*, 1976, hereafter called I and II, respectively), the flow structure of water relative to the crests of wind waves has been investigated experimentally by use of flow visualization techniques. It has been shown that the surface skin flow, in which the stress is supported mainly by the molecular viscosity, exists in the surface thin layer, even when the wind waves have developed as observed also by BANNER and PHILLIPS (1974) and MCLEISH and PUTLAND (1975). In our observation, this flow is not homogeneous along the water surface, but grows only at the windward side of the crest, producing frequently a much thicker shear flow in the inner layer. The drift current developed at the windward side induces a convergence just past the crest and the strong downward thrust of water occurs there. Therefore, if it is observed at a fixed place, the drift current repeats the growth and the destruction with the period of wind waves. One of the meanings of the above results is that it gives some insights on the nature of the momentum

transfer process across the air-water interface. As described in II, the skin friction seems to support most of the shearing stress of the wind, and exerts most intensively near the crests at their windward surfaces. The subject of the present paper is to describe the measurements of the skin friction distribution along the surface of wind waves, and to make a quantitative verification of this concept.

The skin friction may be determined from the measurement of the velocity shear at the water surface. However, the measurements of the velocity profile of the viscous surface skin flow is quite difficult, since its thickness is much less than 1 mm at moderate wind speeds as seen in I and II. We have therefore employed rather simple method using the distortion of hydrogen bubble lines which are produced by the electrolysis of water along a vertical platinum wire. The profile of bubble lines, which are rising across the surface skin flow layer, may represent various forms of parabola in the closest layer to the water surface according to the velocity shear. Their pictures have been taken at various points of the representative waves and analysed. The principle of our method is very simple, and so systematic errors may be considered small. Although the present experiment has been made only at a definite

* Received Dec. 28, 1976 and accepted May, 9, 1977.

** Geophysical Institute, Faculty of Science, Tohoku University, Sendai 980, Japan

wind speed and fetch, the results presented seem to support the ideas described in the previous papers.

2. Method of the measurements

The experiments have been made in the wind-wave tunnel of 4.55 m long, 15 cm wide and 70 cm deep. The hydrogen bubble lines have been produced by applying DC pulse voltage to a platinum wire of 50- μ m diameter, which is vertically stretched through the air-water interface. Pictures of the bubble lines have been taken by use of a 35-mm still camera and a 16-mm cinecamera. The details of the apparatus and the experimental procedure were already described in II.

The determination of the skin friction may be made from the bubble line profile near the water surface. The surface skin flow is not homogeneous along the crest of wind waves nor steady, since its local structure travels with the propagation of the crest of wind waves. However, if we are concerned with much smaller area compared with the wavelength and much shorter period compared with the period of wind waves, it may be assumed as locally homogeneous and steady. Since the thickness of the surface skin flow is very small as less than 1 mm, the direction of the flow may be considered as parallel to the water surface. We assume here that the velocity profile along the z -axis, which is taken normal to the water surface is

$$\left. \begin{aligned} u(z) &= mz + u_0 & \text{for } -d \leq z \leq 0 \\ u(z) &= Ae^{kz} + B & \text{for } z < -d \end{aligned} \right\} \quad (1)$$

where $m = (u_0 - u_{-d})/d$, and u_0 and u_{-d} are the flow velocities at the water surface ($z=0$) and at $z=-d$, respectively. It is noted that the form of the velocity profile below the linear layer is not important, and may be replaced by an arbitrary one with the velocity shear which decreases rapidly with the depth, since the skin friction may be determined, in the present analysis, only from the properties of the linear layer, as will be seen below. If the time t is taken from the instance when a bubble line is emitted in this flow, its profile at $t=t_1$ may be obtained as follows. The depth at t of a bubble which will reach $z=z_1$ at $t=t_1$ is

