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PRELIMINARY STUDIES ON THE TURBULENT CHARACTERISTICS OF OCEAN WAVES

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U.S. NAVAL
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NEWPORT, RHODE ISLAND

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U. S. NAVAL UNDERWATER ORDNANCE STATION
NEWPORT, RHODE ISLAND

TECHNICAL MEMORANDUM

PRELIMINARY STUDIES ON THE TURBULENT CHARACTERISTICS OF OCEAN WAVES

(Buzzards Bay.)

Prepared by: ______________
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July 1965

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FOREWORD

The work discussed in this report is a result of studies presently being made by the Naval Underwater Ordnance Station (NUOS), Newport, R. I., and the Planetary Circulations Project of the Department of Meteorology, M.I.T., Cambridge, Mass.

The objective is to form a better understanding of the dynamic and turbulent motions of wind waves and swell.

ABSTRACT

This report presents the results of preliminary ocean wave studies made in an endeavor to learn more about the turbulent characteristics of wind waves in the open ocean.

A series of hypothetical wave models presented indicate a mechanism of momentum transfer within the waves.

Two series of wave motion measurements were made, one from a Navy pier in Narragansett Bay and a second from Buzzards Bay Entrance Light Station. The measurements were made to obtain rough data on particle velocity motions in various sea states and to examine their variances, covariances and respective spectral properties. These preliminary measurements indicated that relatively large amounts of wind-imparted momentum are transferred through the water column by correlations of the wave motions themselves.

The values of the variances of the particle motions reflected the strong exponential attenuation with depth. The auto-spectra clearly displayed the fundamental frequencies of the wind waves and the low frequency swell. The strong attenuations of the wind wave turbulence with depth is contrasted with the weaker attenuation of the swell.

ACKNOWLEDGEMENTS

The assistance of U. S. Coast Guard personnel aboard the Buzzards Bay Entrance Light Station is greatly appreciated. Also thanks is due the officers and men of the U. S. Naval Air Torpedo Unit, Quonset Point, R. I., for helicopter transportation to and from the Light Station facility.

Computation time on the MIT IBM 7094 digital computer for spectra analysis was provided by the Planetary Circulations Project of the Department of Meteorology, M.I.T., Cambridge, Mass.

Assistance in programming and computer problems was given by Mr. Richard Lavoie of NUOS and Mrs. Judith Copeland of MIT.

INTRODUCTION

The purpose of this report is to discuss the preliminary efforts in the studies of turbulence characteristics in ocean waves. A brief review is made of recent wave measurements together with a discussion of instrumentation procedures. The problem of estimating the turbulent transfer of wind-imparted momentum is considered in conjunction with three hypothetical wave models.

Need for Data on Wave Dynamics

Wind waves in the ocean are known to be composed of water particles whose motion is essentially rotational or turbulent in character. The vast majority of ocean wave measurements have been concerned with recording the time variation of the free surface or the variation of hydrostatic pressure beneath the waves. From these data very little information can be obtained regarding the dynamic properties of the water particles themselves or of the gross turbulent energy in the waves.

To understand the dynamics of wave generation and dissipation, in situ measurements of the particle motions are necessary, since the key to the generation of wind waves is the ability of the surface layers to transfer wind-derived momentum to the deeper layers.

The manner by which wind imparts momentum and energy to the sea surface, causing wind waves and currents, is not well understood. This momentum, however, must be transferred from the sea surface to the deeper layers solely by the motions of the water particles themselves. This vertical transfer of horizontal momentum is done by means of turbulent motions, although the process may be more orderly than is indicated by the term.

Thus, if the momentum transfer through the upper layers is being considered, it becomes apparent that one should also examine the effects of the more regular, quasi-oscillatory particle motions of the waves, since the waves themselves are indeed a manifestation of wind stress.

The question then arises as to what sort of orbital configurations could provide a simple mechanism for the downward transfer of wind-imparted horizontal momentum. One such geometry would be that of a properly tilted ellipse. A particle might then acquire horizontal momentum from the wind stress at the top of its orbit and transfer the momentum downward as it moves in its trajectory. Starr[1] has also shown the probability of some such mechanism on other grounds. The mechanism described in this report should be capable of representation as a Reynolds stress in terms of Eulerian hydrodynamic variables. It is of interest then to consider the problem of measuring these effects.

NARRAGANSETT BAY MEASUREMENTS

The following experiments were reported by the writer[2] and can be summarized as follows:

During August 1963, measurements of the velocity components beneath ocean waves were made utilizing two adjacent ducted current meters mounted orthogonally as to sense the particle velocity components in the plane normal to the wave crests. The meter system is shown in figure 1. This system of orthogonally mounted ducted meters is termed OMDUM I. The cylinders are about 10 cm in diameter and 20 cm long. The OMDUM I was fixed to the end of a vertical steel beam supported rigidly at the end of a naval pier in Narragansett Bay, R. I. Impellers, mounted within the cylinders on jewelled bearings, were neutrally buoyant. The tips of the impellers contained small iron slugs which, upon rotation, perturbed magnetic fields of small induction coils incorporated in an oscillator circuit unit attached to the sides of the cylinders. The output from the amplitude modulated system reflected the pulses as the impellers rotated in the fluid flow. Because of an assymetry of the magnetic fields of the induction coils, the sense of the rotation of the impellers, i.e., the direction of flow, was presented as a unique signature in the output.

A two-channel strip chart recorder was used to register the rate of flow through each of the impellers. The data were hand-converted into a continuous plot of the fluctuating velocities, U' and W', as a function of time. From this time series the sign and magnitude of the U' and W' were selected at 0.3-second intervals and placed on punched cards for computer processing.

The meters were immersed about 15 cm below the trough level of the waves, with the horizontal flow-sensing meter aimed normal to the crest line. Generated over an up-wind fetch of about 5 Km, the waves displayed clearly defined crests, visually estimated at 1.5 second periods. Wind speed was about 9 m sec^{-1}, wave height about 50-75 cm, and water depth below the instrument about 7 meters. The assumption was that the waves were essentially surface (i.e., deep water) waves.

