CHAPTER 29

HORIZONTAL AND VERTICAL WATER PARTICLE VELOCITIES INDUCED BY WAVES

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ABSTRACT

Measurements of horizontal and vertical water particle velocities induced by regular waves, wind waves generated by a wind wave tank and ocean waves in shallow water were made using a Doppler-type sonic current meter. For regular waves, the validity of wave theories such as Stokes and cnoidal waves is investigated by comparison between theoretical curves and the experimental results. For wind waves and ocean waves, power spectra of water particle velocities and cross-correlations between surface displacement and water particle velocity are considered, especially in the latter case, directional spectra calculated from both the records are compared each other.

INTRODUCTION

To obtain the water particle velocities induced by waves is of very importance for the investigation of various phenomena on coastal engineering such as wave force, littoral drift and so on. Although the horizontal water particle velocity by regular waves was measured by Goda (1964), Le Méhauté, Divoky and Lin (1968) and Iwagaki and Sakai (1969) using a propeller-type current meter, tracers of neutrally buoyant particles, tracers of hydrogen bubbles and a hot-film anemometer respectively and compared the results of experiment with finite amplitude wave theories, their conclusions are different each other because of difficulty of the measurement. Moreover, there have little been the previous works on the vertical water particle velocity by regular waves, the water particle velocities by wind waves in a laboratory and ocean waves in shallow water except for the some observational results.

This paper deals with the experimental and observational investigations on the horizontal and vertical water particle velocities by regular waves, wind waves and ocean waves measured using a Doppler-type sonic current meter.

EXPERIMENT ON WATER PARTICLE VELOCITIES BY REGULAR WAVES

(1) Experimental Equipment and Procedure

The wave tank used in the experiment is 78 m long, 1.0 m wide and 1.5 m deep which has the sloping model beach of 1/100, 45 m long, as shown in Fig. 1.

The measurements of horizontal and vertical water particle velocities were made using the Doppler-type sonic current meter of three components, which was set the output of one component to be zero. The principle of this current meter is to make use of the frequency shifts of sonic beam due to the Doppler effect by the motion of buoyant particles in water. Static calibration of this current meter was made moving the carrier equipped with the one, with a various constant speed, and in view of the characteristics of low pass filter which transforms the frequency shifts into the variation of voltage, the response frequency is deduced to be approximately 2 cps, although the dynamic calibration was not carried out. In the experiments, time variations of water particle velocities at a point and the vertical distributions of them including the wave height at the same time were respectively measured for the wide range of wave characteristics.

The wave characteristics used in the experiment are tabulated in Table 1, in which T, h, H and g indicate the wave period, the depth of water, the wave height and the acceleration of gravity respectively.

(2) Experimental Results and Considerations

Fig. 2 shows the comparison between the theoretical curves of finite amplitude waves and the experimental results for horizontal particle velocities at phase of wave crest and wave trough u_c and u_t respectively, in which the notations 1, 2, 3, 4 and c indicate the theoretical curves by Stokes wave theories of each order approximate solution derived by Skjelbreia and Hendrickson (1961) and the cnoidal wave theory of the second approximation by Laitone (1965). These figures show that the degree of increase of water particle velocity at phase of wave crest with wave height is not so large enough to be obtained by the finite amplitude wave theories and that the experimental results at phase of wave trough agree relatively well with the theoretical curves of Stokes waves of the 4th orders and cnoidal waves.

The variation of maximum value of vertical water particle velocity with wave height is given in Fig. 3, which shows that the experimental values are to be good agreement with the cnoidal wave theory, as the value of $T\sqrt{g/h}$ increases.

Fig. 4 shows the vertical distribution of horizontal water particle velocity at phase of wave crest. The experimental results agree with the theoretical curves of the 4th order solution in the case of relatively small value of $T\sqrt{g/h}$ and disagree to be plotted between the theoretical curves of small amplitude and finite amplitude wave theories in the case of large value of $T\sqrt{g/h}$, especially the cnoidal wave theory gives considerably excessive values for large wave height.

Some examples of the time variations of horizontal and vertical water particle velocities which are designated by white and black circles respectively and wave profile are shown in Fig. 5. It is found that the theories are coincided with the experimental results in the figures.

In the experiment of this time, it was verified from above consideration that although the finite amplitude wave theories are applicable for estimation of water particle velocities in the case of relatively small wave height, the deviation of both the results becomes considerably larger with the increase of wave height.