given by

$$z = z_1 - w(t_1 - t) \cos \theta \quad (2)$$

where w is the ascent velocity of the bubble and θ the inclination of the water surface from the horizontal. The velocity of each bubble in the direction of the flow may be replaced by the flow velocity at its depth, since the inertia of the bubble is very small. The displacement S of the bubble from the released point of the wire, in the direction parallel to the water surface, at $t=t_1 (\geq d/w \cos \theta)$, is therefore obtained from (1) and (2) as

$$\left. \begin{aligned} S(z_1) &= \frac{m}{2w \cos \theta} \left(z_1 + \frac{u_0 - B}{m} \right)^2 \\ &\quad - \frac{A}{kw \cos \theta} e^{k(z_1 - wt_1 \cos \theta)} + c_1 \\ &\quad \text{for } -d \leq z_1 \leq 0 \\ \text{and} \\ S(z_1) &= \frac{A}{kw \cos \theta} e^{kz_1} (1 - e^{-kw t_1 \cos \theta}) \\ &\quad + c_2 \quad \text{for } z_1 < -d \end{aligned} \right\} \quad (3)$$

where c_1 and c_2 are the terms which are not dependent on z_1 . It is seen that the profile of the linear layer approaches to a parabola with the increase of t_1 .

We now define

$$\Delta S = \{S(0) - S(-\delta)\} - \{S(-\delta) - S(-2\delta)\}$$

When $\delta \leq d/2$, it is given from (3) as

$$\Delta S = \frac{m\delta^2}{w \cos \theta} \left\{ 1 - \frac{A}{km\delta^2} (1 - e^{-k\delta})^2 e^{-kw t_1 \cos \theta} \right\}$$

Since the skin friction τ is given by $\tau = \mu m$, where μ is the molecular viscosity of water, the above equation is rewritten as

$$\begin{aligned} &\frac{\mu \Delta S w \cos \theta}{\delta^2} \\ &= \tau \left\{ 1 - \frac{A}{km\delta^2} (1 - e^{-k\delta})^2 e^{-kw t_1 \cos \theta} \right\} \quad (4) \end{aligned}$$

Table 1. Some estimates of $\frac{\mu \Delta S w \cos \theta}{\delta^2} / \tau$

	$\delta = d/2$	$d/4$
$t_1 = 2d/w$	0.53	0.47
$4d/w$	0.83	0.81
$6d/w$	0.94	0.93

Table 2. The estimated values of $\Delta\phi$.

ϕ (degree)	0°	-30°	-60°	-90°	-120°	-150°	-180°
t_s (second)	0.01	0.02	0.03			0.05	
v (cm s ⁻¹)		25		15		5	0
$\Delta\phi$ (degree)			20°		45°		70°

If k is large enough, the left hand side of (4), which is determined from the analysis of bubble line profiles, will yield a good approximation of τ for a small t_1 . The ratios of the left hand side to τ have been calculated for some values of t_1 and δ , and the results are presented in Table 1. Here, θ is taken as zero, and A , B and k are assumed as

$$A = 3.29 dm$$

$$B = u_a - 1.99 dm$$

and

$$k = 0.504/d$$

respectively, by putting the assumption, on the velocity profile in the exponential layer, that the velocity gradient decreases to $m/12.4$ at $z = -6d$, similarly to the case of turbulent flow near the smooth solid wall (MONIN and YAGLOM, 1971). It is seen that the skin friction is determined with the accuracy larger than 90 % at $t_1 = 6d/w$.

It may more generally be said that the bubble line profile attains a steady profile in a time determined from the depth at which the velocity shear is considerably smaller than that at the interface, divided by the ascent velocity of the bubble. In the present experiment, the velocity profiles of the surface skin flow have not been determined. However, the time t_s , may be estimated more conveniently from the thickness of the surface skin flow h , which is determined from the bubble line profiles as will be seen in the next section, as $t_s = h/w$. In the present case, t_s is very small as will be seen in Table 2, and we can find some bubble lines which have apparently been emitted more than t_s before the filmed time in each picture. The skin friction may thus be determined from the left hand side of (4), irrespective of the details of the velocity profile near the interface.