The covariance $\overline{U' W'}$ between the 1188 pairs of data was found to be -7.8 cm^2 sec^{-2}, which is an estimate of the magnitude and sign of the Reynolds stress (downward momentum flux). The Reynolds stress is here defined as $\tau = \rho \overline{U' W'}$. ρ is the density of water, which is assumed constant. The linear correlation coefficient between U' and W' was -0.21.

Spectral analysis was made of the time series data utilizing the methods described by Tukey[3]. Autocovariance spectra were made of the time series data of the two velocity components and are shown in the upper curves of figure 2. The spectra show peaks at wave periods of about 1.5 sec, which was approximately the observed wave period. Both of the velocity components exhibit similarly shaped peaks. The co-spectra component of the covariance spectra exhibits a negative peak at the dominant wave frequency. This indicates that the downward momentum flux, due to the negative correlation of the velocity components, occurred at frequencies equivalent to those of the waves.

The interpretation given to dynamics of wave measurements from this statistical analysis is critically dependent upon the sensing character of the ducted meter system. A continuing study is being conducted of the response characteristics of the meters, including a series of laboratory and field tests. (The OMDUM II system was developed and was geometrically similar to OMDUM I. This new system utilized similar magnets mounted on the impellers, and pickup coils in lieu of the oscillator and amplifying circuits which proved unreliable in OMDUM I.)

The OMDUM II was first calibrated for steady-state flow parallel to the axis of each of the cylinders. Then the axes of the cylinders were set at arbitrary angles between 0 and 90° from the direction of steady flow to obtain the variation in instrument response to the "off angle flow". Finally, the impeller response to accelerative flow was measured.

The results indicate that the meters have essentially identical calibrations for steady flow parallel to the respective cylinder axis. The flow response as the meter axis is rotated with respect to the flow direction follows closely the cosine law. In other words, the component of flow varies as the cosine of the angle subtended by the cylinder axis and the mean flow direction. Further tests are being conducted for purposes of assessing the exact angle-response relationships.

To assess the response time of the impellers, the OMDUM II was sinusoidally oscillated vertically in a test tank, and the fluctuating response of the meter was recorded. These velocity variations, obtained from the calibration curve for the steady flow, were compared directly with the output of an accelerometer attached to the meters. The frequency response of the impellers was shown to be greater than 10 cps. This rapid response permits accurate sensing of perturbations of the time scales of wind waves of the period from 0.5 to 8 seconds.

It is realized that there must be a limiting size of eddy or oscillatory configuration for which the volume dimensions of the meter alter or interfere with the inherent motions of the eddies. The effect of decreasing orbital size upon flow sensing is to be determined by measuring the meter response of the ducted meters in a wave generating flume system at the Coastal Engineering Laboratory in Washington, D. C.

THREE HYPOTHETICAL WAVE MODELS

A comprehensive understanding of the analysis and synthesis of the Tukey spectral estimates is essential for drawing valid conclusions and making interpretations regarding the nature of wave motions as derived from their statistical properties. To best assess the application of the spectral analysis upon the two component velocity time-series data, three sets of hypothetical wave data were constructed and analyzed. These sets of data depicted three different wave models: one whose particle motions are (a) quasi-random with an induced bias to give $U' W' < 0$ with no preferred frequency in the covariance spectra; (b) quasi-ideal sinusoidal particle motions with no intentional bias giving $U' W' \sim 0$; and (c) sinusoidal velocity fluctuations with a bias rendering $U' W' < 0$ and having a preferred frequency in the covariance spectra equivalent to the frequency of the quasi-sinusoidal velocity functions.

The three sets of data each contained 600 pairs consisting of the horizontal velocity component U_n and the vertical velocity component W_n. The subscript n indicates the n^{th} data point where $n = 1, 2, 3,$ ------ N, and N being the total number of data pieces equally spaced at time intervals of Δt. Thus, the total period of sampling, T, is equal to $N \Delta t$. For the three time series T is 180 seconds. The amplitude or half range of the velocity components for all three data sets was about 10 cm sec^{-1}. Table 1 lists the pertinent statistical parameters of the three data ensembles. A description of the three models follows.

Biased Random Wave Model (BR)

The first hypothetical wave model can be envisaged as a surface wave field where the particle motion is quasi-random produced by many oscillatory progressive waves moving in many directions. The term "quasi-random" is used for two reasons: (1) the values of time series data were arbitrarily chosen without use of tables of random numbers and (2) about 5% of actual values of data points were altered to give a slight negative correlation function, i.e., a value of the covariance function at zero lag ($U' W'$) less than zero. The actual value of the function is about $-3.98\ cm^2 sec^{-2}$. This simulated value of the stress near the water surface is thus 3.98 dynes cm^{-2} which is of the order of magnitude of assumed mean wind stress upon the real ocean surface. This model will be referred to as Biased Random Wave Model (BR).

Unbiased Simple Harmonic Wave Model (USH)

The second set of data is characterized by representing the horizontal and vertical components as quasi-sinusoidal functions. Assumed is a simple harmonic wave model in the form of an ideal deep water progressive ocean wave as described by Lamb[4]. This model was derived, assuming an irrotational incompressible fluid in which the wave length is much less than the water depth.

The component particle velocity components are described by

$$U(X, Z, t) = \sigma A\, e^{-K Z}\ \mathrm{SIN}\ (K X - \sigma t) \qquad (1)$$

and

$$W(X, Z, t) = -\ \sigma A\, e^{-K Z}\ \mathrm{COS}(K X - \sigma t) \qquad (2)$$

where: A, K, and σ are amplitude (cm), wave number (cm^{-1}) and circular frequency (sec^{-1}), respectively.