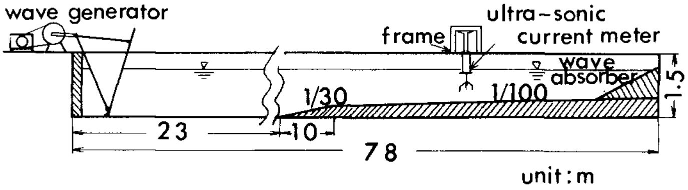


Fig. 1 Schematic sketch of wave tank used

Table 1 Wave characteristics used in experiment by regular waves

T_{sec}	h_{cm}	$T\sqrt{g/h}$	H_{cm}
1.50	55.6	6.30	9.4 ~ 25.3
2.00	55.6	8.40	9.0 ~ 39.6
2.50	55.6	10.50	6.2 ~ 39.1
3.00	55.6	12.60	6.6 ~ 42.2
2.50	27.8	14.85	5.7 ~ 19.5
3.00	27.8	17.82	4.7 ~ 24.8

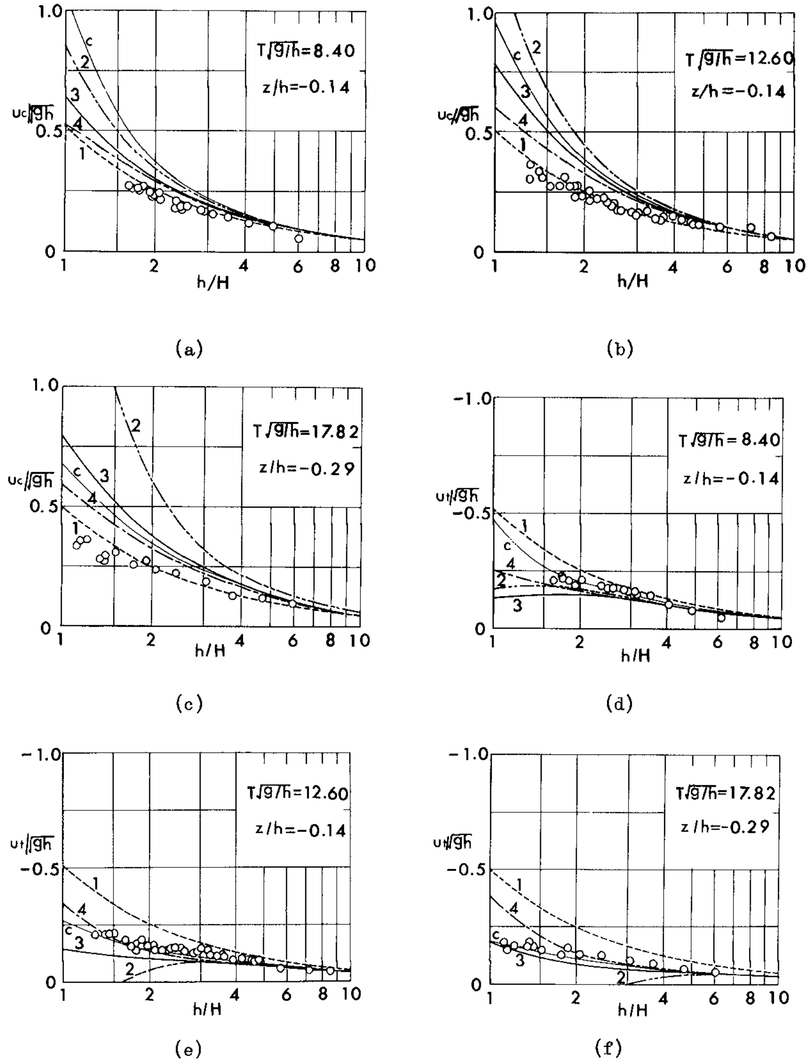


Fig. 2 Variations of horizontal water particle velocity at phase of wave crest and wave trough with wave height

