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A LASER VELOCIMETER FOR USE IN COASTAL BOUNDARY LAYER STUDIES

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ABSTRACT

A single-axis forward scatter laser Doppler velocimeter (LDV) suitable for both laboratory and field use has been designed and built at Woods Hole Oceanographic Institution. A brief description of the instrument and the LDV technique is given. Two applications, one in the laboratory and one in the field, are described to illustrate the utility of the LDV technique and the prototype system; these are a study of the mean velocity structure in a turbulent wave boundary layer and a study of the effect of marine organisms on sediment stability in noncohesive sediments.

INTRODUCTION

In the sixteen years since its introduction, e.g., Yeh and Cummins, 1964[1], laser Doppler velocimetry has become a standard laboratory technique for fluid flow measurements. The substantial literature base on both the laser Doppler technique and its applications attests to this observation[2,3,4].

The appeal of laser Doppler velocimeters (LDV) for use in fluid dynamics studies is multi-faceted. The LDV can be assembled in a variety of physical configurations which allow flow measurements to be made with no mechanical disturbance to the flow. It has an extremely low threshold velocity and its response is intrinsically linear. Calibration of the LDV depends only upon the geometrical configuration of the instrument. Moreover, the small scale, high frequency resolution of the instrument (typically 10^{-4} to 10^{-3} m and 1 to 10^{3} Hz) allows measurements to the Kolmogorov fine scale flow regime. LDV's are not without their problems, however. Among the problems are relatively high power requirements and measurement accuracy which depends on the particles in the flow and the signal processing system used. For many applications in the laboratory, problems with the accuracy of LDV measurements have been addressed. The Proceedings of the Laser Doppler Anemometry Symposium (1975) in Copenhagen[5] give comprehensive discussions of the applications and the problems involved. For shallow water field applications the power contraints are not severe, as the examples given in this paper illustrate.

Several ocean applications of the LDV have been proposed and shallow water prototypes have been built[6,7]. A two-axis, forward scatter LDV developed by DISA Electronics was used in the ocean successfully in a current meter intercomparison test in 1975 [8]. In April 1976 a shallow water, single-axis, forward scatter LDV was designed and successfully ocean tested at the Woods Hole Oceanographic Institution (WHOI)[9]. The success of this ocean test and the nearly ideal characteristics of the LDV for use in near bottom turbulent flow measurements have led to the application of the WHOI LDV in the study of some important coastal processes. Two of the applications, a study of the mean velocity profile in a wave boundary layer, and an investigation of the influence of marine organisms on sediment stability in non-cohesive sediment, are used here as illustrations of the utility of the LDV for the study of small scale, high frequency processes. First, the basic instrument used in these studies is described.

INSTRUMENT DESIGN AND LDV TECHNIQUE

In the design of the prototype instrument particular attention has been paid to simple mechanical design and low cost; the pressure housings are PVC with plexiglass windows, and inexpensive optical components have been used. Figure 1 shows the essential optics of the system. The laser beam is split into two parallel beams by the beam splitter and the prism. A lens then focuses the two beams to a common point in the fluid. The magnitude of the velocity component in the plane of the beams and normal to the beam intersection is measured where the beams cross. The dimensions of the crossover volume define the spatial resolution. Emerging from the fluid, the beams are terminated by an iris. The crossover volume is imaged onto a pinhole so that only light scattered from the intersecting region can reach the photomultiplier tube behind the pinhole. The light scattered from each beam

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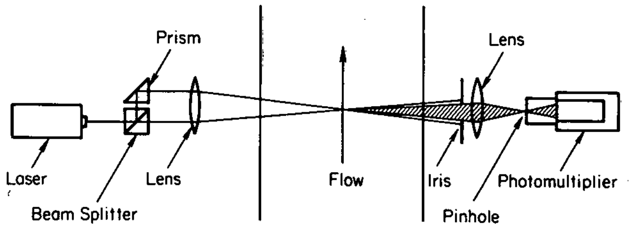

Figure 1. The optics of a single component forward scatter LDV system.

by a moving particle is Doppler-shifted by a different amount because of the angle between the two beams. Heterodyning of these two frequencies by the photomultiplier produces the difference frequency:

$$\nu_D = \frac{2n \sin\theta}{\lambda} V \qquad (1)$$

where n is the refractive index of the fluid, λ is the laser wavelength, θ is the half-angle of the two beams, and V is the component of flow in the plane of the two beams and perpendicular to the optic axis of the system. Actual values for the prototype system are: $n = 1.33$, $\lambda = 6.33 \times 10^5$ cm, and $\theta = 2.61°$; giving $\nu_D = 1.44$ KHz for a flow speed of 1 cm/sec. The laser power is 3 mW. Uncertainties in the angle measurement (the only calibration variable) give an error of 2%; this error can be improved with more precise measurement of the angle. The prototype LDV is sensitive to the magnitude of the velocity component, but not to its direction.