The actual surface skin flow is not homogeneous nor steady, as long as the wind is exerting the water surface and the wind waves exist. We next examine the response of the

bubble line profile to such fluctuating flow. The position of a bubble line relative to the crest of the wind waves changes in the response time t_s by

$$\Delta\phi = 360^\circ \frac{t_s}{T} \frac{C-v}{C}$$

where T , C and v are the period and the phase velocity of representative wind waves and the flow velocity in the surface skin flow layer, respectively. It is considered that our method is available in determining the local values of the skin friction along the water surface of wind waves when the condition $\Delta\phi \ll 360^\circ$ is satisfied.

The characteristic values of $\Delta\phi$ at the windward side of the crest may be estimated from the observed values. In the present experiment, w , T and C are 0.91 cm s^{-1} , 0.23 second and about 40 cm s^{-1} , respectively. The thickness of the surface skin flow h may be estimated from the profiles of bubble lines, and the results at the windward side are presented in Fig. 3 in the next section. The flow velocity at slightly below the water surface has been substituted for v although it may be considerable underestimations, since the strict determination of the skin flow velocity is almost impossible. The results calculated from these values are presented in Table 2. The phase ϕ is taken as 0° at the peak of the crest. The values of $\Delta\phi$ near $\phi = -180^\circ$ will not be considered sufficiently small. These circumstances will also be the same at the leeside, although the appropriate estimation of $\Delta\phi$ is not possible. However, it is evidently seen from the observations of bubble line profiles that the very weak skin friction is exerting the water surface in such regions, and the state of the skin flow does not change so abruptly, except at a little leeside of the crest where the downward thrust of water is occurring. Thus, it may be expected that the results obtained there have also the validity as the characteristic values smoothed in the phase intervals of $\Delta\phi$.

3. The results and discussion

The measurements have been made at 2.85 m in fetch under 6.2 m s^{-1} mean wind speed. The characteristic wave period, wavelength and the wave height are 0.23 second, 8.3 cm and 0.94 cm, respectively. The shearing stress of wind determined from the mean wind profile is 2.96 dyn cm^{-2} . These conditions correspond to Case 2 in the previous paper II. The ascent velocity of bubbles has been determined from the observations of the bubble size. The mean diameter is 0.14 mm from 100 samples, and the standard deviation is 0.018 mm. The ascent velocity may be given from the Stokes' resistance formula of the sphere as 0.91 cm s^{-1} .

The observations of hydrogen bubble line profiles have been made along many representative wave crests. Some pictures of bubble lines are shown in Photo 1. In each pictures the wind is blowing from the left to the right. The air-water interface may be clearly distinguished from the intersections of the bubble lines and their reflections at the underside of water sur-

face, or from the bubbles which align along the water surface in contact with the water surface. It is seen that the bubble lines at the windward side ($a \sim e$) incline abruptly toward the horizontal in the surface thin layer of a depth less than 1 mm, and the depths of their bends will show the lower boundaries of the surface skin flow layer at respective places. It may be noted here that the velocity profile of the surface skin flow will be different from that near the smooth solid surface; namely, the velocity shear seems to decrease rather suddenly near the lower boundary of the skin flow layer as observed also by MCLEISH and PUTLAND (1975). The thickness of the surface skin flow seems to decrease in approaching to the crest. However, except very close to the peak where the thickness of the surface skin flow decreases to less than $100 \mu\text{m}$ (as seen in (a) in Photo 1), the analysis of the profiles is possible and the quantitative determinations of the skin friction may be made from the relation (4).