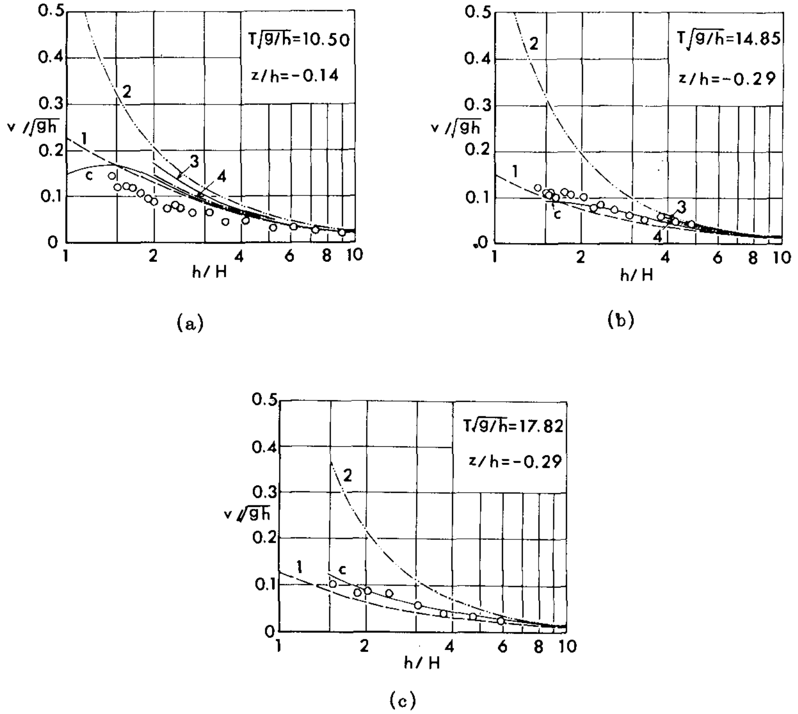


Fig. 3 Variation of maximum value of vertical water particle velocity with wave height

Some factors for this cause are picked up, such as the poor responsibility of this current meter for higher frequency, sheltering and blocking effects for wave motion by the submerged portion of the current meter and so on, in addition to the question for the validity of applying the theories of comparatively lower approximation on a uniform depth to large amplitude waves near wave breaking on a gently sloping beach. Moreover, the more important one may be the wave celerity in most of Stokes wave theories to be calculated on the basis of Stokes' first definition. It has been made clear in the authors' experiment on the vertical distribution of mass transport velocity by waves that the experimental results agree with the theoretical curves derived by Stokes' second definition better than the first definition. This means that the generated waves in a laboratory satisfy approximately the condition of the second definition, which is the average mass transport velocity over a wave length to be zero by addition of a uniform motion. In fact, the 4th order approximate solution calculated using the second definition accounts for the experimental results for wave celerity and water particle velocities better than the first definition. The theo-

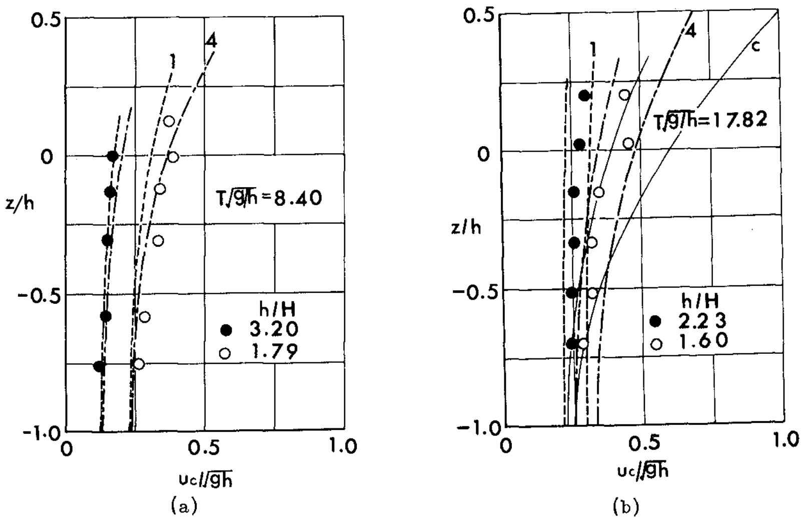


Fig. 4 Vertical distribution of horizontal water particle velocity at phase of wave crest

