Geophysica (1997), 33(2), 9-14

Laboratory Measurements of Stress Modulation by Wave Groups

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Abstract

The direct action of the wind on waves corresponds to a transfer of momentum (or stress) between air and water. However, the distribution of stress contributions with wavenumber remains an open question. In this report direct measurements of the modulation of the stress by the passage of wave groups in a laboratory wind-wave tank are described. It is shown that over half of the incremental stress due to passage of groups is absorbed by the groups themselves.

Key words: wave groups, wind-wave generation, stress modulation

1. *Introduction*

Waves of various lengths and speeds travel on the ocean surface and are amplified or attenuated by favourable or adverse winds. The direct action of the wind on these waves corresponds to a transfer of momentum (or stress) between air and water. In fully rough flow all of the stress is supported by pressure variations in phase with the wave slope. However, the distribution of stress contributions with wavenumber remains an open question. There is general agreement that the short slow moving waves support most of the stress under steady long-fetch conditions when the wave field is mature; i.e. approaching full development. On the other hand, young wind seas show strong peak enhancement and laboratory measurements of very young 'seas' show that this is due, in part, to strong wind input to the relatively long waves near the spectral peak.

There have been various attempts to determine the direct wind forcing to various wave components in rough flow; these include:

1. Observed growth of relatively long paddle-generated waves in a laboratory tank (e.g. *Mitsuyasu* and *Honda*, 1982).
2. Pressure slope measurements in a wave following frame (*Snyder* et al., 1981; *Hsaio* and *Shemdin*, 1983).

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Published by the Finnish Geophysical Society, Helsinki

3. Observed initial growth of short waves from radar measurements in tanks (*Larson* and *Wright*, 1975).

The dependence of the exponential amplification rate, β, from such experiments has been summarized by *Plant* (1982). In general, β is found to be roughly quadratic with the wind forcing paramater, u_*/c (the ratio of the friction velocity of the phase speed of the wave component), although the scatter is considerable. In all cases the value of β obtained is an average over the data record, with no attempt to assess the effect of modulation of the wave amplitudes.

In this paper we report direct measurements of the modulation of the stress by the passage of wave groups in a laboratory wind-wave tank.

2. Experiments

The experiments were conducted in a wind-wave tank having a working section of dimensions of LxWxH: 9x0.6x0.85 m (see Figure 1). Surface elevation measurements were made at 8 equally spaced stations along the tank. A hot film (x-film) thermal anemometer was located at 4.85 m fetch and 0.19 m above the surface to measure streamwise and vertical components of the mean flow and turbulence. The wave data were collected at 20 Hz and the x-film data at 80 Hz.

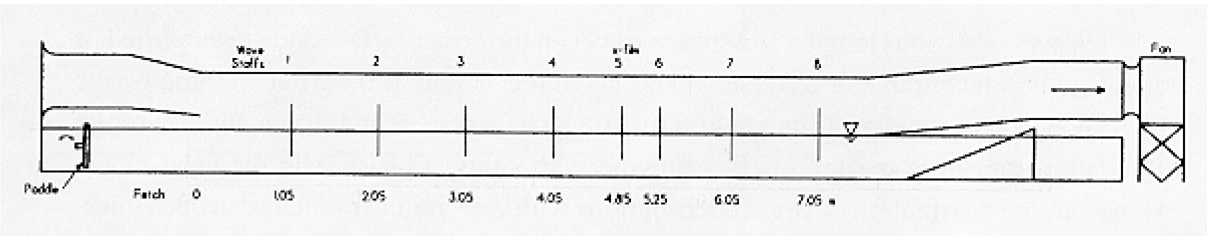

Fig. 1. Sketch of the flume, showing the locations of the wave staffs. The x-film anemometer is 4 cm downwind of wave staff 5.

A hinged paddle wavemaker was activated to produce a Gaussian packet of coalescing waves every 25 seconds (*Pierson* et al., 1992). The time between groups was chosen so that only one group was propagating downtank at any time. The packet was designed to coalesce and break at station #5, the location of the x-film anemometer.

The wind was generated by a fan at the downwind end of a straight-through wind tunnel. In these experiments the fan speed was held constant throughout the passage of 25 groups. The mean wind speed was 9.1 m/s in the measurements reported here.