At the leeside, in contrast to the windward

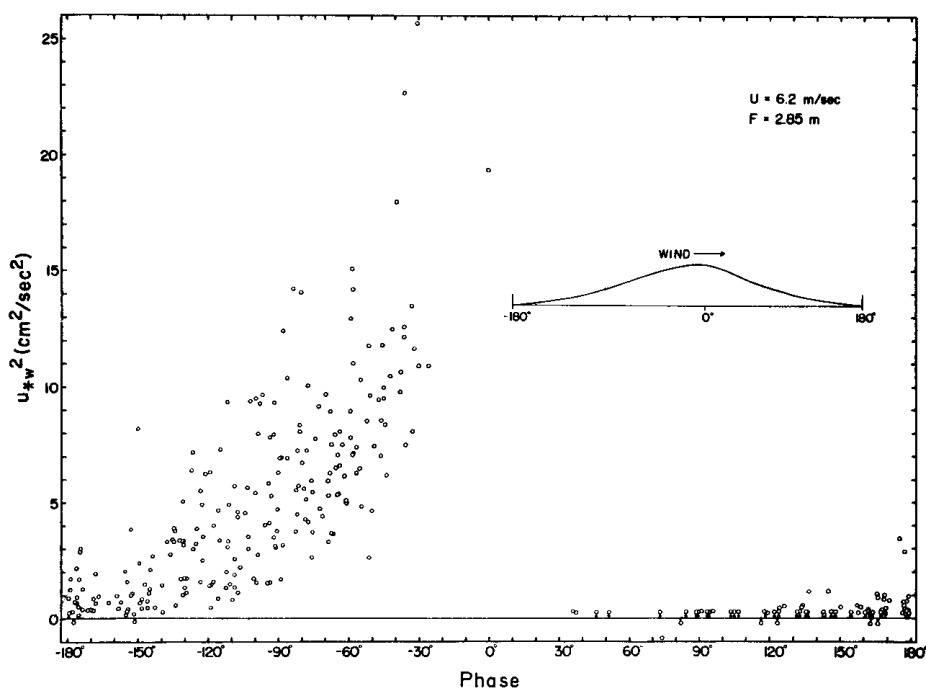


Fig. 1. Observed values of the local skin friction along the surface of representative wind waves. The abscissa is the phase relative to the peak point of the crest and the ordinate is expressed as the square of the friction velocity in water. The circles with arrows are values which are determined as apparently zero from the pictures of bubble lines, without calculations by use of the relation (4). The whole results in the present experiment are presented here.