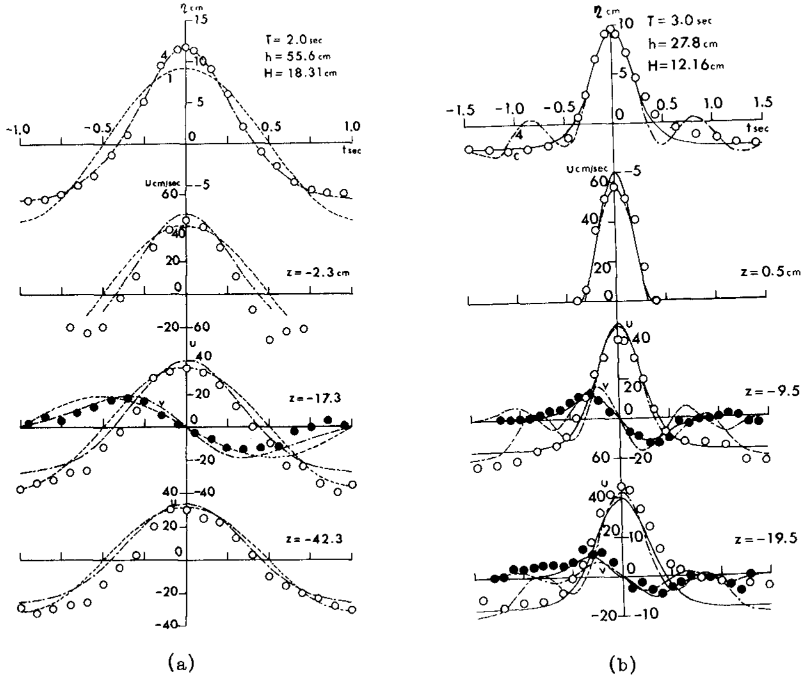


Fig. 5 Time variations of water particle velocities and wave profiles

retical curves of horizontal water particle velocity by the second definition become considerably smaller at phase of wave crest and a little larger at phase of wave trough than those by the first definition and approach the experimental results.

EXPERIMENT BY WIND WAVES IN A LABORATORY

(1) Experimental Equipment and Procedure

A random wave generator used in the experiment is a recirculating wind wave tank which consists of a doughnut-shaped wind wave tank, a blower, a wave direction controller and an experimental straight tank as shown in Fig. 6.

The experiment was carried out by changing wind speed U at constant water depth in the unsteady state that the generated waves are recirculating in the wave tank (called especially recirculating in this paper) and in the steady state such as a usual straight wind wave tank (called non-recirculating). The surface displacement and water particle velocities in quasi-steady and steady states were measured at a portion of recirculating wind wave tank and an experimental straight tank in both the cases. The records were sampled at intervals of 0.1 sec for 1 or 2 minutes and power and cross spectra were computed by the Blackman-Tukey method.

(2) Experimental Results and Considerations

Fig. 7 shows the power spectra of surface displacement and water particle velocities and their coherences ($C_{\eta u}$ and $C_{\eta v}$), in which f is the frequency. It

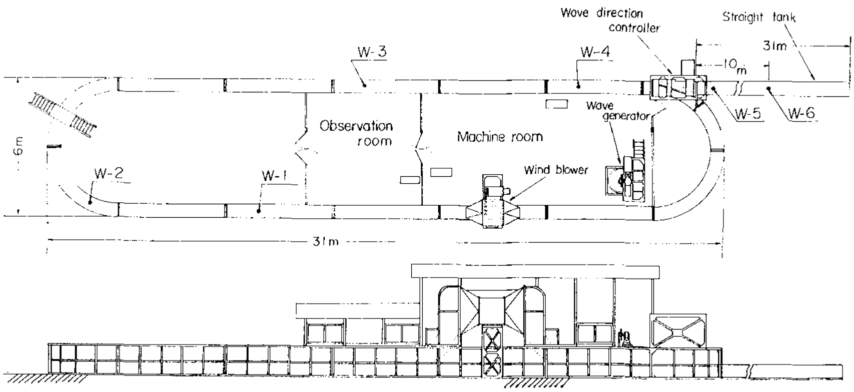
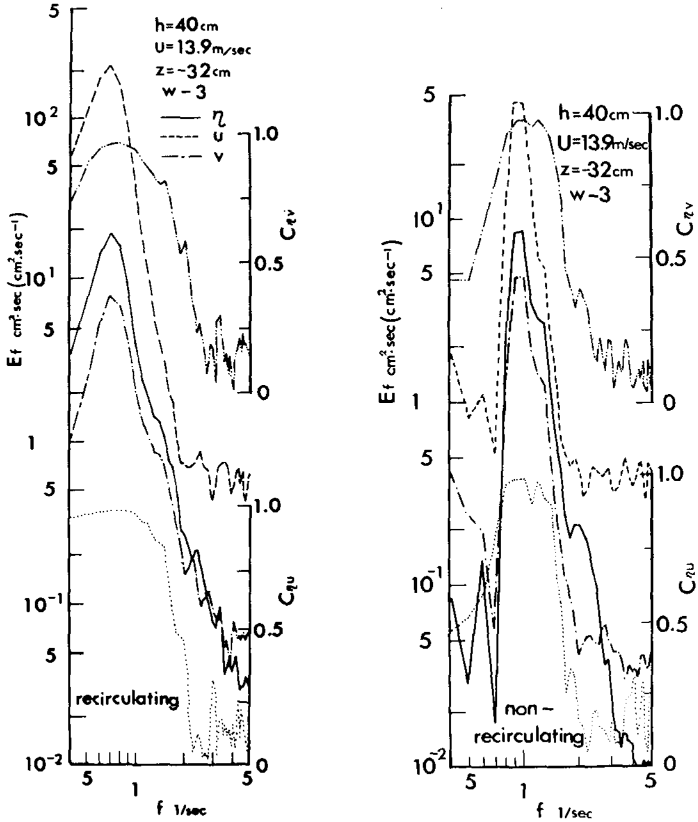