Thus, for a fixed depth Z_o and horizontal coordinate X_o we may write

$$U(X_o, Z_o, t) = U(t) = A'\ \mathrm{SIN}\ \sigma t \qquad (3)$$

and

$$W(X_o, Z_o, t) = W(t) = -A'\ \mathrm{COS}\ \sigma t \qquad (4)$$

where $A' = \sigma A\, e^{-K Z_o} = \text{Constant}.$

The second data series is represented in equations (3) and (4) as simple harmonic oscillators mutually out of phase by $\pi/2$ or one quarter of a wave period. Actually, the sinusoidal functions were only approximated, since they were hand-drawn over a time-amplitude grid having the proper frequency and amplitude. The data points were then picked off the two curves at $\Delta t = 0.3$ seconds. The value of $\overline{U' W'}$ is identically zero for the long train of waves represented by the sine and cosine functions in equations

(3) and (4). Since the data were only approximately sinusoidal, the value of $\overline{U' W'}$ for USH (table 1) is small but not zero.

Biased Simple Harmonic Wave Model (BSH)

The third hypothetical wave model is described as a Biased Simple Harmonic Wave function. This model is identical in every respect with USH except that the U(t) function has been slightly increased at its positive maximum point. This intentional biasing was done for two reasons: (1) to synthesize a desired negative value of $U' W'$ for the BSH model and (2) to bias the BSH model by a simple mechanism, perhaps not unlike that existing in natural ocean waves.

This technique seems reasonable since, as stated previously, any energy and momentum within the wave must be transmitted through the actual wave surface by a frictional drag and/or a form drag of the wind. Thus, the wind blows effectively horizontally across the waves and causes an actual tractive stress on the crests of the waves and probably a pressure force upon the "upwind" side of the waves. Accepting this as fact, it can then be assumed that the transfer of momentum downwards in the waves is caused simply by turbulence in the water. The wind momentum is transferred by an eddy process in which the eddies are just the water waves themselves. Both of these forcing mechanisms could produce a sensible acceleration of the particles at the crest, i.e., when the U(t) component is positive and maximum.

This is the reason for placing within the horizontal oscillatory component of the BSH model a biasing component which is of the frequency of the waves themselves. Hence, at a fixed point in the water column, a momentum transfer of this sort would appear as a direct coupling effect occurring at the dominant wave frequency.

STATISTICAL CHARACTERISTICS OF THE HYPOTHETICAL WAVE MODELS

The three sets of data were analyzed for pertinent statistical parameters using the Tukey spectral estimate program prepared by Convair on the MIT IBM 7090 Computer.

The statistical parameters of the three pieces of data are listed in table 1. The number of pieces of data, the period of sampling, and the time spacing are identical for all three sets of data. None of the mean values of the horizontal and vertical velocity components, designated by U' and W', exceed 0.5 cm sec^{-1}.

The variances $\overline{U'^2}$ and $\overline{W'^2}$ (which are equivalent to the auto-covariance function at zero lag) are about 15.16 cm^2 sec^{-2} for the BR model and between 49 and 55 cm^2 sec^{-2} for the USH and BSH models (figures 2, 3, and 4). The covariance function for the two biased models, BR and BSH, is -3.98 and -2.57 $\mathrm{cm}^2\,\mathrm{sec}^{-2}$ respectively. The covariance for the ideal sinusoidal function is, of course, much smaller, i.e., -0.045 $\mathrm{cm}^2\,\mathrm{sec}^{-2}$.

The correlation coefficient, R_{UW}, for the BR model is -0.21 and for the BSH model is -0.05. For the USH model the correlation coefficient is even smaller at -9×10^{-4}.

The auto-covariance and covariance spectra (which are the Fourier transforms of the respective functions) of the three sets of data are plotted in figures 3, 4, and 5. The "in phase" or real part of the covariance spectra (termed co-spectrum) is plotted below the power spectra pairs in these figures.

The power spectra of each velocity component, i.e., Φ_U and Φ_W, are plotted as $\mathrm{cm}^2\,\mathrm{sec}^{-2}$ per cycle per second versus frequency (and period) on the abscissa. The values of Φ_U and Φ_W for BR are similar, with each showing a dominant low frequency peak between 0.2 and 0.3 cps. This peak is well defined and drops sharply at about 0.4 cps. From 0.4 through to the limiting frequency of about 1.7 cps the Φ_W fluctuates in a similar manner as Φ_U except that the latter displays two peaks, one at 0.8 cps and one at about 1.1 cps. These oscillations of the power spectrum functions are mostly due to chance since the data were generated in a quasi-random fashion.

The cross spectrum shows repeated fluctuations, displaying negative peaks at 0.3, 0.8 and 1.25 cps. There is, however, no extreme peaking indicative of predominant coupling at any one frequency. The co-spectral function is, in general, negative throughout the frequency range.

The power spectra of the unbiased sinusoidal waves, USH, figure 4, show the expected sharply defined peaks at 0.5 cps, which is the chosen frequency of the sinusoidal velocity components.

The co-spectrum function displays only a very slight negative perturbation, at about 0.5 cps, which is less than 10% of the magnitude of the cross spectra of the BR.

Turning to the power spectra of the biased simple harmonic waves (BSH), figure 5, again the pronounced peaks of the velocity functions occur at a band between 0.3 to 0.6 cps. The base of the peak for the BSH model is broader than for the USH.

The co-spectrum of the BSH model, figure 5 (bottom), is of special interest since it displays a strong negative peak centered at 0.5 cps. It appears as almost a mirror image of the power spectrums above.

Thus, by altering the magnitude of the amplitude of the U(t) component by about 5% in a cyclic fashion, co-variance function is increased by almost two orders of magnitude, and the co-spectra are completely modified to show a strong negative correlation at a frequency associated with the waves themselves. This type of simple (BSH) mechanism may well be primarily responsible for the downward flux of wind-imparted momentum through the water column.

OPEN OCEAN MEASUREMENTS

A series of preliminary "open ocean" observations were made with the slightly modified wave meter termed OMDUM II at the Buzzards Bay Entrance Light Station, which is situated in 20 m of water off the southern coast of Massachusetts (figure 6). The meter system was supported in a semi-rigid geometry by an array of supporting guys above it and a 50 kgm vertical damping weight suspended below it.

The measurements were made on 11 May 1964 during a period of steady wind conditions, with a mean wind speed of about 6-8 m sec^{-1}. The spectra results of velocity data taken at a depth of 1 meter and 4 meters below the wave trough level are shown in figures 7 and 8.

