SOME EVIDENCE OF ORGANIZED FLOW OVER NATURAL WAVES

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Abstract. Measurements of the flow characteristics at 2 m over unobstructed wave surfaces on Lake Michigan were made using an anemometer-bivane as a velocity sensor. During one 40-min period of measurement, significant energy concentration was observed at the frequency of dominant surface waves in the vertical and cross wind spectra. Cross spectra between the surface elevation and vertical motions in the flow indicate that the surface lags the vertical motions by about 55° at the frequency of dominant waves.

1. Introduction

The importance of the mechanisms for the transfer of energy across the sea-air interface has been stressed in many reviews such as the study of the Joint Panel on Air-Sea Interaction of the National Academy of Sciences, U.S.A. (1962). Determination of the nature of mechanisms of the transfer is basic to the understanding of the interactions between the sea and overlying atmosphere.

Stewart (1967) has presented a dimensional argument that indicates, for a 'saturated' wave field, that the energy and momentum contained in the wave motion equals that possessed by the mean air stream to a height of about one wavelength above the surface. For a typical deep water wave, this can mean that the wave field energy is equal to the energy of the mean flow in approximately the lowest 60 m. The wave energy, then, greatly exceeds that contained in the turbulent components of the air flow and one must look to the mean flow as the source of energy for wave generation.

The mechanisms for the transfer of energy from the mean air flow to water have been soundly argued from basic principles by Miles (1957) and Phillips (1957). These two theories and their later enlargements have appeared to provide adequate theoretical explanations for the growth of wave fields. Excellent physical interpretations of the theories are presented by Lighthill (1962) and by Kinsman (1965). Experimental evidence to confirm the validity of these theories has, however, been slow in developing, possibly due to the difficulty in making accurate measurements over unobstructed wave surfaces of significant amplitude. It is probably due to this difficulty that attempts have been made to adapt results of measurements over solid surfaces or over protected water surfaces to predict behavior of flow over water. As a result, much confusion

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exists in the past literature as summarized by Roll (1965). An experimental program has been conducted over the open water of Lake Michigan in an attempt to obtain measurements of the flow characteristics over natural, unobstructed, wind-generated waves.

2. Description of Measurement Site and Instrumentation

Measurements of flow characteristics over wave surfaces were made from a fixed tower located 1.75 km from shore in Lake Michigan near Muskegon, Michigan, in a mean water depth of about 16 m. The tower is a self-supporting structure resting on the lake bottom and is exceedingly stable, exhibiting no perceptible oscillations in response to the wave forces.

The tower location, shown in Figure 1, on the east side of Lake Michigan,* provides nearly optimum exposure for measurements of unrestricted flow over a wave surface. The existing wave field is a result of the existing wind; swell from distant disturbances does not exist in the lake. Over-water fetches of greater than 100 km are available for wind directions of from 180 to 330°. Instrumentation was mounted on the westward facing side of the tower so that winds having a significant over-water fetch were not influenced by the tower structure. The lake bottom is gradually sloping and the shore has no abrupt protuberances so that a minimum of shore influence is acting at the tower site.

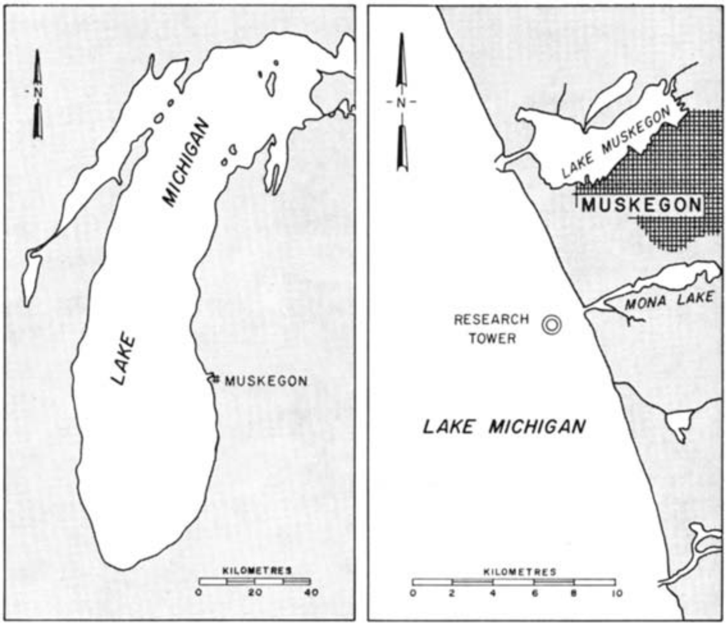

Fig. 1. Location of Lake Michigan research tower.