Fig. 6 General view of recirculating wind wave tank

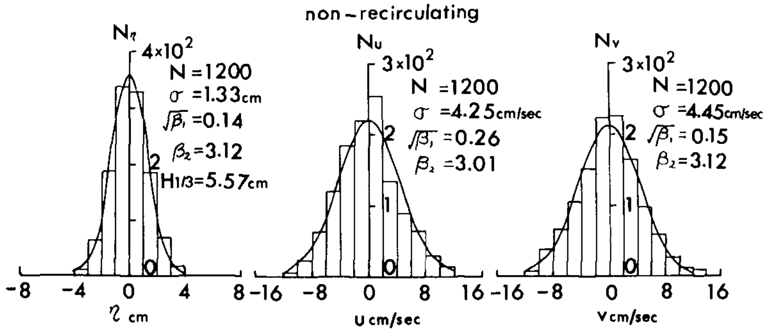


(a) (b)

Fig. 7 Power spectra of water particle velocities and surface displacement of wind waves

is found that the correspondence between them is good in the neighbour of peak frequency, but that poor in the region of higher frequency because of the noise, and less responsibility of this current meter and the effect of hydraulic filter. This is also obvious from the characteristics of their coherence.

Fig. 8 is an example of the comparison between the experimental results and the curves of Gaussian distribution, in which N, σ, $\sqrt{\beta_1}$, β_2, and $H_{1/3}$ are the number of samples, standard deviation, skewness, kurtosis and significant wave height respectively. It shows that the frequency distributions of them are approximately described by Gaussian distribution in spite of a little distortion on the left side.

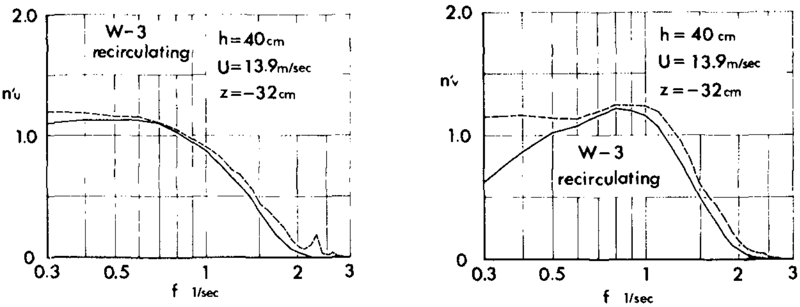


(a) (b) (c)

Fig. 8 Frequency distribution of surface displacement and water particle velocities

In the next, the cross-correlation between them is considered introducing the correction coefficients, because in general the frequency response function calculated from measured records by the spectral analysis G(f) disagrees with the one from small amplitude wave theory due to the effects of non-linearity, irregularity of waves and so on. The correction coefficients for horizontal and vertical water particle velocities n_u' and n_v' are given respectively as

$$n_u' = \{2\pi f \cosh k(h+z)/\sinh kh\}/G(f), \quad n_v' = \{2\pi f \sinh k(h+z)/\sinh kh\}/G(f)$$