The auto-covariance spectra of the U' and W' values at both depths indicate peaks at about 3-4 seconds, which agrees with the visual estimates of the wave periods. There is a strong attenuation of the U' component spectra relative to the W' at periods greater than about 1.3 seconds. This effect, apparently caused by a swinging motion in the horizontal direction, is the reaction of the meter system to the back-and-forth U' velocity component. Thus, the reaction of the meter system tended to attenuate the amplitude of the U' fluctuation component due to the gross wave motions. This effect has been largely eliminated by modifying the wire support system and using a heavier damping weight. At the time of this writing a new, smaller meter system has been constructed and tested which has about half the cross sectional area as the original device. Raw data from this smaller meter are strongly indicative that, due to the reduction of drag, the reaction to the oscillatory horizontal motions has been effectively removed.

Returning again to figures 7 and 8, note the effective reddening of the spectral peaks of both pairs of spectra with depth, i.e., the high frequencies are damped more effectively with depth. Measurements were made at 0 (just under the trough level), 1, 2, 3, 4, and 5 meters. This shift to more dominant low frequencies with depth is characteristic of the data.

Other than observing the gross attenuation of the frequencies above, say, 1.8 cps, the reader should be cautioned of the possible limitations of the meter's detectability of turbulent or eddy structures which approach the scale dimensions of the meter itself. Although the impellers have a fast response character, the variations in velocity at the higher frequency bandwidths will likely be associated with smaller eddy scales approximating the dimensions of the meter, i.e., 20 cm.

When examining the depth variation of a particular velocity component, say, W', one finds that the variance $\overline{W'^2}$ decreases in an exponential manner. Note that the area under the spectrum curve of $\Phi_W(f)$ versus frequency is equal to the variance of the particular component caused by fluctuations occurring between the frequency ranges studied.

Thus,

$$\overline{W'^2} \approx \int_0^{f_1} \Phi_U(f)\, d f \qquad (5)$$

The turbulent kinetic energy may be defined by the relation:

$$E_K = 1/2\, \rho\, (\overline{U'^2} + \overline{W'^2}) \qquad (6)$$

Thus, the spectra of the velocity components are in fact true energy density spectra, since the area under the spectral curve for a particular velocity component must be equivalent to the turbulent energy contribution of the component of velocity.

The covariance spectra (bottom curves) display a negative peak which occurs at the spectral band of the waves. The auto-covariance function at zero lag for the 1-meter depth was -23.3 cm^2 sec^{-2} and the linear correlation coefficient was -0.17. For the 4-meter depth the covariance function was -14.1 cm^2 sec^{-2} and the correlation coefficient was 0 - 0.30. As with the Narragansett Bay measurements, these covariances seem extremely large in terms of the usual empirical estimate of stresses of the order of 1 dyne cm^{-2}.

Based on the hypothetical wave model data, it appears that if the stresses in the surface regime are about 1 dyne cm^{-2}, then only very small velocity correlations of about -0.05 are required to produce a Reynolds stress of this value. Probably the ducted meter system will be unable to detect such small correlations because of the masking effect of relatively large scale perturbations caused by the interaction of the meter with the flow around it.

However, the results so far available indicate strong negative correlations peaking at the periods of 3-6 seconds. It is difficult to imagine that the meter system, properly mounted in the wave regime, would artificially produce correlations at these relatively low frequencies.

No quantitative conclusions can be made yet regarding the momentum flux mechanisms. However, there is no prior justification for discounting the values of covariance functions obtained from them since there are no previous direct measurements of stress to refer to.

A series of wave motion observations were made 7 December 1964 in order to test a newly constructed orthogonally mounted ducted meter system OMDUM III. This meter is a smaller version of the OMDUM I and II previously described. The cylinders are about 8 cm in diameter and about 14 cm in length. In the OMDUM III system the drag on the meters, caused by the oscillatory wave motions, caused the meters to move with the horizontal motions, resulting in a damping of the amplitude of the U(t) record. The variances of U(t) were usually from 0.5 to 0.1 times the W(t) variances. Drag is reduced since the new meter has a cross sectional area of about half that of the OMDUM II. Also, more overall stability is provided by a pyramidal suspension with added vertical weight.

The three series of observations were made from 1300-1430 hours. The sky was mostly clear and the air temperature 0.5°C. Sea state was 1-2, with waves estimated at 3-4 m in wavelength and 20-40 cm wave heights. From WNW a slight swell was detected but was too ill-defined for estimates of its parameters.

The wind was light and relatively steady at 2.5 - 4.5 m sec^{-1} from the WNW. The U meter was aimed at 285°-290° true; the wind wave directions seemed to vary from 280 - 295.

A summary of the statistical data, along with the meteorological conditions, are presented in table 2.

There was still a disproportion of the response of the U meter with respect to the W meter, as shown by the variances of U and W at the various depths. However, these first results were preliminary in nature, since the OMDUM III system had not been calibrated for absolute speeds and the impeller design had been somewhat modified.

It is instructive, however, to examine the auto-spectra of the two velocity components shown in figures 9 and 10.

The U spectra (designated by $\Phi_U(f)$) at the depths of 0.5, 1.0, and 2.0 meters, in figure 9, display the strong attenuation with depth at all frequencies from 0 to 2.5 cps.

Two obvious peaks are displayed, the highest at about .100 to .200 cps (T - 5-10 sec), and the smaller at .35 - .45 cps (T - 2.2 - 2.9 sec).

The low frequency peak is caused by swell and ambient low frequency oscillations from meandering motions of the tidal currents about the tower. There is a strong indication of low frequency oscillatory current motion with periods ranging from 8 sec to 30 or 40 sec. The large values of the covariance function at zero lags in table 2 are caused primarily by these lower frequency components and not by correlations of wind wave frequencies of, say, 1-5 seconds.

The 2 m peak rises above the 0.5 and 1 m spectrum curves, below 0.25 cps. This is indicative that oscillations occurred during the different sampling periods which were not stationary. This is further suggested by the mean values of the horizontal component which vary from 13.6 to 21.6 cm sec^{-1}, indicating a low frequency meandering motion.