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* The Lake Michigan Research Tower was furnished by the U.S. Army Corps of Engineers, District, Lake Survey, Detroit, Michigan.

The three orthogonal components of the air flow at a height of 2 m over the mean water surface were measured by an anemometer-bivane as described by Hewson *et al.* (1962). Performance tests of this instrument indicate that both the speed and direction sensors attain approximately 63% response to gust lengths of 3 m. Significant overshoot is not experienced at any wavelength. Accurate observational data should, therefore, be obtained to an upper frequency limit of about 2 Hz in a mean wind of 6 mps. A photograph of the instrument as exposed on the tower is shown in Figure 2.

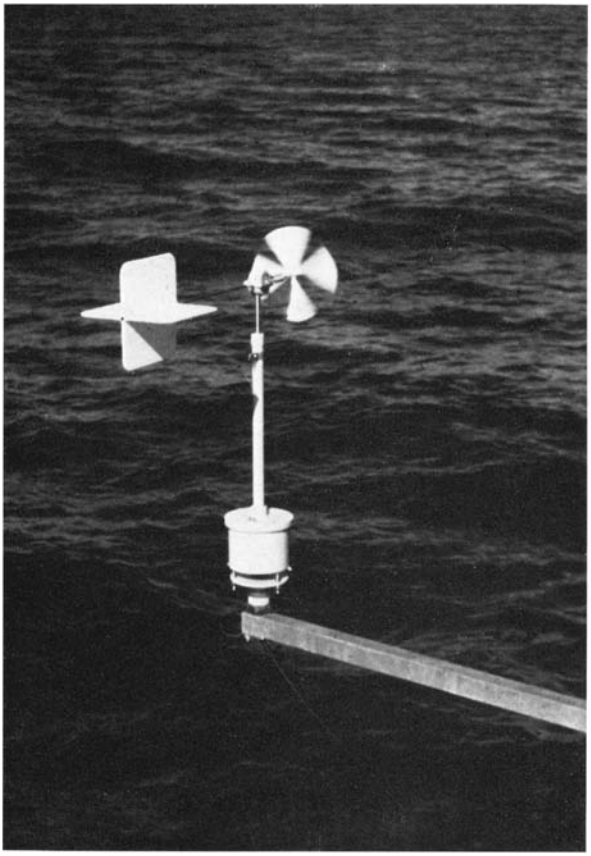

Fig. 2. Anemometer-bivane exposed over the water surface on research tower.

The water surface elevation was measured by an incremental wave staff having electrical contacts at 6 cm intervals. The incremental signal was integrated to give a smooth record of the gravity waves while filtering the higher frequency capillary ripples. The instrument has been described by Caldwell (1961). Exposure of the wave staff was directly beneath the anemometer-bivane so that exact spatial and time comparisons are possible between the records from the two sensors.

Measurements of the wind velocity and water surface fluctuations were recorded on a multi-channel magnetic tape recorder capable of recording simultaneously all of the variables. Linear frequency response of the recorder is adequate to record the highest frequencies contained in the data without distortion. Simultaneous recording of the data on parallel tracks of the same tape retains the phase relationships for subsequent analysis.

3. Data Processing

The analog records of the variables were translated into binary digital format for machine processing. Because of the upper limit of bivane response, the digital sampling rate was chosen as 4 per sec giving a Nyquist Frequency of 2 Hz. The data were filtered with a fourth order filter having a half-power point at 1.5 Hz prior to digitization to prevent aliasing of the noise or other extraneous data contained above the Nyquist Frequency. The analog to digital conversion was accomplished through parallel channels, thus retaining phase relationships for cross spectral analysis. Sample time for the analog-to-digital conversion was less than 1 millisec and, therefore, can be considered instantaneous in the time scale of concern.

The anemometer-bivane data were reduced to the three orthogonal components termed U, V, and W, where the mean vertical wind $\bar{W}$ is assumed to be zero and U is defined as the downwind component, i.e. $\bar{V}$ is defined as zero. The means and trend were removed from each data period prior to spectral analysis.

The spectrum and cross spectrum analysis were based on the Fast Fourier Transform technique as described by Bingham *et al.* (1967), using 40 min data periods or about 9000 data points. A simple cosine bell data window was applied and enough zeroes added to produce a total record length of 16 384 points.*

Power spectra and cross spectral estimates were obtained for each of the variables or set of variables. This procedure gives estimates at 8192 harmonics of the artificially extended analysis period. The results were summarized to produce 94 spectral estimates by integration over frequency bands that are roughly proportional to the frequency. Thus, the spacing of points on a logarithmic scale is nearly uniform and more detail is provided at the low frequency portion of the spectrum. The confidence of the spectral estimates varies, therefore, being least at the lower and greatest at the upper end of the spectrum. In terms of degrees of freedom, the variation is from about 5 at 0.01 Hz, 10 at 0.1 Hz, and 100 at 1 Hz, being about 20 at the frequency of the surface waves.

