Indian Journal of Marine Sciences
Vol. 17, September 1988, pp. 189-194

Effect of Phase Coupling on Surface Amplitude Distribution of Wind Waves

M J VARKEY
Physical Oceanography Division, National Institute of Oceanography, Dona Paula, Goa 403 004, India

Received 29 *March* 1988

Nonlinear features of wind generated surface waves are considered here to be caused by nonrandomness (non-Uniform) in the phase spectrum. Nonrandomness in recorded waves, if present, would be generally obscured within the error level of observations and computations. Hence some numerical experiments are tried by inserting known nonrandomness in the phase spectrum to study the nonlinear effects. The results show significant changes in the surface amplitude distributions. The possible occurrence of nonrandomness in phase spectrum in natural situations is discussed.

While discussing strong nonlinear interactions Ming-Yang Su and Green[1] presented a detailed tabulation of different types of interactions of wind waves. Some of the nonlinear processes like resonance, Benjamin-Feir instability, wave current interactions and white capping and breaking are widely studied and discussed. Wave breaking and associated aspects are presently studied vigorously.

In an earlier work[2] basic importance of phase spectrum in nonlinear interactions has been highlighted. It is pointed out[2] that nonrandomness (non-Uniformity) of various types in phase spectrum can give rise to surface wave profiles of various types with various degrees of nonlinearity. In the present paper, this concept is extended to some new cases of nonrandomness in phase spectrum.

Phase coupling and locking (hence nonlinearities) of wind wave systems can occur in natural situations depending on the state of the wave system (growing, breaking, shoaling, etc.). It is known that linear superimposition of component sinusoidal waves is not valid for nonlinear waves. It seems to be true that self resonance at the spectral peak is a strong factor during the exponential stage of growth which can lead to strong nonlinearities like wave groups, drift currents and wave breaking. This is so, because the interaction becomes closer, longer and stronger in the peak region than between any other frequency bands, since the individual waves are in phase (for solitons) and locked up to interact for long time till they loose their identities. It was pointed out[3] that the amplitude of the resonant tertiary is dependent on the total distance (hence time) over which the interaction has been taking place. Here, it should be mentioned that the wave components at the spectral peak may not possess exact sinusoidal wave structures, especially, in the nonlinear phases, but would be better described by nonlinear wavelets in which case the attribute of phase coherency and locking acquire special significance.

Methods

A variable ITUNE (= 1, 2, 3, 5 and 6) has been defined[2] in a computing algorithm to assign various forms of non-Uniformities to the phase spectrum. Two additional cases with ITUNE values equal to 7 and 4 are defined below.

ITUNE = 7 [phase spectrum is allowed to be equal for 2 nearby wave components at 2 or more frequencies selected at random; $\phi(i)=\phi(i+1)=\phi(j)=\phi(J+1)=\phi(k)=\phi(k+1)=$ ....; i, j, k .... are at random]

ITUNE = 4 [phase spectrum is allowed to be equal over the harmonic frequency ranges fs-$(W/4)$ to $fs+(W/4)$ and $2{*}fs$-$(W/4)$ to $2{*}fs+(W/4)$ where W is the half energy width of the swell peak (fs)]

ITUNE = 3 [phase spectrum is allowed to be equal over the swell peak for the frequency band fs-$(W/4)$ to $fs+(W/4)$. ITUNE = 3 is defined in a slightly different way for the present study]

ITUNE = 5 [assigns the observed phase spectrum without any change]

The random couplings are worked out as follows. First the relative phase spectra are computed. These random (theoretically Uniform) values are grouped into 24 classes of 15°. This process would give a mean class frequency value of 147/24 for a Uniform distribution. The wave records are digitised with a sampling interval of 1 sec for a recording length of 512 sec giving the variance spectrum for the range 0