The secondary peak is at 0.400 cps (T - 2.5 seconds) and is characteristic of the wind waves observed at the time of measurement. In this wind wave frequency band and upwards to the cutoff frequency, the spectral density decreases markedly with depth. This shows that the motions in this band (0.40 - 2.50 cps or 2.5 - 0.4 sec period) are of stationary character. In other words, the spectral characteristics of the wind wave motions seem not to have changed over the period of sampling, whereas the lower frequency motions apparently show marked variations or trends. The auto spectra function of the vertical velocity component $\Phi_W(f)$ is similar to the function $\Phi_U(f)$. The low frequency peak again shows indication that slowly varying motions occurred of frequencies in the range from 0.10 - 0.25 cps.

The wind wave peak occurs at about 0.40 - 0.50 cps, indicating a slightly lower frequency peak than the U spectra.

The 0.5 m spectra indicate a lingering of energy existing in the region from the wind wave peak out to the cutoff value of 2.5 cps. That is, the $\Phi_U(f)$ curve for 0.5 m tends to flatten out at a value of 0.5 cm^2 sec^{-1} between 2.30 - 2.50 cps, whereas in this same frequency range the $\Phi_W(f)$ curve drops to about 0.05 cm^2 sec^{-1} as seen in figure 10.

Both sets of spectra indicate the presence of the wind waves at frequencies centered at 4.0 - 5.0 cps and an exponential decrease in the variance contribution at this band.

Both the variances and spectra of the U and W component at 2 m are similar. This could indicate that at the sea surface the turbulent wave motions cause artificial perturbations on the meters and distort the spectra of the motions. At a deeper depth this gives a truer picture of the wind wave oscillatory patterns. Thus at the depths beneath the 0.5-1 m levels, means are available for faithfully reproducing gross orbital motions of the particles.

Wave measurements in a variety of meteorological conditions are being continued at Buzzards Bay Entrance Light Station, and further results of these "open ocean" measurements will be reported at a later date.

Round Hill Field Station of MIT is being funded from NUOS to utilize and study the potential of the Buzzards Tower for making wind stress measurements. It is hoped to coordinate wind and wave momentum flux measurements to provide a better understanding of the interactions and transfer of energy between the wind and ocean and hence provide dynamic pressure and acceleration data for the design specifications of high speed vehicle and hydrofoil systems.

CONCLUDING REMARKS

The statistical calculations using hypothetical wave models indicated that very small negative correlations between the horizontal and vertical particle motions can provide relatively large stresses in the wave regime.

These first attempts to evaluate Reynolds stresses in open ocean waves produced relatively large stresses in the range of -20 cm^2 sec^{-1} and even larger. Similarly, the linear correlation coefficients are of the order of -0.1 to -0.2. The covariance spectra indicated that the main contribution to the covariance occurs at the ambient wave frequencies.

It is concluded that types of instruments as OMDUM III can prove useful in the assessment of spectral characteristics of wave motions as a function of meteorological conditions, sea state, and depth from the free surface. Properly applied instrumentation such as described in this report can be used to determine ambient turbulent conditions caused by wind waves for comparison with artificially produced turbulence caused by vessels.

Further studies are being made of the dynamic response characteristics of the ducted meter system, with particular emphasis on its response to small scale eddy sizes and "off-angle" flow. Also, use of a drag sphere system for sensing shear stresses is under investigation.

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TABLE 1

SUMMARY OF STATISTICAL PARAMETERS OF HYPOTHETICAL DATA

	No. of Pieces of Data	Sampling Period	Sampling Interval	Max Values		Means		Variances		Covariance	Correlation Coefficient
Set	N	T	ΔT	W_m	U_m	$\overline{W}$	$\overline{U}$	$\overline{W'^2}$	$\overline{U'^2}$	$\overline{U'W'}$	R_{UW}
(1) Random Biased (BR)	600	180	0.3	10	10	+0.16	-0.27	15.43	16.41	-3.98	-0.205
(2) Ideal Sinusoidal (USH)	600	180	0.3	10	10	-0.15	+0.10	50.62	50.03	-0.045	-0.0009
(3) Biased Sinusoidal (BSH)	600	180	0.3	10	10	+0.31	-0.05	49.56	54.30	-2.57	-0.05