4. Results

Figure 3 shows a composite of the U, V, and W, and the surface wave spectra for 18 August, 1967. The observations were made over a decreasing wave field where the dominant waves had a period of about 4.9 sec giving a phase velocity of 7.4 mps. The

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* A complete description of the methods is contained in 'On the Kinetic Energy Spectrum Near the Ground', Abraham H. Oort and Albion Taylor, *Monthly Weather Review*, **97**(9), pp. 623–636, September, 1969.

measurements were, thus, made much below the Miles critical height (for further explanation see Lighthill, 1962) where the wind speed equals the wave phase velocity, the mean wind speed being 3.3 mps. The significant wave height was 0.58 m so that the measurements were 3 to 4 wave heights above the wave crests.

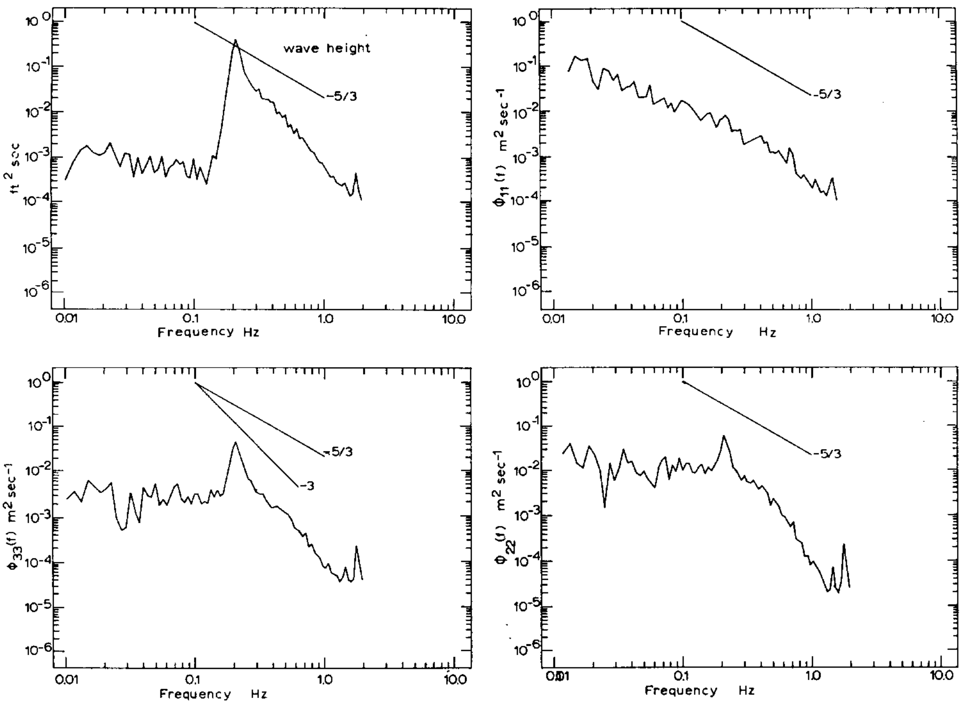

Fig. 3. Power spectral density estimates of wave height, vertical, downwind, and crosswind, velocity components, 18 August, 1967, Lake Michigan research tower.

The spectra are plotted as logfrequency vs. logspectral density and are, thus, not equal area graphs. Instead, the slope of the energy density is retained and the low frequencies are accentuated. Extra lines having slopes of $-\frac{5}{3}$ and -3 are provided for visual comparison.

The dominant feature of the spectra is the concentration of energy in the *W* and *V* spectra at the frequency of the surface waves. This pronounced peak is not present in the downwind spectra but even there a departure from the expected $-\frac{5}{3}$ slope is observed to coincide with the wave frequency. Uncertainties as to the sensor response function leaves the exact slope of the spectrum above 1 Hz in question. The spectral definition in the region of the surface wave frequency is, however, quite well established.

The cross-spectral density function between the surface waves and the velocity components at 2 m height shows significant energy only near the peak of the wave spectrum. In this frequency interval of significant coherence, it is possible to relate the energy contained in the cospectra and quadrature spectra to assess the relative phase relationship between the variables as described by Panofsky (1958). At the frequency of the dominant waves, the phase relationships shown in Figure 4 are observed.

