AN EXPERIMENTAL STUDY ON THE GENERATION AND GROWTH OF WIND WAVES (SECOND PAPER)

BY

Hideaki KUNISHI

1. Introduction

In a previous paper the author has shown from a wind-flume experiment that there are at least three regimes—initial tremor, initial wavelet, and sea wave—in the course of the generation and growth of wind waves. Fig. 1 gives the con-

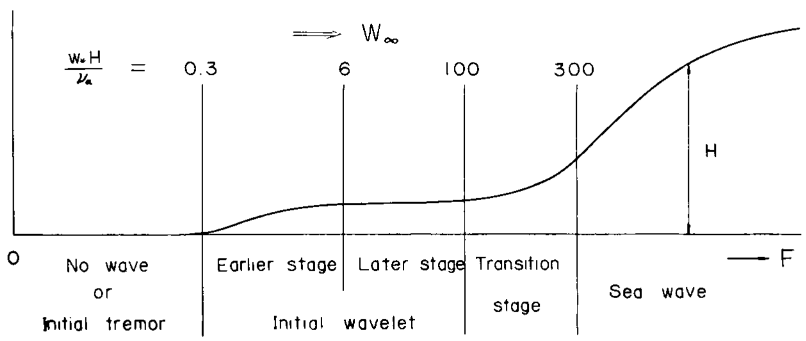

Fig. 1 Schematic figure of the feature of the generation and growth of wind waves.

cept of this feature of the appearance of wind waves in the steady wave state, where the abscissa and the ordinate represent the fetch and the average wave height respectively.

In the previous paper it has been shown that the initial wavelets are recognized as roughness elements on the water surface, and an empirical relation independent of the fetch has been found for this regime. In this paper the other empirical relation, dependent on the fetch, is shown with the discussion on the solution system of the initial wavelet.

2. Dimension-analytical consideration

The regime of initial wavelet may be described by the following twelve quantities:

$$\rho_a,\ \rho_w,\ \nu_a,\ \nu_w,\ g,\ S,\ W_\infty,\ F,\ w_*,\ z_0,\ H,\ L, \qquad \text{(a)}$$

which are respectively density of air, density of water, kinematic viscosity of air, kinematic viscosity of water, acceleration due to gravity, surface tension of water, free wind velocity, fetch length, friction velocity of air, roughness parameter, average wave height, and average wave length. These quantities give nine nondimensional quantities. We can consider that the values of the first eight quantities in (a) are known or given, hence five of nine non-dimensional quantities can be considered to be known. Therefore the system of the initial wavelet is determined by four non-dimensional relations between nine non-dimensional quantities.

Some of such four relations may contain both quantities W_∞ and F or either of them. There is, however, the possibility that some of these relations are independent of both W_∞ and F. It is useful for us to know how many such universal non-dimensional relations, independent of each other, are possible. Such relations are described by the following ten quantities:

$$\rho_a,\ \rho_w,\ \nu_a,\ \nu_w,\ g,\ S,\ w_*,\ z_0,\ H,\ L. \qquad \text{(b)}$$

These quantities give seven non-dimensional quantities. Provided that the first six quantities and one of the last four quantities in (b) are known or given, four non-dimensional quantities can be thought to be known. Hence, if we get three independent relations, the remaining three quantities in (b) will be uniquely determined by the quantities assumed konwn or given. For example, the values of ρ_a, ρ_w, ν_a, ν_w, g and S being known, the values of z_0, H and L will be uniquely determined for a given value of w_*, obviously these quantities z_0, H and L have no such nature, therefore only two universal relations between seven non-dimensional quantities are possible at most.

In our experiment three non-dimensional quantities, ρ_w/ρ_a, ν_w/ν_a, and $S/\rho_w\nu_w(g\nu_w)^{\frac{1}{3}}$ remain constants, so that the number of the effective non-dimensional quantities is reduced by three, but the number of relations discussed above is not altered. Thus the regime of initial wavelet in our experiment is perfectly determined by four non-dimensional relations between six effective non-dimensional quantities, and there is the possibility that two of those four relations are independent of both W_∞ and F.

In the previous paper, the author has found the following two relations in the regime of initial wavelet.

$$\frac{w_* z_0}{\nu_a}=0.105+0.1\frac{w_* H}{\nu_a} \quad \text{for} \quad \frac{w_* H}{\nu_a}<100, \qquad \text{(I)}$$

$$\left.\begin{aligned} \frac{w_* L}{\nu_a}&=270 && \text{for} \quad \frac{w_* H}{\nu_a}<6, \\ \frac{w_* L}{\nu_a}&=94.9\left(\frac{w_* H}{\nu_a}\right)^{7/12} && \text{for} \quad 6<\frac{w_* H}{\nu_a}<100. \end{aligned}\right\} \qquad \text{(II)}$$

The former relation (I) has the physical meaning that the initial wavelet is the roughnees element itself of natural type on the water surface, while the latter (II) is an empirical relation whose physical meaning is not known. Both relations (I) and (II) obviously have the universal nature, independent of both W_∞ and F, therefore no other independent universal relations are possible.