3. Results

The envelope of each surface elevation signal was computed using Hilbert Transforms (*Huang* et al., 1992). These envelopes are shown at the top of Figure 2. The packet can be clearly distinguished from the background envelope of wind waves as it passes from station #1 to station #8. The surface elevation trace at station #2 is shown in the middle panel. In the bottom panel is displayed the stress as averaged products of the streamwise and vertical components of the wind velocity -- where the average is a running mean of two seconds, or about two periods of the carrier wave of the group.

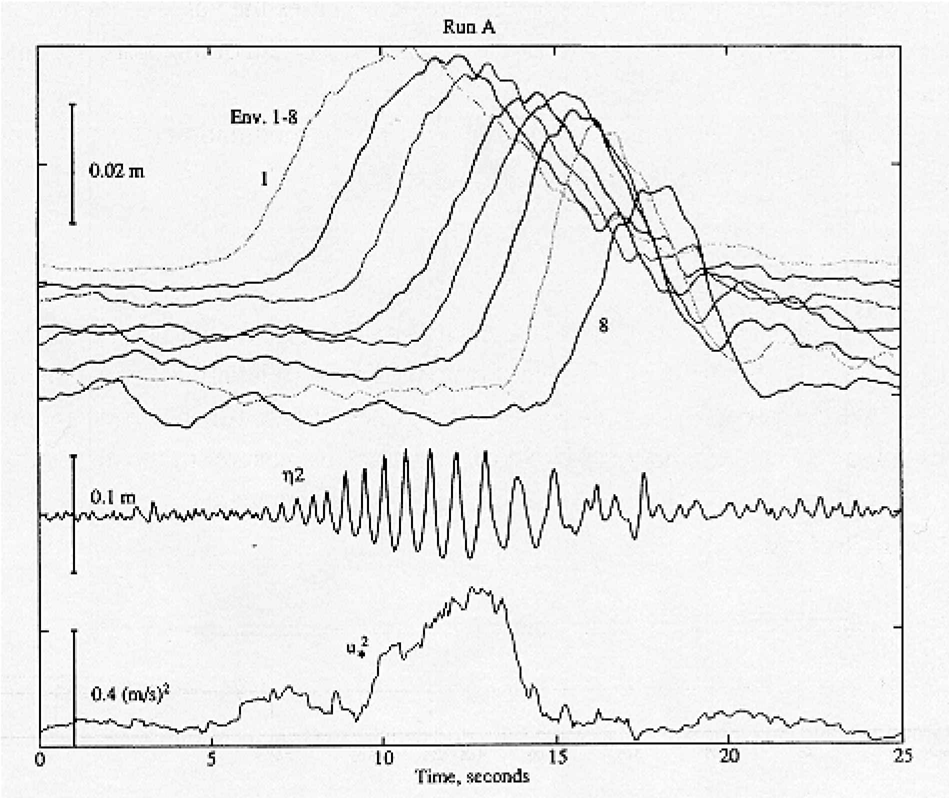

Fig. 2. Group averages, for Run A, of: the envelopes of the waves at wave staffs 1-8 (Env. 1-8), vertically offset for clarity; the surface elevation at wave staff 2 ($\eta 2$); the stress at the x-film anemometer, u_*^2.

It is apparent that the passage of a group produces an enormous enhancement of the stress -- approximately a factor of four or five. Note, however, that the stress enhancement, observed at 0.19 m above the mean water level, precedes the arrival of the group at that station by several seconds. In fact, the stress enhancement is roughly simultaneous with the passage of the group through station #2, some 2.8 m upstream. This is shown in Figure 3, where the envelope of the waves at station #2, squared, is plotted with the simultaneous (wind) stress measurement at station #5. Clearly, the stress perturbation (the source weight function or footprint, see *Schmid*, 1994) produced by the coalescing group diffuses into the boundary layer as it is advected by the wind at a speed in excess of the group velocity of the packet. This growing internal boundary layer is observed downstream at the altitude of the x-film anemometer. Using the group velocity of the characteristic frequency of the group, the mean propagation speed of the disturbance in the air assuming a logarithmic profile, based on the mean u_* caused by the group, the source location of the disturbance that is measured simultaneously by wave staff #2 and the x-film is at fetch 1.72 m. This is shown schematically in Figure 4. The calculated rate of vertical diffusion of the stress perturbation is 0.46 m/s, which is comparable to the mean u_* caused by the group of 0.51 m/s.