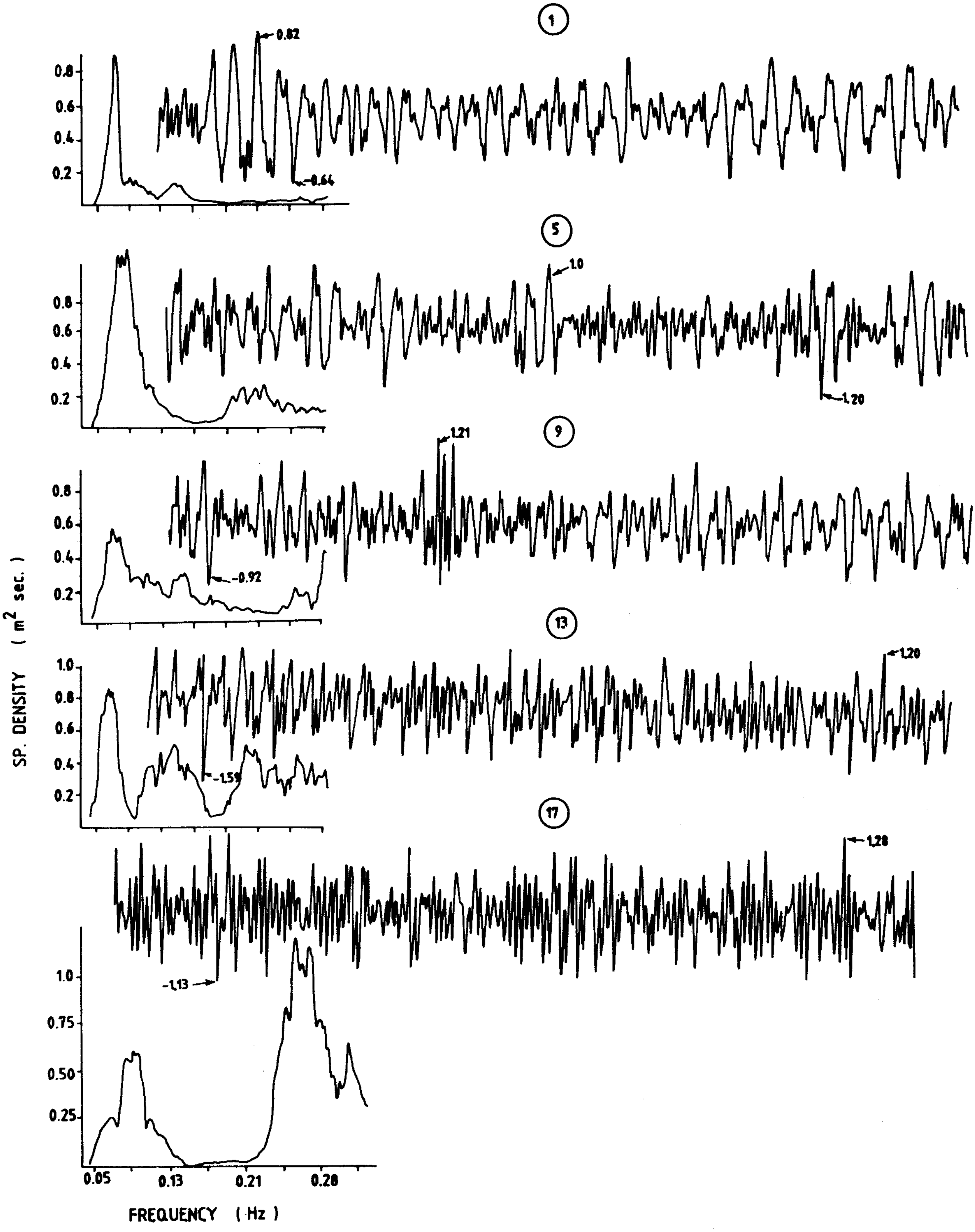

Fig. 1—Autospectra and corresponding surface wave profiles of selected wave records

to 0.5 Hz with 256 fourier coefficients. Since the shipborne wave recorder is reliable[4] only within the range 0.05 to 0.33 Hz, the reliable number of phase estimates are only 147. The computing algorithm is programmed suitably to pick up the first class (0-15°, 15-30°, 30-45°, etc.) whose class frequency is > 7. It is assumed here that these 7 events within the range 0.05-0.33 Hz occur at random. These 7 fourier components and their + 1 components are assigned equal phases for ITUNE = 7. Sometimes, there would occur only 5 or 6 random couplings since at times 2 nearby wave components can have the same phase. The tuned phase spectra (ITUNE = 3, 4, 5 and 7) are used to compute the transformed surface wave profiles.