(a) (b)

Fig. 9 Correction coefficient for water particle velocities of wind waves

Some examples are shown in Fig. 9, in which full and dotted lines are correction coefficients determined by power spectra and cross-spectra respectively. It can be seen that the values of them are a little larger than 1 in the neighbour of peak frequency and that rapid decrease appears in the higher frequency region. In this way, the power spectra for horizontal and vertical water particle velocities can be inferred from the surface displacement when the characteristics of these correction coefficients are given.

OBSERVATION BY OCEAN WAVES IN SHALLOW WATER

(1) Observational Method

The simultaneous obserbations of ocean waves and water particle velocities in shallow water were made at the pier on the Ogata Coast facing the Japan Sea in October 1971. Waves were measured by capacitance wire gages arranged the Delta prove array at three stations (St-1, St-2 and St-3) of which distances are 15.4 m (St-1∼St-2), 18.8 m (St-1∼St-3) and 18.8 m (St-2∼St-3) respectively and water particle velocities of three components by the sonic current meter mentioned above which was set on the almost same place as the wave gage (St-2) at the location of 1.65 m below the still water level. The direction of sensors of this current meter was decided by photographs taken directly downwards from the pier. The average depth of water is about 5.7 m.

These records for 5 or 10 minutes were digitalized at intervals of 0.4 sec and power and cross spectra were computed as well as in the previous section.

(2) Observational Results and Considerations

Fig. 10 is one of examples for power spectra of surface displacement at three stations. Spectral form of each other is closely similar and the law of f^{-5} proved by Phillips (1958) holds good in the equilibrium range of higher frequency.

Fig. 11 is the power spectra of water particle velocities of three components and corresponding surface displacement, in which u_x and u_y are two horizontal velocity components in the orthogonal directions and it shows good correspondence each other. An example of correction coefficients for vertical water particle velocity is shown in Fig. 12.

Various methods to measure directional spectra have been proposed. For example, Barber (1961) gave a method of calculating the directional resolving power for array of wave gages and directional spectrum and Nagata (1964) described the directional spectrum to be calculated using a current meter of three components on the basis of the same method as Longuet-Higgins et al (1961).

The directional spectra for peak frequency obtained from simultaneous records of three wave gages and sonic current meter of three components are compared in Fig. 13. In most cases, mutual correspondence is poor owing to the lack of directional resolving power, as shown in Fig. 14 which indicates the one of this array for each direction of incident waves α in the case of frequency of 0.2 cps. Fig. 14 is one of examples for the directional spectra obtained during the observations.

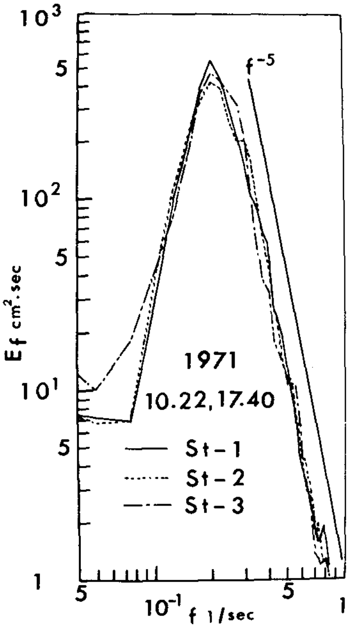


Fig. 10 Power spectra of surface displacement of ocean waves at three stations

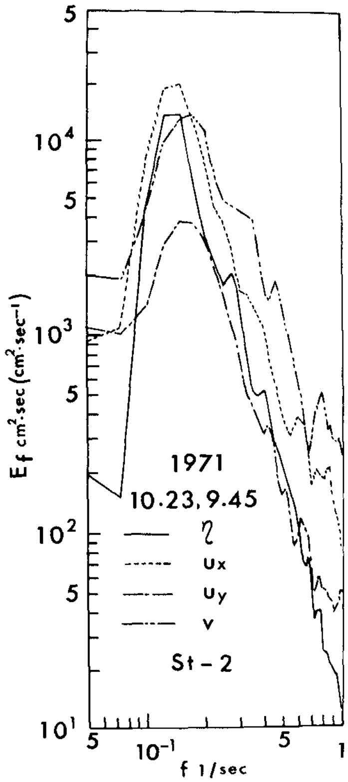


Fig. 11 Power spectra of water particle velocities and surface displacement of ocean waves