At this point it must be noted that, though in the previous paper the author has given the numerical value of 200 as the critical value of w_*H/ν_a at which the transition to sea wave occurs, it seems to be more adequate to consider the range between 100 and 300 in w_*H/ν_a as the transition stage between the regime of initial wavelet and that of sea wave.

3. Behavior of gz_0/w_*^2

The other two relations which make up the solution of the initial wavelet with the above two relations must be related to either W_∞ or F or both of them. They may possibly come from the momentum or energy consideration about the air or the water. The momutum consideration of the air flow will give the expression of the drag coefficient $C_f=2w_*/W_\infty^2$ in terms of two non-dimensional quantities $W_\infty F/\nu_a$ and $W_\infty H/\nu_a$, if our problem is simply analogous to that of the rough flat plate. This problem will be treated in another paper. The last relation may be considered to be given from the energy consideration of the initial wavelet. There are, however, some difficulties in accomplishing this procedure, and such method will not be adopted here. Rather the author will show an empirical non-dimensional relation containing the quantity F.

In the previous paper the author has stated that the quantity gz_0/w_*^2 seems to be directly dependent on the fetch F in the regime of initial wavelet. It is revealed by closer inspection of our experiment that the quantity gz_0/w_*^2 behaves in a very interesting manner against the quantities w_*F/ν_a and gF/w_*^2 This behavior is shown in Fig. 2 and 3. The experimental data of gz_0/w_*^2 are plotted against w_*F/ν_a in Fig. 2, both on a logarithmic scale, and against gF/w_*^2 in Fig. 3.

The data obtained at the same fetch are linked by short thin solid lines, and the number which indicates the fetch as shown at the lower right part of Fig. 3 is affixed to it. As the wind velocity increases, the quantity gz_0/w_*^2 in any fetch moves toward the right in Fig. 2 and toward the left in Fig. 3 in the manner that its value at first decreases, next rapidly increases, and then gently decreases, and lastly rather suddenly changes into a nearly constant value.

Of special interest is that the second rapid increase of its value seems to be governed by the one relation

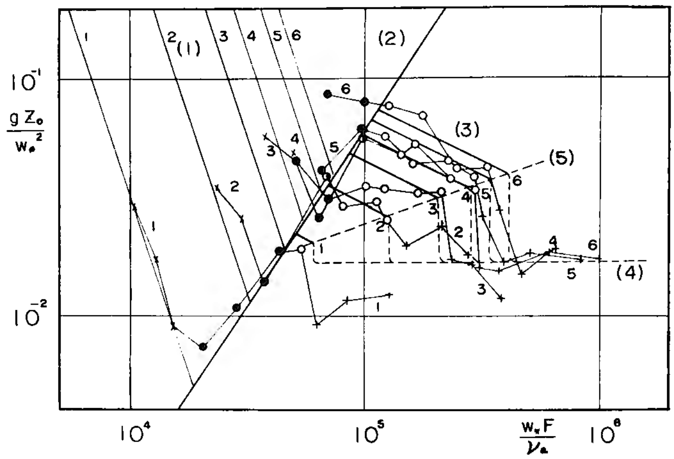

Fig. 2 Behavior of gz_0/w_*^2 against w_*F/ν_a.