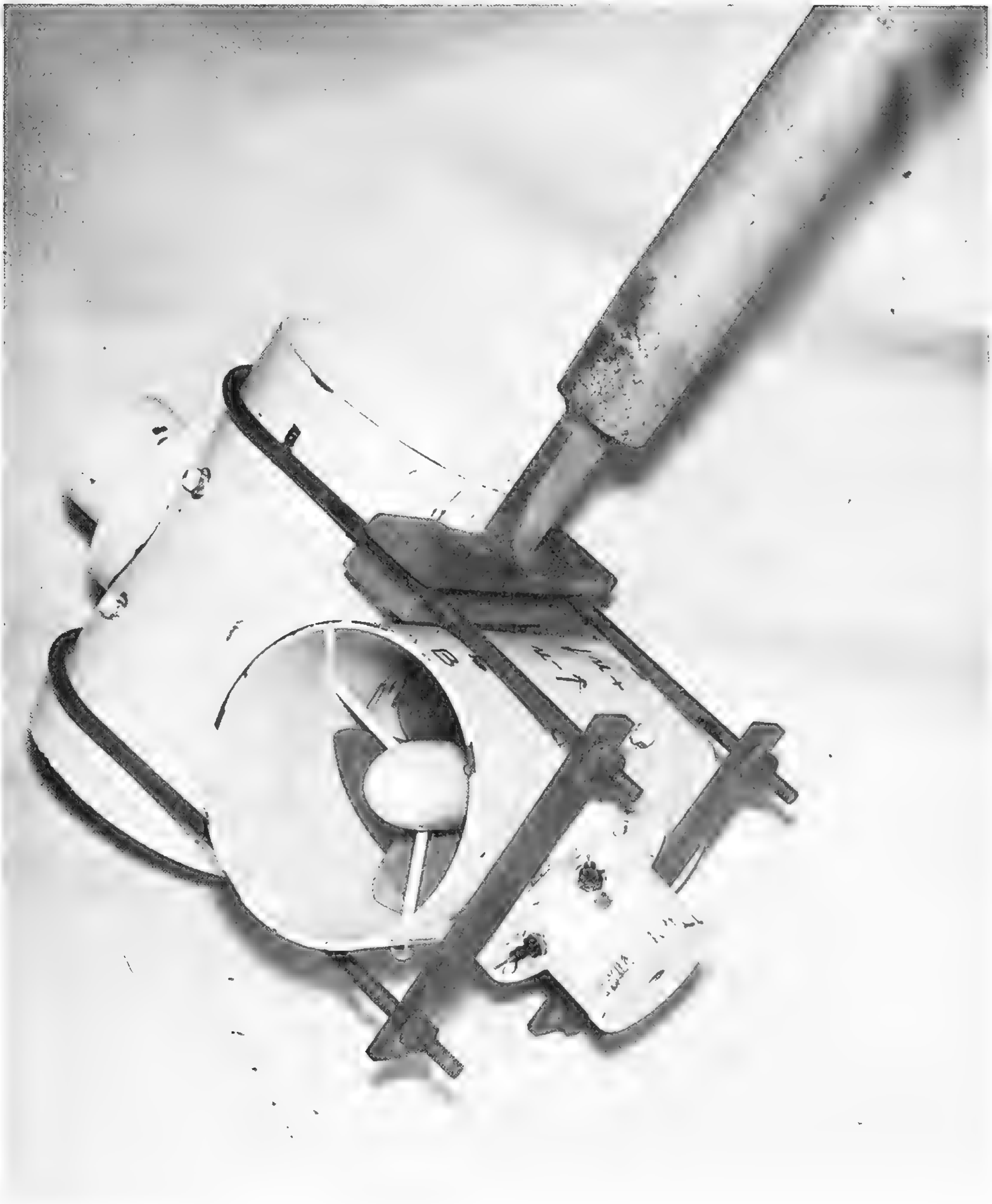
TABLE 2

SUMMARY OF STATISTICAL DATA OF BBELS #8*

WIND: Light Variable 2-5 - 4-5 m sec^{-1} from W-NW
SEA: Light H ~ 0.2-0.4 m L ~ 3.4 m from W-NW
SWELL: Slight - from South

Time	Depth(m)	N	T	ΔT	.r	$\overline{W}$	$\overline{U}$	$\overline{W^{12}}$	$\overline{U^{12}}$	$\overline{U'W'}$	R_{UW}
1324-1329	0.5	1576	315	0.2		2.3	16.8	701.0	354.1	-46.92	-0.094
1310-1315	1.0	1245	250	0.2		6.4	21.6	348.2	183.8	6.36	+0.025
1337-1342	2.0	1359	270	0.2		2.9	13.6	250.6	239.7	76.6	+0.313

