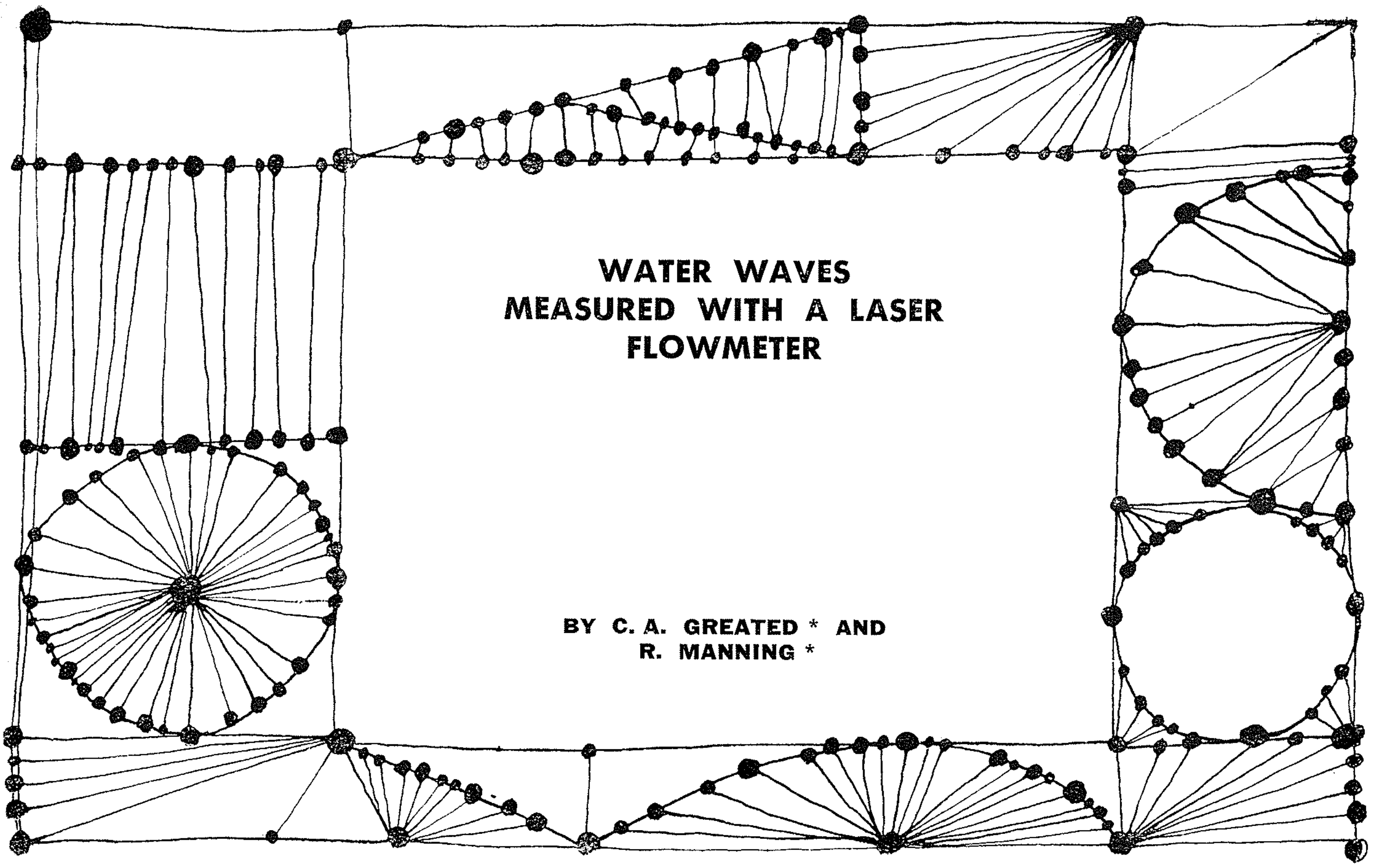


WATER WAVES MEASURED WITH A LASER FLOWMETER

BY C. A. GREATED * AND R. MANNING *

Introduction

The laboratory measurement of velocity fields under water waves, which is fundamental to the study of many coastal and oceanographic phenomena, has up until now been hampered by lack of satisfactory instrumentation. Photographing of small floats or tracer particles has been used extensively to measure the fluid motion in a Langrangian manner (e.g. Russell and Osorio 1957), but the analysis of data is extremely tedious and furthermore, for engineering purposes, we are more often interested in measuring to an Eulerian frame of reference. For this purpose propeller meters have been used and these can be made as small as 5 mm in diameter and capable of registering down to about 0.5 cm/s. The problem here is that their response to a sudden change in velocity is delayed by the inertia of the propeller and, furthermore, several revolutions must be recorded before an accurate velocity reading is obtained, meaning that it is impossible to measure instantaneous velocities with any accuracy. Although hot film anemometry is in principle capable of overcoming these limitations, it has never become a practical system for water wave measurements because of the problems of calibration drift when using contaminated water.