Results and Discussion

The numerical experiment is performed for 5 widely differing spectral shapes (Fig. 1) to obtain maximum possible variations in computed surface profiles (Fig. 2). The computed surface profiles are fitted with Normal probability law (Table 1). Fig. 1 shows the different spectra and the corresponding wave records selected for the study. WAPD01 is a very narrow band swell (Hs = 0.69 m) with a very mild background sea. WAPD14 is stronger swell (Hs = 1.02 m) with stronger background sea. WAPD10 is stronger swell (Hs = 0.91 m) compared to WAPD01 but the swell regime is very wide. WAPD07 is a sea dominated double peaked sea state with Hs = 1.23 m. WAPD17 is a multipeaked sea state (Hs = 1.21 m) with the maximum spectral peak at the low frequency swell side. For all the spectra the $2*fs$ frequency region contains some amount of energy which can be programmed to interact with the swell peak region.

In Table 1 the wave records are tabulated in order depending on their effective spectral widths[5]. Considering ± 10% differences in the confidence levels of different profiles with different ITUNE values to be only of marginal significance, arising out of the presence of 1 or 2 abnormally high waves, the confidence levels very significantly increase as the γ (effective spectral widths) values increase for WAPD07 and WAPD17. The two narrow band swell dominated spectra (WAPD01 and WAPD14) show only limited changes in their confidence levels. The wide band swell (WAPD10) shows a significant change in its confidence levels from those of WAPD01 and WAPD14. The α_2 (kurtosis) values for WAPD01, WAPD14 and WAPD10 (for ITUNE = 3 and 4) show similar variations within them (ITUNE = 3 and 4) and between the other sets (ITUNE = 5 and 7). In the case of random coupling (ITUNE = 7) WAPD14 showed a significant change in α_2 from the recorded profile (ITUNE = 5) but the same effect is not noted

Table 1—Computed Statistics for 5 Records with Different ITUNE's

Record	Eff. spect. width (γ)	Hs (m)	Profile No.	ITUNE	R M S wave height (σ)	Skewness (α_1)	Kurtosis (α_2)	Chi. sqa. (χ^2)	Deg. fre. (D.F.)	O'K at % level
WAPD01	0.089	0.69	1	5	0.244	+0.093	3.212	11.74	7	10
			2	7	do	+0.079	3.202	13.39	8	8
			3	3	do	−0.068	3.753	11.45	8	15
			4	4	do	−0.041	3.801	18.56	8	1
WAPD14	0.191	1.02	5	5	0.363	−0.159	3.369	20.19	11	2
			6	7	do	−0.139	3.994	26.77	14	2
			7	3	do	−0.055	4.707	18.53	11	5
			8	4	do	−0.184	4.819	17.78	11	5
WAPD10	0.230	0.91	9	5	0.324	0.224	3.499	14.66	11	15
			10	7	do	0.103	3.416	10.36	14	75
			11	3	do	0.222	4.057	28.39	11	No
			12	4	do	−0.102	4.799	34.90	11	No
WAPD07	0.293	1.23	13	5	0.435	0.096	2.844	5.16	14	98
			14	7	do	0.094	3.028	18.12	14	20
			15	3	do	0.112	2.846	19.82	12	5
			16	4	do	0.081	2.698	10.67	13	60
WAPD17	0.444	1.21	17	5	0.429	−0.116	2.999	14.69	14	40
			18	7	do	0.021	3.159	6.50	14	95
			19	3	do	−0.088	3.085	7.19	14	90
			20	4	do	0.060	3.038	9.49	12	60