The vertical components of the air motions are observed to lead the water surface elevations by approximately 55°. The coherence for the downwind components is less due to the smaller concentration of variance in the wave frequency. In this case, a phase relationship shows the downwind component leading the water surface by 130°. The crosswind component also leads the water surface by 130° and has significant coherence indicating the three-dimensional nature to the flow. This may reflect the fact that, in reality, the waves are not long crested as assumed in the simplified drawing of Figure 4, or that the waves may have had a significant component of motion across the mean wind. Direction of wave propagation was not measured.

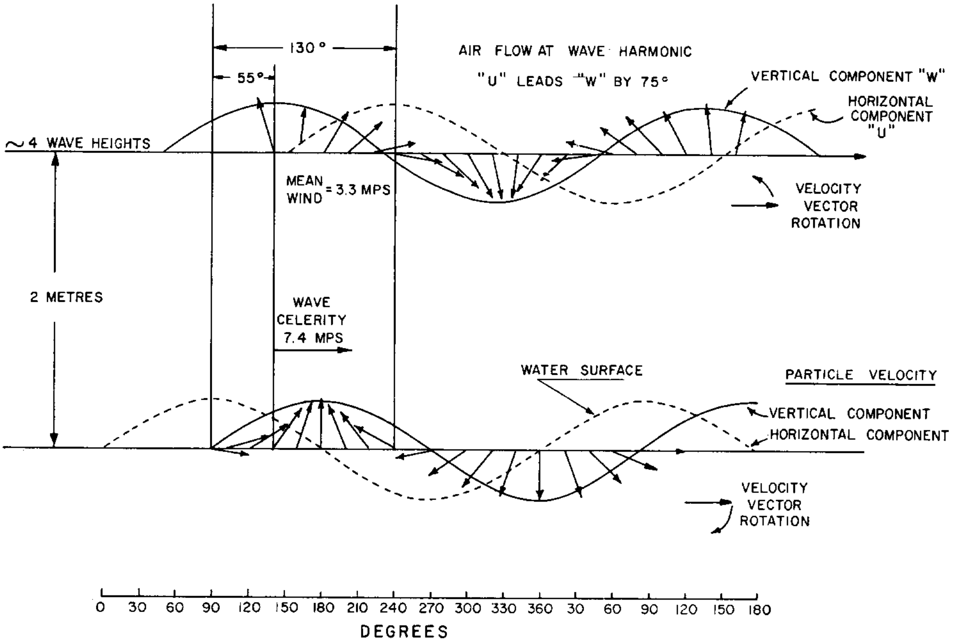

Fig. 4. Indicated phase relationships and velocity vectors for water surface and air-flow, 18 August, 1967, Lake Michigan research tower.

5. Interpretation

In the physical explanation of the Miles theory of wave generation, Lighthill (1962) shows a streamline configuration with reference to the moving wave. A circulation associated with the wave crest and moving at the wave phase velocity is indicated. The motion is an organized, non-turbulent, wave-like flow superimposed on the turbulent flow which is assumed to exist.

Stewart (1967) and later Pond (1968) have stated that such organized flow had not been observed in their experiments. More recently, Seesholtz (1968) has reported observations with cup anemometers showing energy peaks near the wave frequency. The data shown here and others previously reported by Elder and Soo (1967) tend to indicate that organized motion does exist in the region below the critical level. Pond (1968) has pointed out that motion of the sensor support can account for concentration of spectral energy at wave frequencies in some reported results. This does not appear to be a possibility in this instance as the tower structure was extremely rigid and showed no detectable response to wave forces.

The results of the cross spectral computation shown in Figure 4 give a tentative indication of the phase relationships of the velocity components to the water surface fluctuations. It may be noted that these results are in good agreement with those reported by Shemdin (1969) for measurements in a laboratory channel for the zone in which the mean wind speed is less than the wave celerity.

An approximation of the velocity vectors of the fluid motion for both the water surface and for the air at the height of measurement, as indicated by the phase relationships obtained from the cross spectra, has been sketched in Figure 4. The indicated magnitude of the components is speculative but the phase relations indicate an organized flow having a velocity vector whose rotation is in a sense opposite to that of the water motions. These observations agree in general with the bubble observations reported by Easterbrook (1968), in that downward motions follow and upward motions precede the crests of an advancing wave.

More observations must be examined to determine the generality of the results reported herein. In particular, it should be determined how the phase relationships depend upon proximity to the critical layer. While these results differ significantly from the model shown by Lighthill (1962), the results obtained by Shemdin (1968) would indicate significant phase shift as the critical layer is approached. The existence of an organization in the flow related to the surface waves appears to be strongly indicated.

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