In a study of wave velocities near the bed, Sleath (1970) has used a novel device consisting of a fine fibreglass wire stretched across the channel. The force on the wire at any instant is then recorded and is a measure of the water velocity. This overcomes the difficulty of response time but cannot easily be used to produce detailed information on velocity fields as firstly it is not directionally sensitive and secondly it gives an integrated recording across the channel.

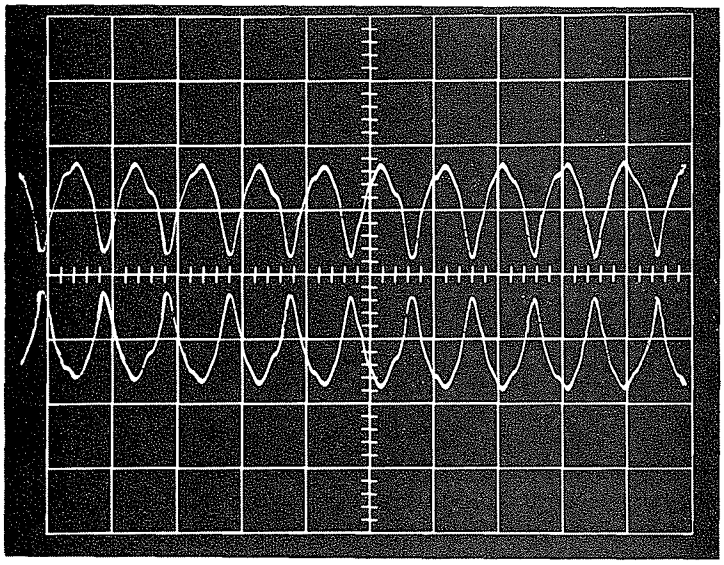
In a recent article (Greated 1969) a laser system for measuring turbulent fluctuations in a flow of constant mean velocity was described, which introduces no disturbance into the water and produces extremely reliable results. In this, two beams originating from the same source are brought to a focus to produce a fringe pattern extending over a small observation volume in the region where the velocity is to be measured. Minute particles in the water passing through the measuring volume, then produce a signal which has a frequency component proportional to their velocity. In this paper we will describe how the instrument has been developed to measure both horizontal and vertical components of the reversing velocities under waves and will present the first results in a detailed investigation of velocity fields under deforming waves.

We are at present studying the motions of waves as they approach the breaker zone, and it is obviously going to be extremely difficult to make these velocity measurements in the sea itself. A successfull example was described by Miller and Zeigler (1966), but they were not able to take measurements on the larger waves which occur during storms. We hope to get results for these larger waves which were not obtainable from the field measurements.

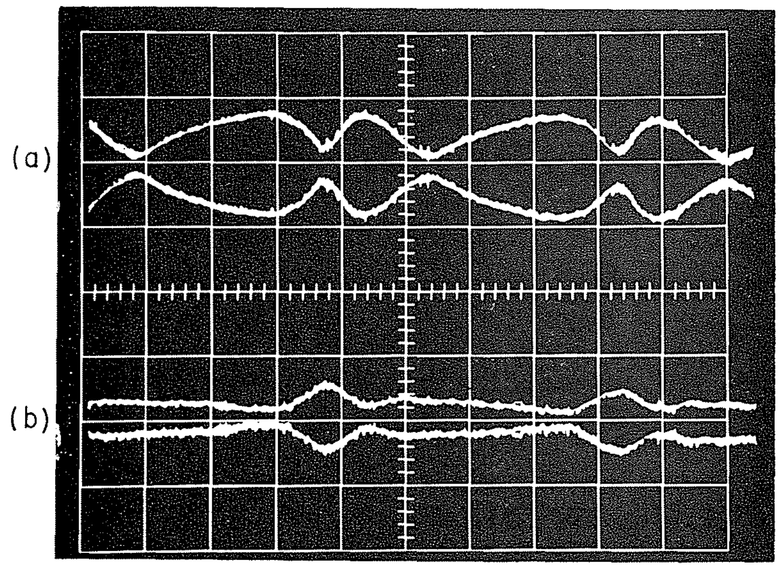
A wide range flowmeter

In the study of turbulence Rudd (1969) described a type of instrument suitable for use where the velocity range does not vary by more than ± 50 percent from the mean. From the spectrum of signal frequencies information could be obtained about two parameters of the