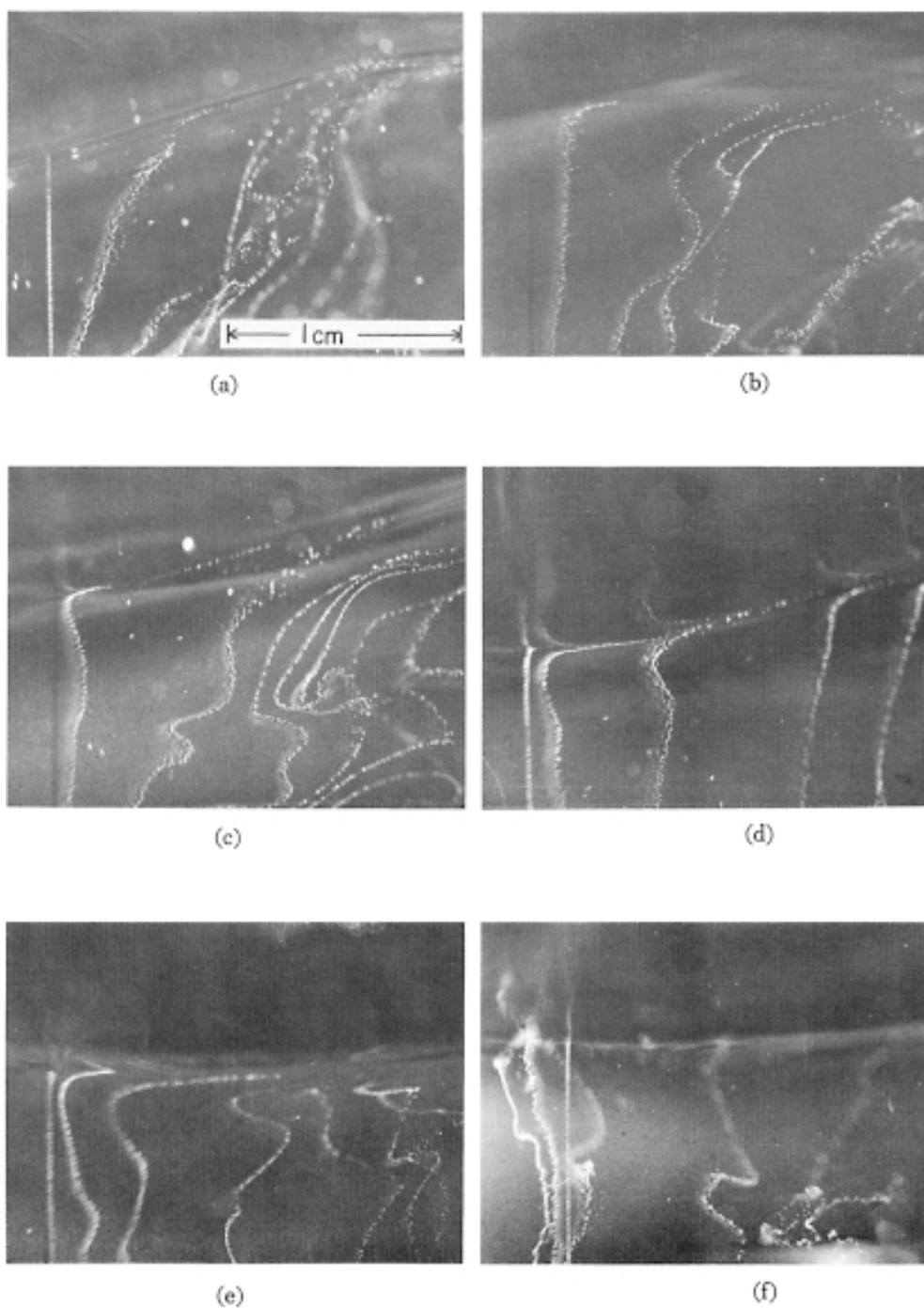


Photo 1. Some pictures of hydrogen bubble line profiles taken by a 35 mm still camera. The wind is blowing from the left to the right at 6.2 m s^{-1} mean wind speed. The water surface may be distinguished from the intersections of the bubble lines and their reflections at the underside of the water surface. (a)~(e) are those taken at the windward side of the crest and (f) is at the leeward side.

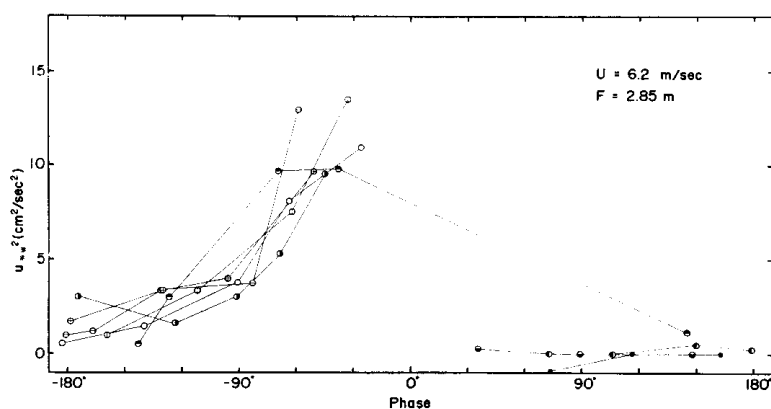


Fig. 2. Examples of the momentary distribution of the local skin friction along the representative wind waves. They have been determined from some successive pictures taken in the passage of the crests. Each crest is distinguished by different symbols.