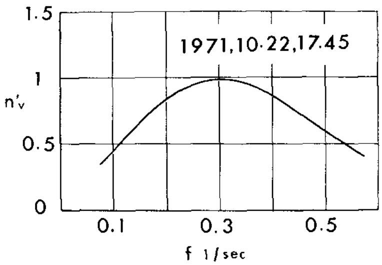


Fig. 12 Correction coefficient for vertical water particle velocity of ocean waves

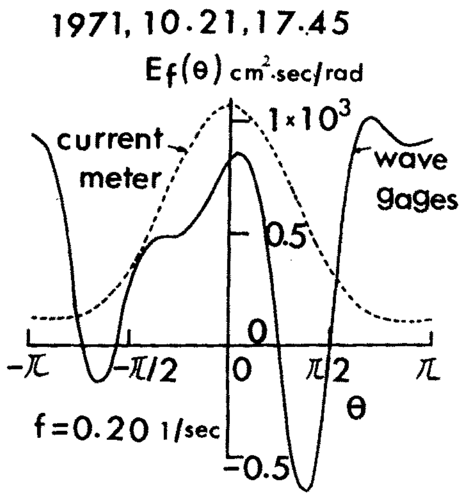


Fig. 13 Comparison between directional spectra obtained from records of waves and water particle velocities

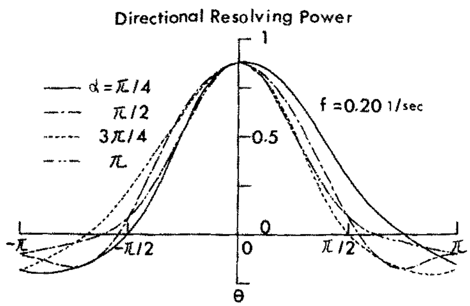


Fig. 14 Directional resolving power for Delta array used in observation

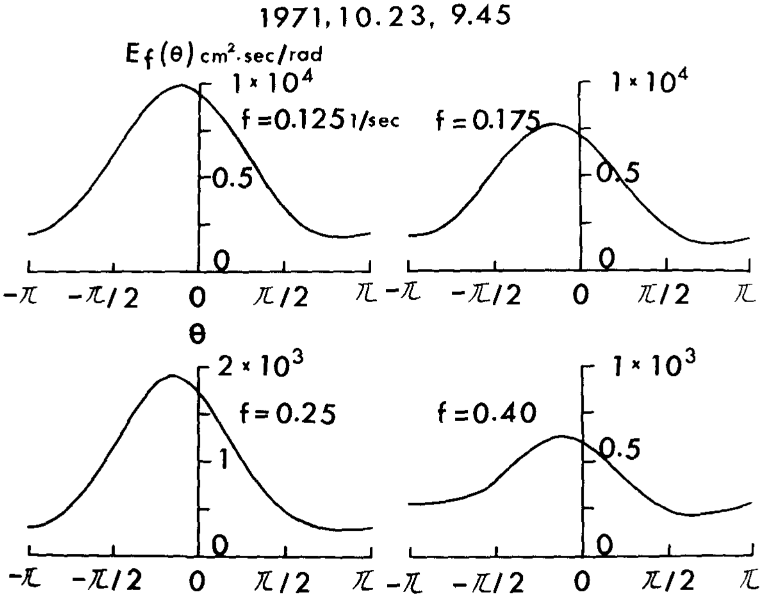


Fig. 15 An example of directional spectra of ocean waves obtained by sonic current meter

CONCLUSIONS

The experimental and observational investigations on the validity of theoretical expressions for horizontal and vertical water particle velocities induced by regular waves, wind waves and ocean waves in shallow water were made using the Doppler-type sonic current meter. For regular waves, it was verified from comparison between the theoretical curves of finite amplitude wave theories and the experimental results that the theories are applicable in the case of relatively small wave height. For wind waves, a method of estimation of power spectra for water particle velocities was proposed. In addition, the directional spectra obtained from the records of waves and water particle velocities at the Ogata Coast were compared each other.

ACKNOWLEDGEMENT

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