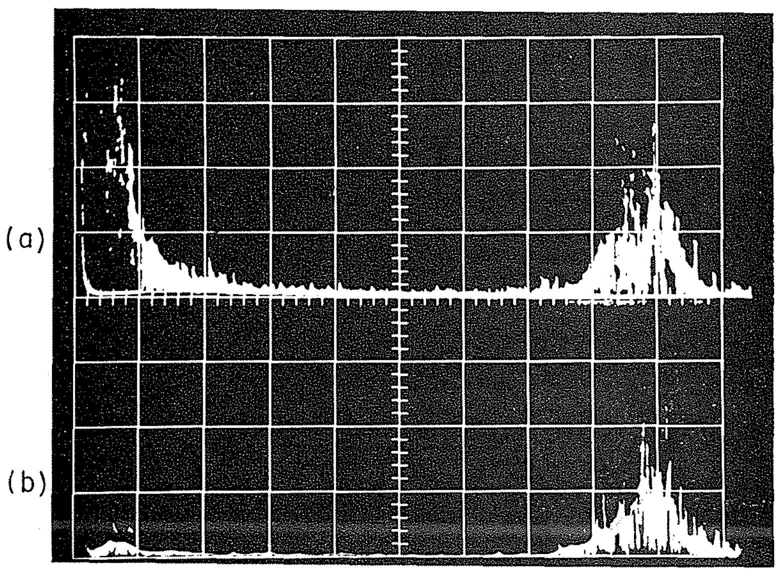
* Mathematics Department, Southampton University.



1/ Response to a sine wave of 25 Hz.



2/ Velocities at point B.



3/ Signal spectra (*a*) before filtering and (*b*) after filtering.

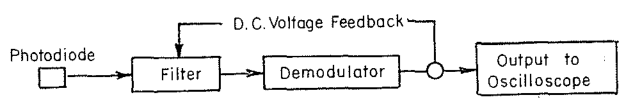
velocity field, first the average velocity, and secondly the spread of velocities on either side of the mean.

The velocimeter developed by Greated in 1969 went further by giving a continuous output of the instantaneous velocity in the fluid, but this instrument was still limited to the same range of ± 50 percent from the mean. The difficulty is in preventing random low frequency noise from masking the true Doppler part of the signal. Figure 3 shows a signal spectrum produced for a constant velocity field and below this the same spectrum after the low frequencies have been removed by an electrical filter. It can be seen in the unfiltered spectrum how the energy output contained at Doppler frequency is small compared to the large amount of low frequency noise. The problem of analysis is to keep the signal to noise ratio as small as possible.

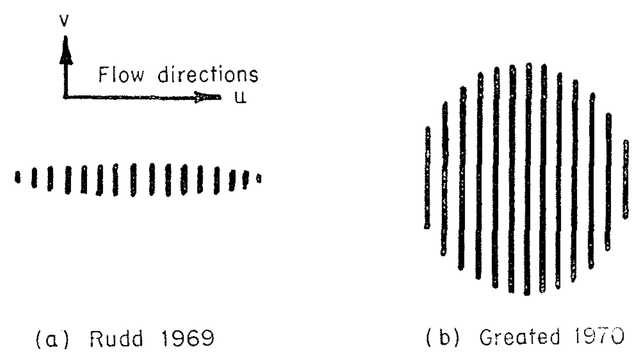
To remove the low frequency noise a certain lowest frequency of interest has to be arbitrarily decided upon and used as the cut off frequency of the filter. This cut off frequency then corresponds to a "cut off" velocity below which measurements cannot be made.

In order to study wave motions a velocity range is needed which goes very much closer to zero than previous instruments allowed, and it must rise up to its maximum velocity within a fraction of a second. Initially we made a few measurements with a manually controlled filter, but our final velocity records have all been made with the greatly improved instrument described by Wilmshurst et al (1970) and which automatically controls the filter frequencies.