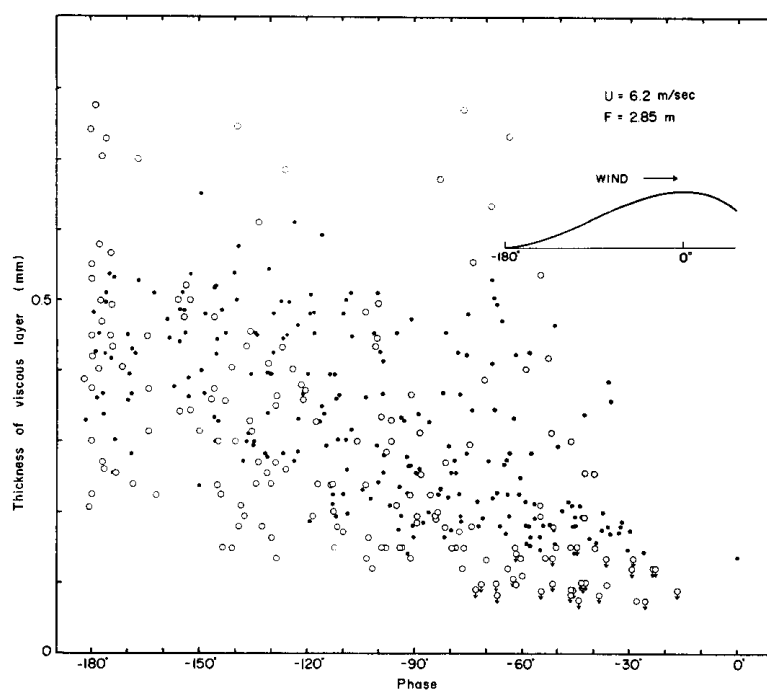


Fig. 3. The thickness of the surface skin flow at the windward side of the crest determined from the bubble line profiles. The solid circles are those from which the determinations of the skin friction have been made. The open circles with arrows show the maximum estimations when the thickness of the surface skin flow is too small to determine it strictly.

side, the bubble line profiles are almost vertical up to the very water surface in most of the cases (f). The present method will not be applied to such a case, but the skin friction may safely be determined as zero. Reflections

of the flushed light at the air side of the water surface occur when the water surface is irregular by the presence of short capillary-gravity waves. Especially at a little leeside of the crest where the short capillary-gravity waves are accumu-

lated, halations near the water surface have almost always concealed the bubble line profiles near the water surface. The determination of the skin friction, therefore, has not been made in this region.

The measurements of the skin friction have been made along more than 80 representative wave crests by use of 16 mm cine-pictures taken at 42 frames s^{-1} . The whole results are presented in Fig. 1, and those taken successively at various phases with respect to some of the crests are in Fig. 2. The abscissa represents the phase relative to the peak of the crest, and the ordinate the square of the friction velocity in water (skin friction divided by the density of water). The zero values determined without the analysis by use of the relation (4), as mentioned above, are shown by circles with arrows.

It is apparently seen that the intensity of the skin friction varies greatly along each crest of wind waves. It increases rather abruptly or continuously at the windward side of the crest and attains, near the peak, a value about four times that obtained from the mean wind profile. However, at the leeside, the skin friction is considered as substantially zero. It seems to decrease suddenly near $\phi=30^\circ$, and suggest that the separation of the air flow occurs at a little leeside of the crest.