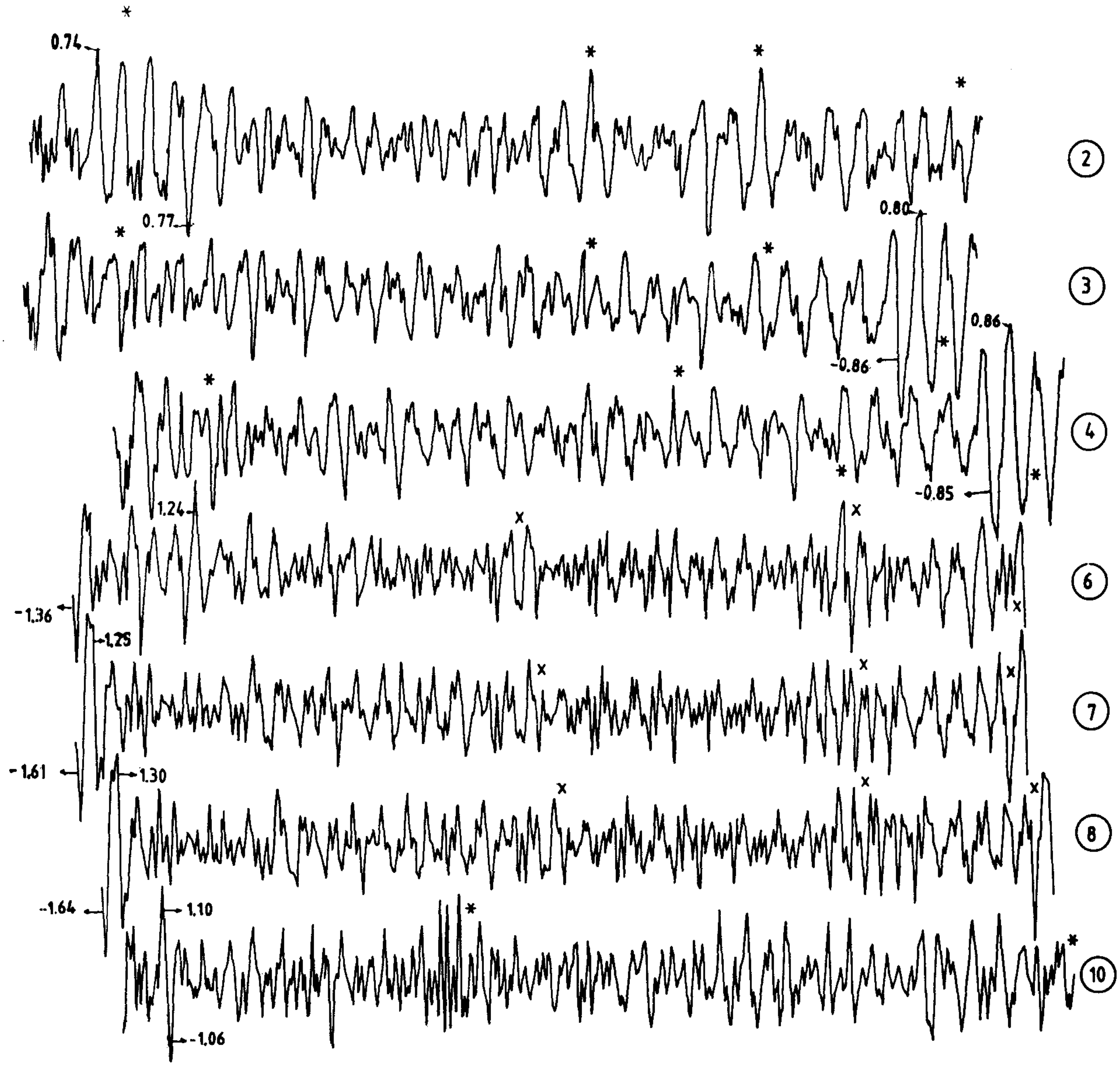

Fig. 2—Computed surface wave profiles with different ITUNE values [Profile numbers 2 to 4, 6 to 8 and 10 as in Table 1]

in the cases of WAPD01 and WAPD10. This is considered to be a normal result as the random couplings can take place anywhere in the valid spectral range (0.05-0.33 Hz) wherein the spectral densities vary very much from the peak to a minimum (see last para). The marked increase in the confidence levels of WAPD07 and WAPD17 is definitely due to the wide band nature of their spectra (Fig. 2). The same goodness of fit is noticed in their α_1 (skewness) and α_2 values also. Here, it should be noted that for WAPD07 and WAPD17 the couplings (7 and 4) occur at frequencies with considerably more energy contents compared to WAPD01 and WAPD14 (Fig. 1).

For ITUNE = 3 the assigned phase coherency at the spectral peak would cause the peak to behave like soliton and when ITUNE = 4 the peak interacts with a second harmonic component. Varkey[2] has found that by assigning a Normally distributed phase spectrum (ITUNE = 6) the surface profiles become abnormally nonlinear with α_2 varying from 9 to 32 for a narrow band pure swell (similar to WAPD01) to a wide band multipeaked wave system (similar to WAPD07), respectively covering all possible sea states. Hence, it could be generalised that the phase couplings can be grouped into 3 classes; (a) ITUNE = 5 and 7, (b) ITUNE = 3 and 4 and (c) ITUNE = 6. It is also possible to generate a profile with ITUNE = 7 with a large number of couplings (the present maximum number of couplings is only 7) which will be very similar to a profile with ITUNE = 6.