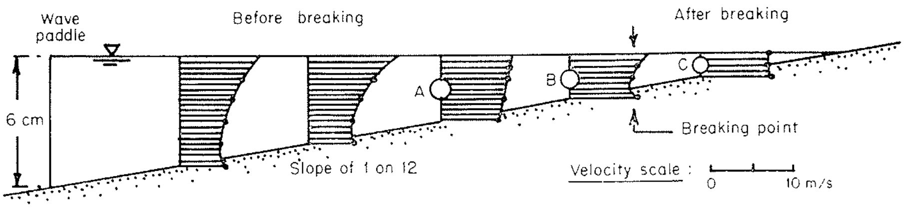
The instrument may be termed a Wide Range Flowmeter to distinguish it from the earlier instruments which had a limited range of about 3: 1. Its other feature is the precisely linear nature of the output voltage in relation to the velocity being measured. A block diagram of the electrical circuit (Fig. 4) shows how the d.c. output voltage is used as a feedback to the filter. The signal collected by the photodiode passes through the filters where the unwanted frequencies are removed and the Doppler frequencies continue to the frequency-to-voltage converter. Once the instrument is set up it can measure velocities continuously over a 30: 1 range, and at the throw of a switch the velocity range is altered to values ten times greater. The final output is a d.c. voltage from



4/ Block diagram of the electrical circuits.



5/ A comparison of the fringe patterns.



6/ Field of maximum horizontal velocities on a slope of 1 on 12.

0 to 4 volts which can be recorded on a chart recorder or an oscilloscope.

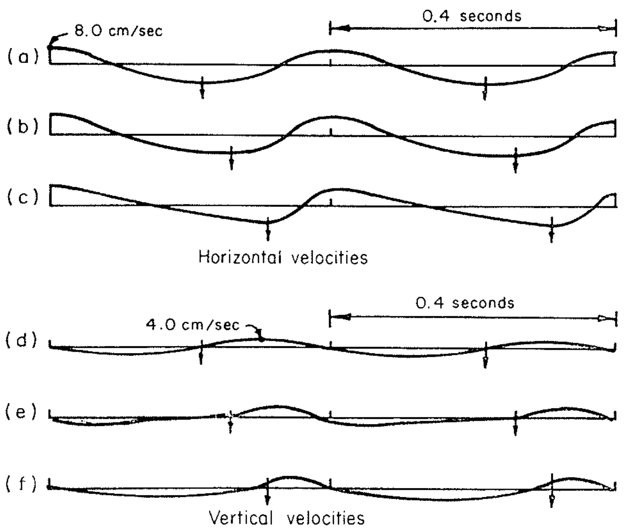
The frequency response to velocity fluctuations required in the wave flume is 2,5 Hz whereas our flowmeter can measure much more rapid fluctuations. Figure 1 shows the response to a sine wave velocity fluctuation of 25 Hz, and slight imperfections can be seen at this frequency. Immediately below in Figure 2 is a typical velocity record in the wave channel from which the records of Figure 7 were reproduced. At the frequency of 2,5 Hz used in the experiments the flowmeter can be relied upon to measure accurately in the operating range.

An additional feature which we have found useful in wave recordings is the optional "double trace" output which can be used with an oscilloscope. Following one branch of the double trace output in Figures 1 and 2 allows the forward and backward velocities of the motion to be followed as a smooth curve.

Directional properties of the laser flowmeter

In the laser flowmeter, velocities are measured within a small observation volume containing the fringe pattern, the precise shape and size of which can be controlled by suitable choice of optical configuration. The Rudd system (1969) which produces a wide observation volume as shown in Figure 5*a*, has proved satisfactory in turbulence measurements but is not suitable for wave recordings where the vertical v velocity may be as large or even larger than the horizontal u component during part of the wave cycle. This is because an observation volume of this type does not give satisfactory separation of the horizontal and vertical components of velocity. A modified system described by Greated (1970) was therefore used which gives the observation volume shown in Figure 5 *b*. It is seen that with the Rudd system, particles moving out of the horizontal direction will pass only a few fringes and therefore the signal will be lost but with the modified system, using a taller fringe volume, this problem is overcome.

A series of tests on the two fringe systems showed that if the cross velocity is sufficiently strong the u component can be completely lost. At quite modest angles to the measuring direction the velocity measured by the Rudd system ceases to operate whereas the Greated circular fringe shape works quite easily up to angles of 70°. The situation where this arises is shown in the velocity records of Figure 2 where it is seen that the maxima of horizontal velocities generally correspond with the minimum values of the vertical component. Clearly a certain amount of fuzziness is to be expected at the minimum values of vertical velocity.



7/ Velocity records at mid-depth for the three points A, B and C. Vertical arrows indicate times of minimum horizontal velocity.

Velocities on a sloping beach

Theories have long been known which will indicate the changes in motion which occur in shallow water provided always that the vertical amplitude of the wave motion is assumed to be small. The assumption of small amplitudes in theoretical analysis seems to be valid until the amplitude is quite large, but it ceases to apply at the important stage where the amplitude increases just before breaking. It is what happens at this point which controls the flow assumptions valid for the breaking process.