In Fig. 3 is shown the thickness of the surface skin flow at the windward side of the crest,

estimated from the bubble line profiles as seen in Photo 1. The solid circles are those from which the determinations of the skin friction have been made. The thickness of the surface skin flow seems to be inversely correlative with the value of the skin friction in Fig. 1. The thickness of the viscous sublayer close to the smooth solid surface is approximately 5 times the molecular kinematic viscosity divided by the friction velocity (MONIN and YAGLOM, 1971). Assuming the similar relation expressed by $h = \alpha \frac{\nu}{u_{*w}}$, where h is the thickness of viscous surface skin flow layer, u_{*w} the friction velocity, and ν the kinematic viscosity of water, then the values in Fig. 1 and Fig. 3 give the constant of the proportionality α of approximately 5 in an average. Although the value will be rather arbitrary since the determinations of h have not been made from the strict observations of the velocity profiles, it is interesting that it is almost constant irrespective of the phase, except the regions very close to the crest and the trough, and the value of α of 5 may be interpreted as supporting the validity of the value of u_{*w} estimated by our procedure.

The values in Fig. 1 have been averaged with phase intervals of 10° , and the results are shown in Fig. 4. The value of the shearing stress of wind determined from the mean wind profile, 2.96 dyn cm^{-2} , is shown by the dashed horizontal

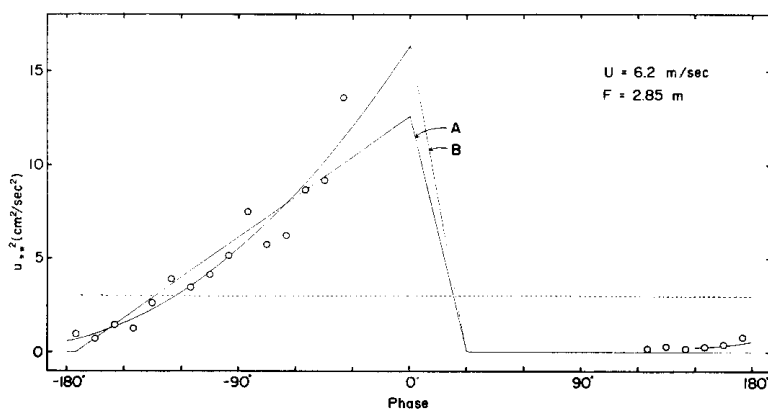


Fig. 4. The distribution of the skin friction along the representative wind waves, obtained by averaging the values presented in Fig. 1 with phase intervals of 10° . The dashed horizontal line indicates the stress value determined from the mean wind profile. The solid line A is an assumed distribution of the values with a linear increase at the windward side, and B is one with a quadratic increase toward the crest.

line. The assumed distribution of the skin friction may be represented by the solid curve designated by A, or by B. The mean intensity of the skin friction along the representative wave crest may be calculated by $\bar{\tau} = \frac{1}{360^\circ} \int_{-180^\circ}^{180^\circ} \tau(\phi) d\phi$. If $\tau(\phi)$ is taken along A, it amounts to 3.60 dyn cm⁻², and along B, 3.99 dyn cm⁻². These values exceed the shearing stress of wind determined from the mean wind profile. However, this result is not curious if we consider that $\bar{\tau}$ is not the statistical average determined from measurements at all situations of water surface, but the conditional average determined for the restricted representative wave crests. The water surface is not a simple train of representative wind waves, but consists of waves with various scale, and there exist even the regions where distinguishable wind waves does not exist except for very short capillary-gravity waves. The result may be explained as that the skin friction exerts the water surface more intensively around the representative wave crests. If the statistical average of the skin friction were taken, it would give a value smaller than the above values. Although the shearing stress of wind determined from the mean wind profile may not directly be compared with $\bar{\tau}$, it may be possible to say that the shearing stress of wind is transferred to water primarily by the skin friction even when the wind waves have developed.

As seen in our previous paper II, the shearing stress of wind before the generation of wind waves, which was determined from the velocity shear of surface skin flow at the water surface, was only 0.74 dyn cm⁻². Since the stress value determined from the mean wind profile when the wind waves developed was 2.96 dyn cm⁻², it is seen that the wind stress increases greatly with the growth of wind waves. STEWART (1974) has suggested that the momentum transfer across the air-water interface is supported mainly by the pressure drag when the wind waves exist. One of the basis of his discussion lies in the fact that the drag coefficient over the wind waves is greater than that estimated under the assumption that the water surface is smooth. However, the present results do show that this fact must be attributed almost solely to the intensification of the skin friction by the

growth of wind waves, and not to the predominance of the pressure drag.