* Buzzards Bay Entrance Light Station



The First Orthogonally-Mounted Ducted Meter System - OMDUM I

Figure 1

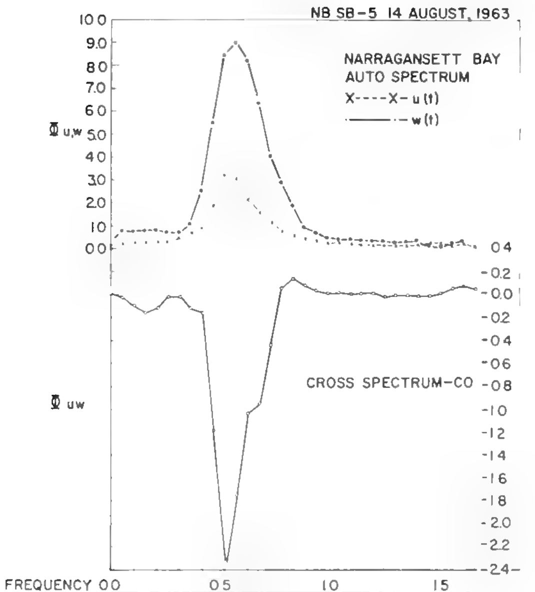


Figure 2

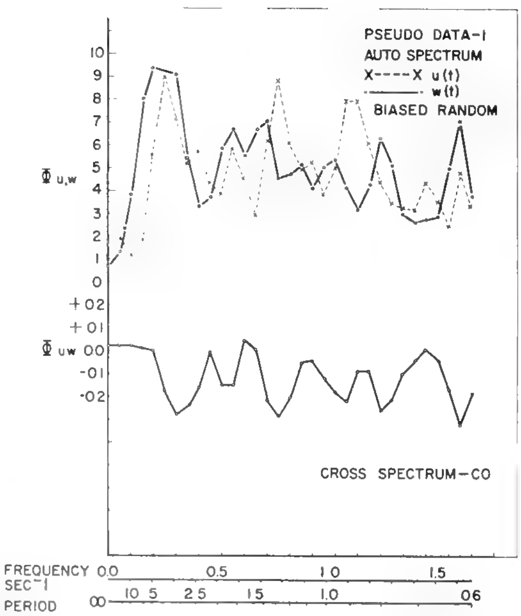


Figure 3

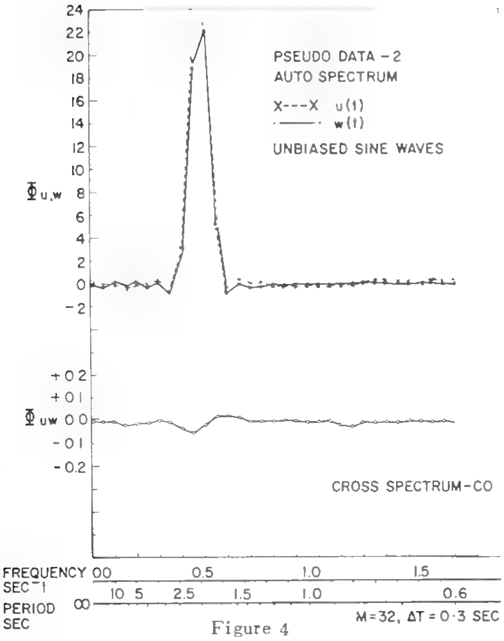


Figure 4

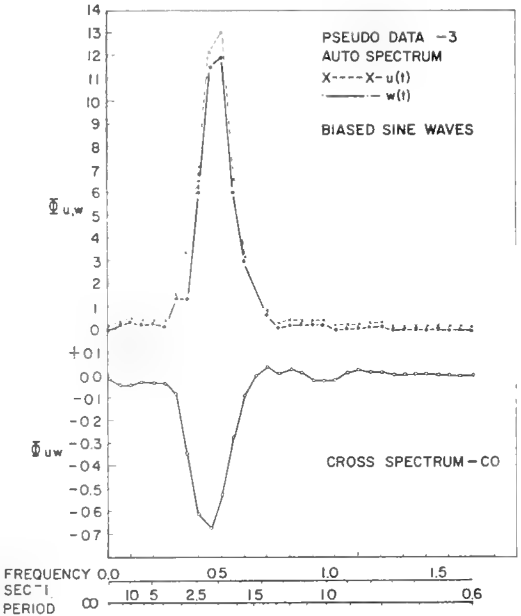
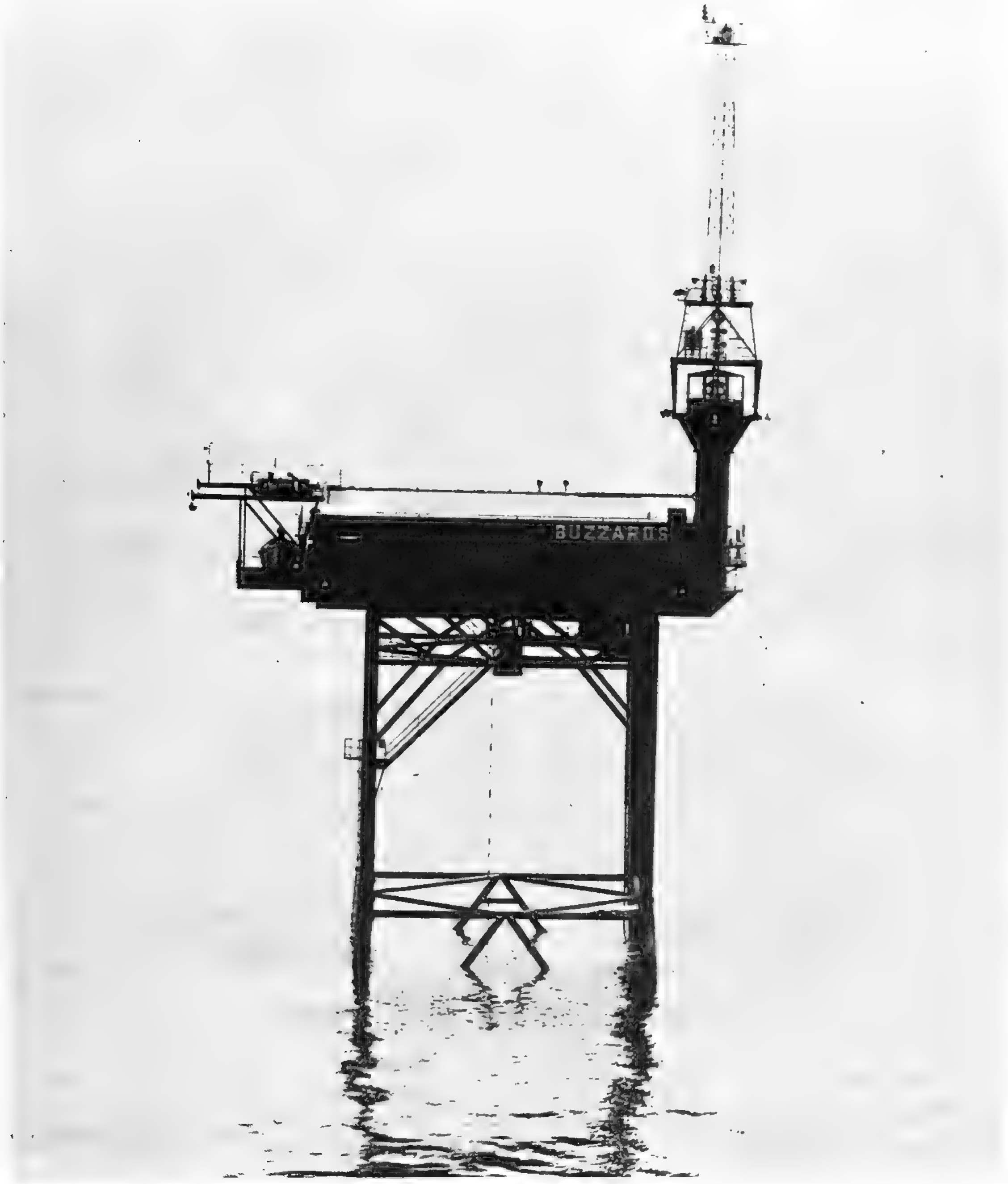


Figure 5

Auto and Cross Spectra of Real (Fig. 2) and Hypothetical (Figs. 3, 4, and 5) Wave Particle Velocities