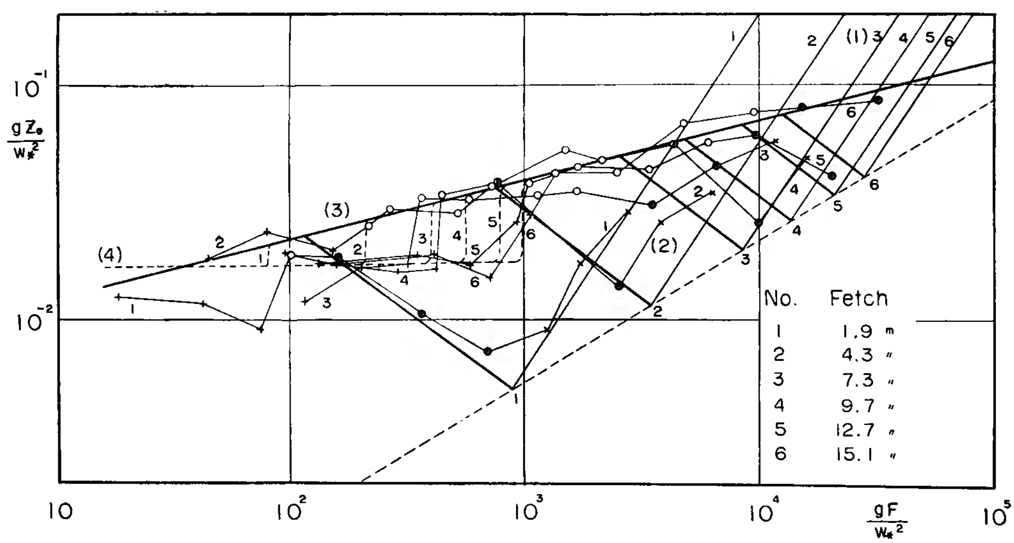

Fig. 3 Behavior of gz_0/w_*^2 against gF/w_*^2.

$$\frac{gz_0}{w_*^2}=2\times10^{-9}\left(\frac{w_*F}{\nu_a}\right)^{\frac{3}{2}}, \qquad (2)$$

as represented by the thick solid line, steeply sloped up toward the right, in Fig. 2, and the third gentle decrease by the other one relation

$$\frac{gz_0}{w_*^2}=7\times10^{-3}\left(\frac{gF}{w_*^2}\right)^{\frac{1}{4}}, \qquad (3)$$

as represented by the thick solid line, gently sloped down toward the left, in Fig.

3. The relation (2) can be represented in Fig. 3 as a family of lines with one parameter gF^3/ν_a^2, and it is shown by the six thick solid lines to each of which is affixed the number indicating the fetch. The relation (3) in Fig. 2 is also expressed in like manner.

In these figures, the nature of smooth surfaces

$$\frac{gz_0}{w_*^2}=0.105\frac{g\nu_a}{w_*^3} \qquad (1)$$

is also shown by the six thin solid lines. The behavior of the data shown by the × marks, which have the values of w_*H/ν_a smaller than 0.4, may be understood with the aid of these parametric lines.

The quantity w_*z_0/ν_a at the intersection of the lines (2) and (3) is given as a function of the quantity gF^3/ν_a^2, and the numerical values for our six fetches are given as 10.2, 3.50, 1.75, 1.20, 0.84, and 0.67 in order of fetch. The data each of which has the value of w_*H/ν_a larger than 0.4 and the value of w_*z_0/ν_a smaller than the above critical value are shown by the solid circles in the figures. The semi-solid circles represent the critical data each of which has a value very close to the above critical value of w_*z_0/ν_a. These ride well on the line (2) with the exception of two data, the second at the fetch of 7.3 m and the first at the fetch of 15.1 m.

Here it must be mentioned that the value of w_*z_0/ν_a reaches the first maximum in the transition stage to sea wave, and after slight decrease, it increases again as the wind velocity increases. Although such maximum seems to occur at the larger value of w_*H/ν_a for larger fetch, it is uncertain whether such maximum value itself is dependent on the fetch or not. The observed values lie between 10 and 23. The data before reaching such first maxima are represented by the blank circles in the figures, and all of these data ride well on the line (3).

If we suppose that the relation (3) breaks down at

$$\frac{w_*z_0}{\nu_a}=16\,, \qquad (5)$$

and the quantity gz_0/w_*^2 suddenly reaches the constant value

$$\frac{gz_0}{w_*^2}=0.017\,, \qquad (4)$$

the behavior of gz_0/w_*^2 shown by the broken lines in the figures will be obtained. The broken straight line (5) in Fig. 2 represents the intersection of the relations (3) and (5). This behavior seems to explain rather fairly the actual one which is seen through the data shown by the cross marks, though the actual mechanism of this transition may be more complicated.

Thus, the quantity gz_0/w_*^2 is considered to be governed by the four relations (1) to (4), the transition from (3) to (4) being assumed to occur at (5).

4. Some additional remarks

In the first place, it must be noticed that the transition from (1) to (2) does not occur at the intersecting points of (1) and (2), but the value of gz_0/w_*^2 departs from the line representing smooth surfaces (1) before reaching the line (2), since the initial wavelets generate before the line (2) is reached. Therefore this transition needs to be investigated more closely. It is, however, difficult to carry on such investigations from our present data.

In the second place, it must be mentioned that the change in the behavior of gz_0/w_*^2 is considered to occur in the smallest fetch, smaller than about 1.3 m, and in the fairly large fetch, larger than about 60 m, because the interrelation of the relations (1) to (5) changes there as far as those relations are correct. It must be noted here also that the functional form of the empirical relations (I), (II), and (2) to (5) may be altered so that they are consistent with the reasonable theory of the generation and growth of wind waves which is not yet established, though the author wishes to do this task with the aid of both the boundary layer theory on rough flat plates and the energy consideration of waves.

Acknowledgement

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References

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