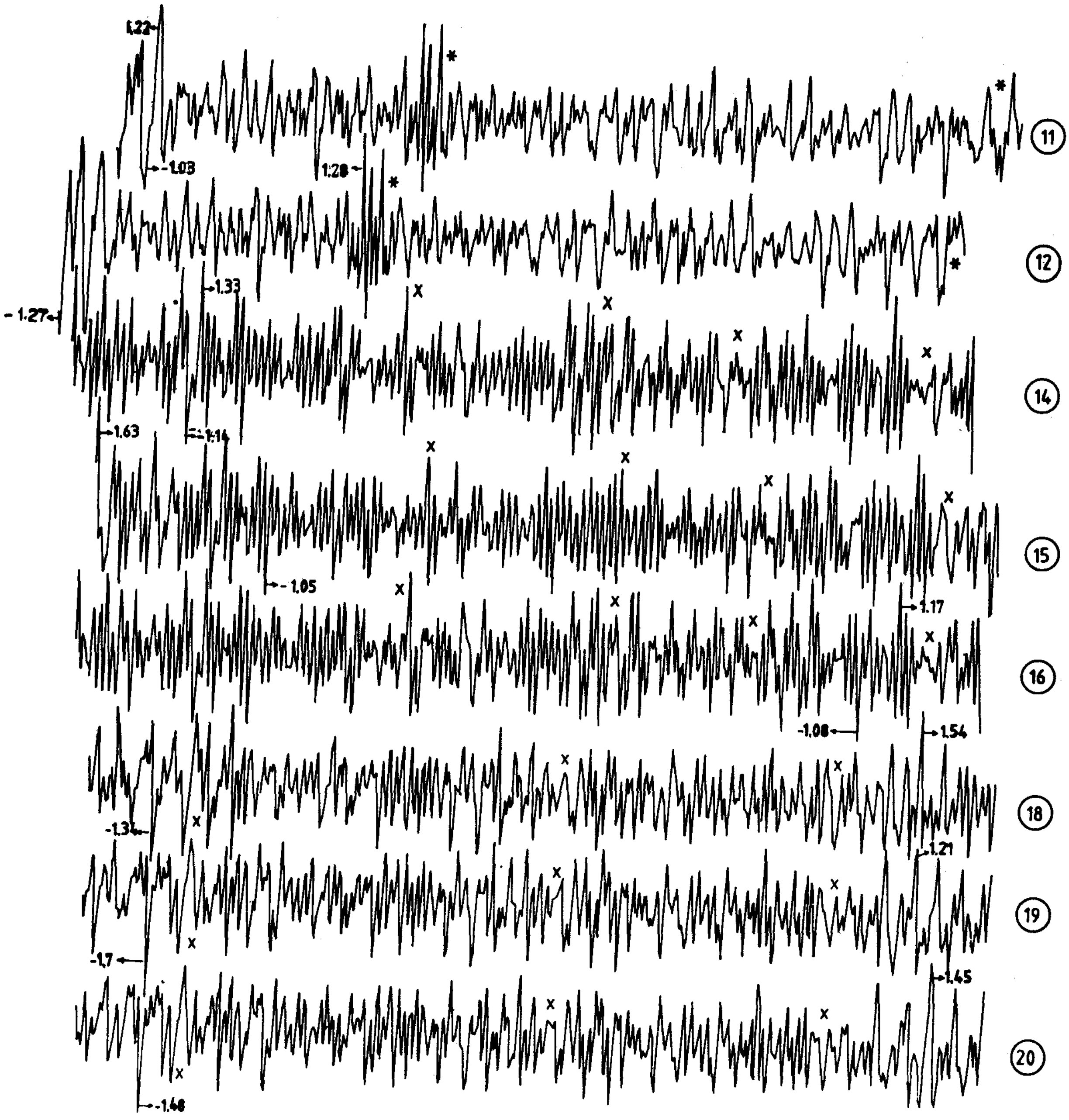

Fig. 2—Computed surface wave profiles with different ITUNE values. [Profile numbers 11, 12, 14 to 16 and 18 to 20 as in Table 1]

A close scrutiny of Fig. 2 shows the effect of different couplings on the time scale. Marked contrasts between profiles from the same spectrum are noted along the profiles with a cross or asterisk. The numbers noted against each profile are the same profile numbers in Table 1. The highest peaks and the lowest troughs are also marked (in m.) over the profiles for comparison.