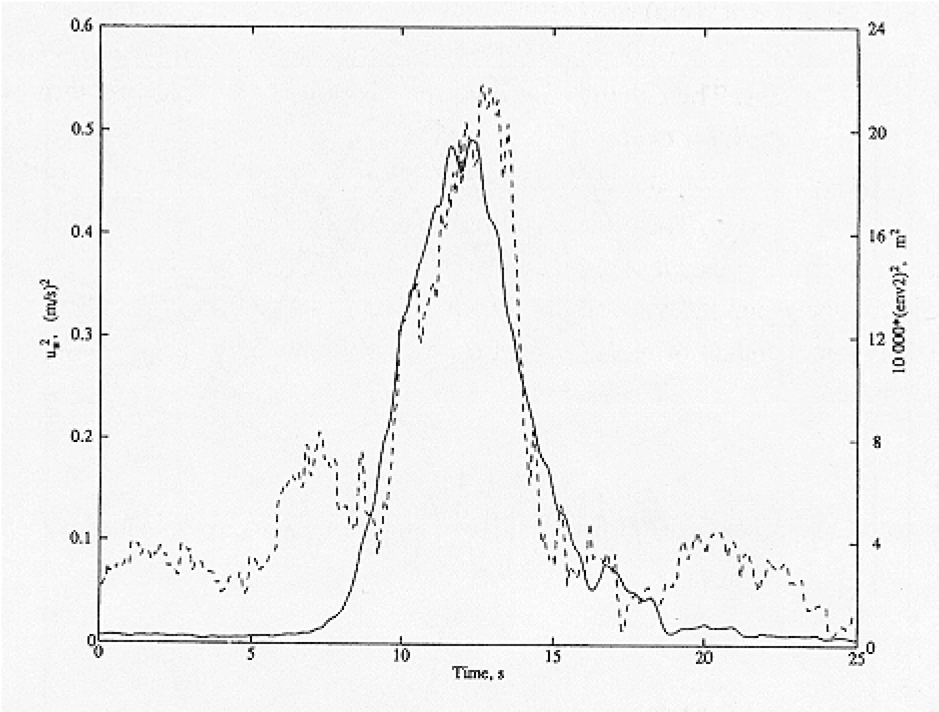

Fig. 3. Group average envelope squared at wave staff 2 (-) and the stress at the x-film anemometer, u_*^2, (--).

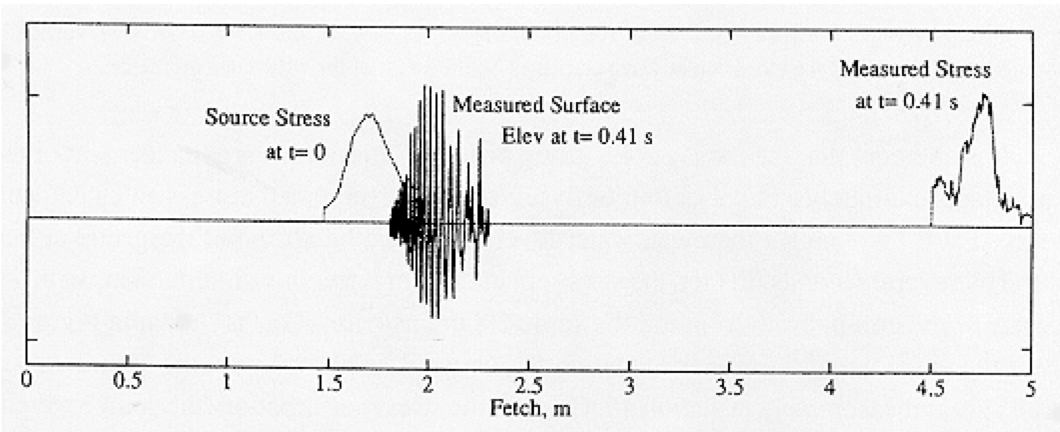

Fig. 4. Sketch depicting the source stress produced by the wave group upstream at t=0, and the subsequent simultaneous observation of the wave group at wave staff 2 and stress measured in the air at the anemometer at t=0.41 s. The group velocity of the waves is 0.81 m/s, and the mean propagation speed of the disturbance in the air is 7.68 m/s.