Figures 2, 3, 4, and 5



Buzzards Bay Entrance Light Station Looking East

Figure 6

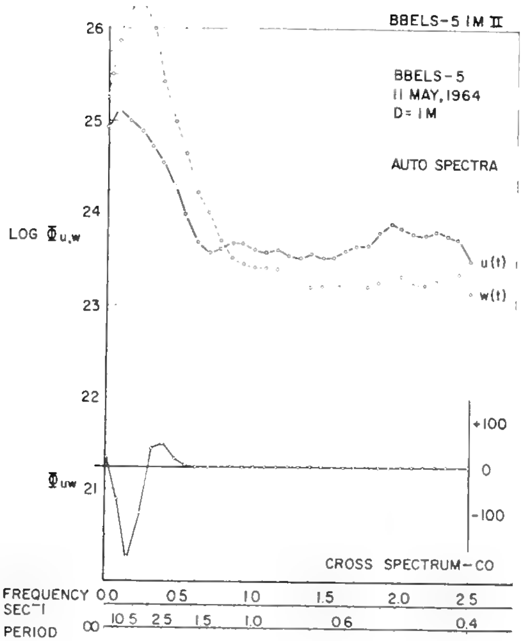


Figure 7

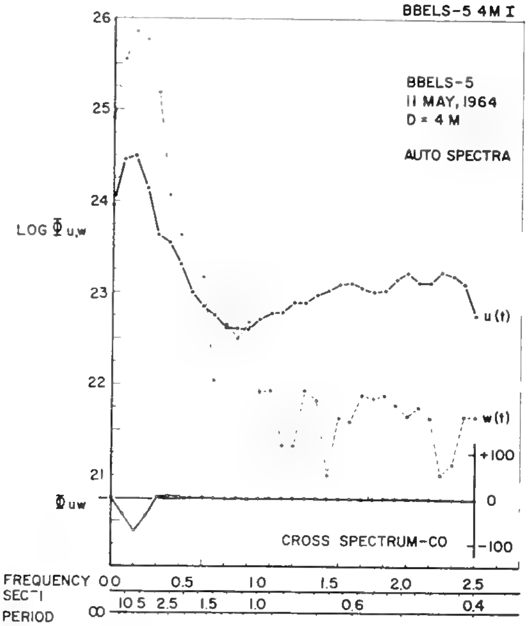


Figure 8

Auto and Cross Spectra of Particle Velocity Motions at Buzzards Bay Entrance Light Station Using OMDUM II

Figures 7 and 8

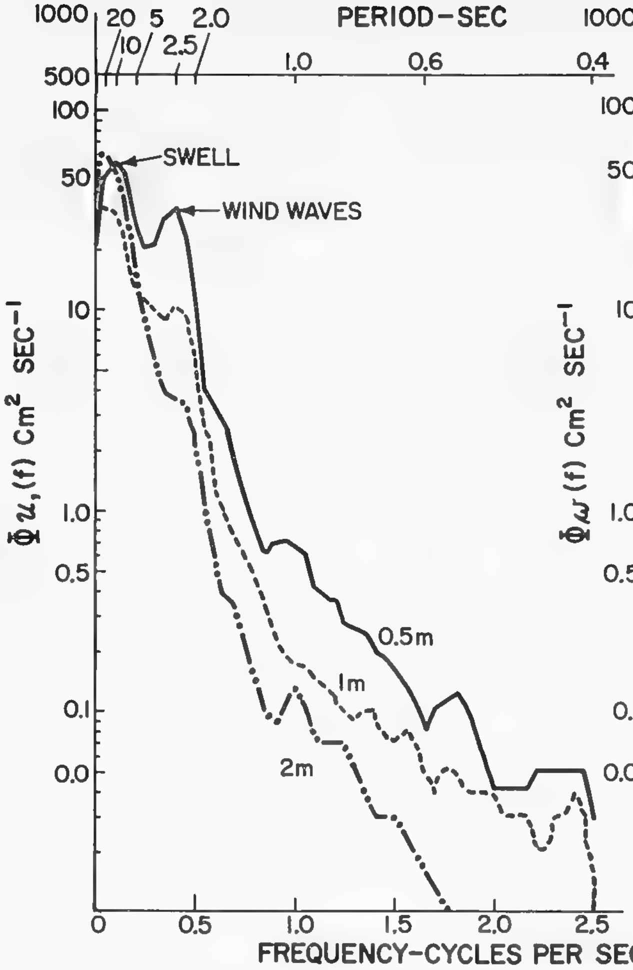


Figure 9

Auto Spectra of Horizontal Particle Motions, u(t), at the Buzzards Bay Entrance Light Station

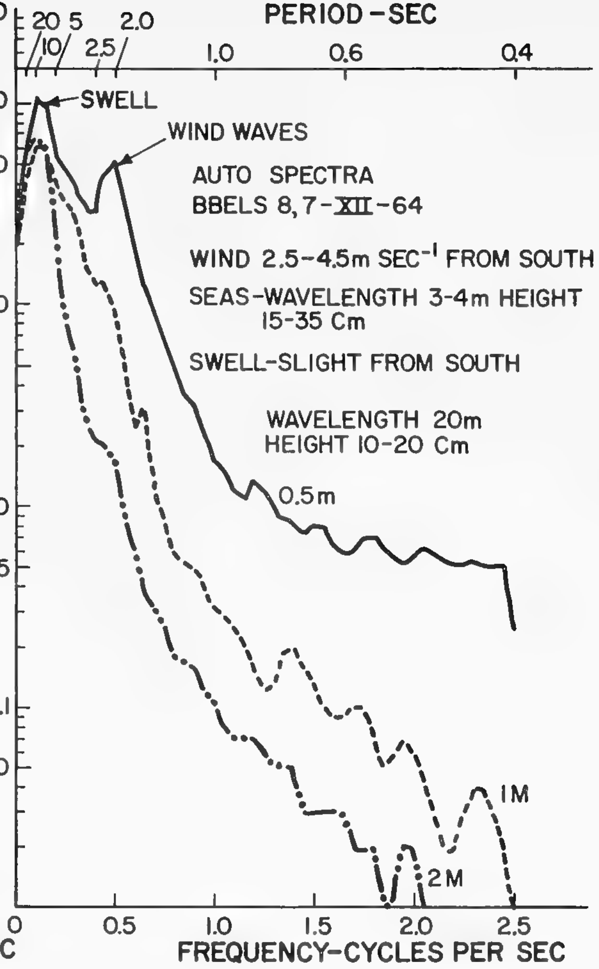


Figure 10

Auto Spectra of Vertical Particle Motions, w(t), at Buzzards Bay Entrance Light Station

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A series of hypothetical wave models presented indicate a mechanism of momentum transfer within the waves.

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2. Ocean Waves
3. Wave Characteristics
4. Turbulence (Ocean Waves)

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