External factors like currents, wind, boundaries (shoaling) and other wave systems can cause phase spectral changes during evolution of sea states[2]. Mollo-Christensen[6] has suggested that processes like current variability in space and time, underlying swell, gustiness and the time history of wind and waves can influence the non-linear group dynamics of waves. The interaction of multisourced and multidirectional wave systems with local wind and sea of different intensities is a very complex situation in which complex phase spectral changes (due to nonlinear wave components) may take place which in turn give rise to profile changes. Toba *et al.*[7] while discussing the interaction of wind with regular waves have suggested that the strongly vortical wind drift would have a primary role in the evolution of local sea state. His experimental results can be similarly extended to an open ocean situation in which a local sea builds up over a regular swell. Such a double peaked situation has been studied by Varkey[2,5] for peculiarities in phase spectrum and changes in surface profiles with different types of non-Uniformity in phase spectrum. The results show noticeable differences in observed phase spectrum of a double peaked sea dominated sea state compared to that of a narrow band swell system.

A noteworthy feature is the pronounced effect of the tuning range along the frequency axis on the computed surface profile. It is noted[2] that when the phase spectrum of the record WAPD07 is tuned at the sea side of the swell peak over the range fs to $fs+(W/2)$, the values of α_1 and α_2 are 0.039 and 4.164, respectively. But when the tuning is done exactly over the swell peak (in the present study) from $fs-(W/4)$ to $fs+(W/4)$, the values of α_1 and α_2 are 0.112 and 2.846, α_2 decreasing very much towards normal values for Normal law. This sensitivity seems to be due to the sharp changes in the spectral density values over the 2 different tuning bands (in the 2 studies) and the closeness of the tuned wave components to the peak point. When the wave components extended beyond $fs+(W/4)$ by a width $W/4$ in the previous work[2] α_2 increased much from the Normal value (3). But when the tuning range involved only the peak high energy components the α_2 value is close to Normal value. This result seems to indicate that in naturally occurring sea states (at least in cases similar to WAPD07) the peak wave components are always in some sort of coherency pointing to the fact that the peak wave components (when viewed individually) are better described by solitons[8,9] (in the sense highly nonlinear). This point appears to be corroborated by the observed bispectral peaks due to self interaction at the spectral peaks[10-12].

Acknowledgement

The author thanks Dr J S Sastry for encouragement and the staff of the Physical Oceanography Division and Computer Group for co-operation.

References

1. Ming-Yang Su & Green A W, in *Wave dynamics and radio probing of the ocean surface*, edited by O M Phillips & K Hasselmann (Plenum Press, New York) 1986, 231.
2. Varkey M J, Wind wave surface profile changes caused by phase spectral adjustments (communicated to *J. Phy Oceanogr*).
3. Kinsman B, *Wind waves: their generation and propagation on the ocean surface* (Prentice-Hall Inc, New Jersey) 1965, 608.
4. Crisp G N, *An experimental comparison of a shipborne wave recorder and a wave rider buoy conducted at the Channel Lightvessel*, Rep no 235 (Inst Oceanographic Sci, Wormley, UK) 1987, pp 181.
5. Varkey M J, *Indian J Mar Sci*, **17** (1988) 181.
6. Mollo-Christensen E, in *Measuring ocean waves from space*, Proceedings of the Symposium held at the Johns Hopkins University, Baltimore, USA, April 15-17, 1986.
7. Toba Y, Hatori M, Imai Y & Tokuda M, in *Wave dynamics and radio probing of the ocean surface*, edited by O M Phillips & K Hasselmann (Plenum Press, New York) 1986, 117.
8. Lake B M & Yuen H C, *J Fluid Mech*, **88** (1978) 33.
9. Hatori M, *J Oceanogr Soc Japan*, **40** (1984) 1.
10. Hasselmann K, Munk W & MacDonald G, in *Scripps Institute of Oceanography, Coll. Reprints*, Vol. **33**, Contribution No. 1477 (1963) 73.
11. Liu P C, *Spectral growth and nonlinear characteristics of wind waves in Lake Ontario*, NOAA Tech. Rep. ERL 408-GLERL 14 (U S Department of Commerce) 1979, pp 58.
12. Sengupta D & Mahadevan R, *Bispectra of sea surface waves*, Tech. Rep No. 1/83 (Nat Inst Oceanography, Goa, India) 1983, pp 36.