The average growth of the wave groups for repeat Runs A and B are indicated in Figure 5, where the variances are plotted against fetch. In addition the Zero Run indicates the losses due to friction at the bottom and walls (we note in passing that the losses are in excellent agreement with the theory formulated by *Hunt*, 1952). Following the method of *Mitsuyasu* and *Honda*, 1982, the slopes of regression lines (corrected for mean current and the losses in the absence of wind) yield estimates of the fractional energy increase per radian to the wave groups (0.0072 and 0.0058 for Run A and Run B), and subsequently the estimate of the increase in stress. The calculated growth rate is roughly in accord with previous estimates as summarized, for example, by *Plant* (1982). The momentum fluxes absorbed by the dominant waves in the group (deduced from Figure 5) are 0.30 and 0.18 $(m/s)^2$ for Runs A and B respectively. The corresponding shear stress increments ($\Delta\tau$) measured by the x-film anemometer in the air are 0.394 and 0.319 $(m/s)^2$. The ratios of incremental stress as measured by the group growth and by u_* are, for Run A 0.76, and for Run B 0.56. This suggests that more than half of the incremental stress is absorbed by the large waves in the group.

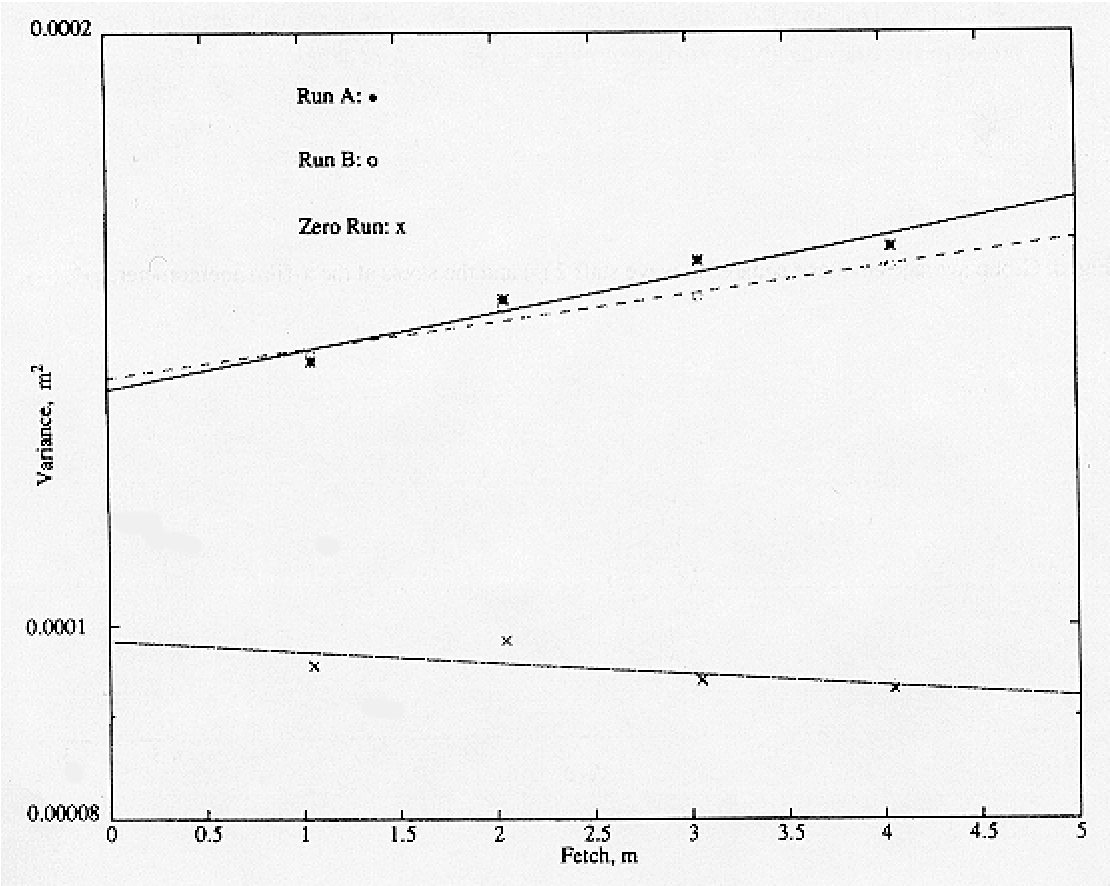

Fig. 5. Variances of the wave groups indicating the growth for Runs A and B, and corresponding decay for Zero Run in the absence of wind. The corresponding slopes are 0.0446, 0.0325 and -0.0131.

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