We present here the preliminary results for our study of velocity profiles near the breaker zone. Complete velocity records are shown at mid depths for both vertical and horizontal velocities and records were available to us at all depths right down to within a millimeter of the bottom. With the smooth perspex bottom the boundary layer was extremely small and our present observations were well outside. For this purpose the thickness of boundary layer is taken at 90 percent of the asymptotic bed velocity.

The closeness to the bottom with which velocities can be measured is extremely useful in wave studies, and it is hoped to verify independently some of the results obtained by Sleath (1970) on velocities within the boundary layer.

To give an overall impression of the flow field the maximum positive values of horizontal velocities u have been plotted on vertical sections and are shown in Figure 6. As the water depth becomes less the velocities increase and the velocity at the bottom becomes closer to that at the surface. The assumption that horizontal velocities are constant on a vertical section is in general confirmed in the shallow water, and if we wish the assumption to be correct within 10 percent then our experiments indicate that this is reasonable in water depths less than $L_0/8$, where L_0 is the deep water wavelenght.

At three points in the flow field typical velocity records are shown at mid-depth (Figure 7). At point A the velocities in both horizontal and vertical directions deviate considerably from sinusoidal and show fairly sharp peaks and long troughs. However, the orbital motion is not far from an elliptical path with major axis in the horizontal direction. At point B there is a steep front in the horizontal velocity as the wave crest arrives at the observation point and at the same instant there is a short upward peak in the vertical velocity record. The motion of a particle no longer conforms to a smooth elliptical path. Instead there is one half of the path which is more rapidly traversed as the water level rises from trough to crest.

The vertical velocity in all our records such as Figure 2 *b* follows closely the rate of change of horizontal velocity. An explanation is more easily understood when we consider the results of other experiments in which a simultaneous record of surface elevation is compared with the horizontal velocity record. It is found that these two curves are of very similar shape and that as the crest of a wave passes the measuring point so the forward velocity is at its maximum. However there are slight deviations in the relationship which can only be explained as second order effects.

Other features of the flow field arise close to the bottom where the net forward migration near the boundary layer makes for higher maximum velocities in Figure 6. Beyond the breaking point the opposite kind of migration shows on the horizontal velocity record. This negative migration occurs at all points permanently below water surface, and the flow balance is maintained by forward pulses at levels where flow occurs intermittently with the passage of each wave crest.

Beyond the breaking point there is a considerable turbulence in the water which makes observations more difficult. Within the observation volume of the flowmeter small eddies cause the particles to emit a wide range of Doppler frequencies which tend to give a confused output. However we have succeeded in making velocity records which refer to point C immediately after breaking of the wave. The vertical record shows a short upward surge as the wave front passes and the horizontal velocity has a sudden increase which can be associated with the theory of a hydraulic jump.

Conclusion

The authors have found that the new laser methods of flow measurement produce very reliable results for continuous tracing of wave motions and can be used at the extremely low velocities which are present in small models. For continuous velocity records there seems little doubt that laser doppler will become a widely used laboratory technique.

References

[1] GREATED (C. A.). — An improved method of flow measurement in water. *La Houille Blanche*, n° 6, (1969), p .631-633.

[2] GREATED (C.A.). — Measurement of Reynolds stresses using an improved laser flowmeter. *J. Sci. Inst.* (*J. of Phys. E.*), séries 10, vol. 3, (1970), p. 753-756.

[3] MILLER (R.L.). and ZEIGLER (J.M.). — The internal velocity field in breaking waves. 9th Conf. on Coastal Engineering (1964), p. 103-122.

[4] RUDD (M.J.). — A new theoretical model for the laser Dopplermeter. *J. Sci. Inst.* (*J. of Phys. E*), series 2, vol. 2, (1969), p. 55-58.

[5] RUSSELL (R.C.H.) and OSORIO (J.D.C.). — An experimental investigation of drift profiles in a closed channel. 6th Conf. on Coastal Engineering (1957), p. 171-193.

[6] SLEATH (J.F.A.). — Velocity measurements close to the bed in a wave tank. *J. Fluid Mech.*, vol. 42, part 1 (1970), p. 111-123.

[7] WILMSHURST (T.H.), GREATED (C.A.), and MANNING (R.). — A Laser Fluid Flow Velocimeter of wide dynamic range. *J. Sci. Inst.* (*J. of Phys. E.*), in press.