The results obtained here show that the pressure drag is only small fractions of the total wind stress, although its existence is supported from the fact that the separation of air flow occurs just past the crest. It may be estimated as at most several percents. It will not be adequate to discuss, from the present results only, the validity of Phillips and Miles mechanisms in which the pressure distribution along the water surface is essential for the generation and the growth of wind waves, since the measurements have been made only at restricted wind and wave conditions, and the statistical average of the skin friction has not been taken. Our results, however, seem to suggest the possibility that the skin friction has a crucial role in the growth of wind waves. The particular flow structure in the wind waves, described in I and II, may be maintained by the skin friction which acts concentrically near the crests at the windward side as seen in Fig. 4, and is part of the essential character of the momentum transfer process across the air-water interface. It will not be so unrealistic to consider that the wind waves and the drift current very close to the water surface interact with each other, and a portion of the momentum provided to the drift current is transferred to the wind waves. In fact, the drift current near the water surface converges just past the crest and induce the downward thrust of water there. The wind waves will grow if only a portion of the converged water mass is consumed to increase the wave height.

References

- BANNER, M. L. and O. M. PHILLIPS (1974): On the incipient breaking of small scale waves. *J. Fluid Mech.*, **65**, 647-656.
- MCLEISH, W. and G. F. PUTLAND (1975): Measurements of wind-driven flow profiles in top millimeter of water. *J. Phys. Oceanogr.*, **5**, 516-518.
- MONIN, A. S. and A. M. YAGLOM (1971): *Statistical Fluid Mechanics*. English Edition Vol. 1, Section 5.3, The MIT Press, Cambridge, Mass. USA and London, England, pp. 270-284.
- OKUDA, K., S. KAWAI, M. TOKUDA and Y. TOBA (1976): Detailed observation of the wind-exerted surface flow by use of flow visualization methods. *J. Oceanogr. Soc. Japan*, **32**, 53-64.

STEWART, R. W. (1974): The air-sea momentum exchange. *Boundary-layer Meteor.*, **6**, 151-167.
 TOBA, Y., M. TOKUDA, K. OKUDA and S. KAWAI

(1975): Forced convection accompanying wind waves. *J. Oceanogr. Soc. Japan*, **31**, 192-198.

風波の波面に沿った粘性応力分布の測定

奥田邦明*, 河合三四郎*, 鳥羽良明*

要旨: 水面での粘性応力の値が, 風洞水槽で発生させた風波の波面に沿った数多くの点で, 局所的に, 測定された. 測定は, 平均風速 6.2 m s^{-1} , 吹走距離 2.85 m で行い, 粘性応力の測定には, 水素気泡列の水面付近でのプロフィールを用いた. 測定結果は, 粘性応力が風波の波面に沿って, その位相とともに, 大きく変化していることを示している. 粘性応力の値は, 波面の風上側では, 峯に近づくにつれて連続的に増加しており, 峯付近で 12

dyn cm^{-2} にも達している. ところが, 峯の少し風下側において, その値は急激に減少し, 波面の風下側では, 粘性応力は, 実質的には, ほとんど動いていない. また, 代表的な風波の波面に沿って決定されたこのような値から計算された, 水に働く平均的な粘性応力の値は, 水面直上の風速分布から決定された風の応力の値 3.0 dyn cm^{-2} を越える 3.6 dyn cm^{-2} を与えた. ここで得られたこのような結果は, 風の応力のほとんどは, 水面での粘性応力によって維持されており, そしてそれは, 風波の代表的な峯の風上側に最も強く働いていることを示している.

* 東北大学理学部地球物理学教室
〒980 仙台市荒巻字青葉