Figure 2 shows the physical configuration of the instrument. A rigid aluminum frame holds the receiving optics package in alignment with the transmitting optics package. The measurement volume is 38 cm below the frame, 30 cm from the transmitting optics window, and 22 cm from the receiving optics window. Underwater cables are used to power the instrument from the surface and to return the voltage signal from the photomultiplier. This signal is high-pass filtered, to remove low frequency fluctuations in the light level arising from the Gaussian intensity distribution of the beams, and recorded on an instrumentation recorder. Real time or play back signal processing is done with a Rockland Model 512S spectrum analyzer. The resulting Doppler frequency can then be used in equation (1) to determine the velocity, V.

APPLICATIONS

A study has been undertaken at WHOI to determine the effect of animal reworking on the onset of initial sediment motion in non-cohesive sediments[10]. Velocity profiles measured in the lower three cm of a laboratory flume using the LDV were used to determine the value of the boundary shear stress at which initial sediment motion was observed to occur. Flume runs were made over

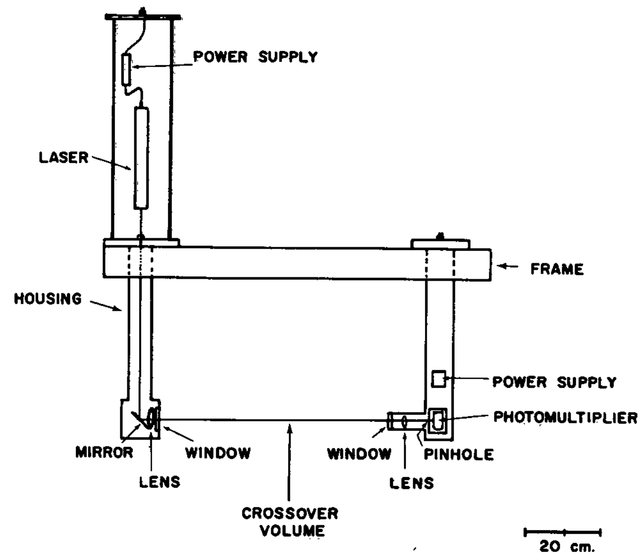

Figure 2. Physical configuration of the WHOI LDV.

sediment cores taken from a local tidal flat before and after animal reworking occured and control cores made by sterilizing the associated field cores. Comparison of control core stress values at initiation of motion with corresponding values from Shields curve[11] showed good agreement. For single profiles, up to 10 points in the lower 2 cm of the boundary layer extending down to 0.25 mm from the bed were obtained successfully. A summary of the flume velocity measurements made in the study is given in Figure 3 in a standard Clauser plot[12]. Results of runs over control

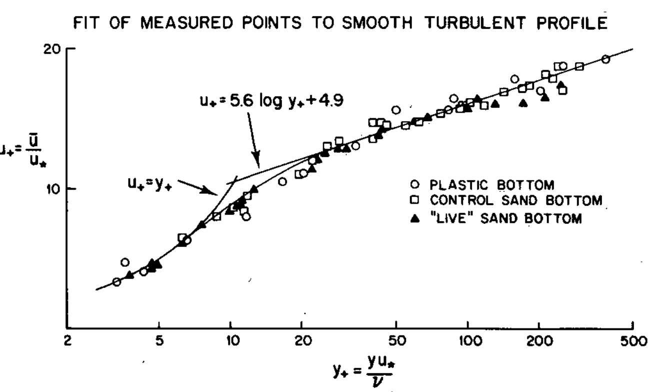

Figure 3. Clauser plot summarizing runs in animal sediment interaction study. u_* is the shear velocity, $\overline{u}$ is the mean velocity, y is the vertical coordinate, positive upward and ν is the kinematic viscosity of water. The points for the "live" beds in the range y+ > 120 deviate systematically from the curve; this is probably due to the effect of a greater roughness change in these runs from the upstream plastic bottom to the rough sand bed.

cores and "live" cores, i.e., undisturbed field samples in the unworked and reworked states, are shown; for reference, velocity measurements over a smooth plastic bottom in the same flume are shown. The study has allowed quantification of the effect of animal interaction on the stability of non-cohesive sediments for the first time. Equally important, however, the study has demonstrated the advantage of the LDV for use in sediment transport studies where undisturbed flow measurements extending down to the bed are essential; any mechanical disturbance will scour the bed and effect the local flow structure. Moreover, once sediment motion was initiated, signal drop out due to large sediment particles crossing the measurement volume did not seriously degrade the velocity profiles.

In a second study, the LDV is being used to obtain field measurements of velocity in the boundary layer under surface gravity waves[13]. For typical wind waves in shallow water the wave boundary layer is of the order 5 to 10 cm; too small for conventional current meters to be able to resolve the velocity, but well within the capability of the LDV. Since the present LDV can respond only to the magnitude of the velocity, an array of four three-axis acoustic current sensors, stacked in the vertical[14], is mounted above the LDV to keep track of direction under the wave. The record count from the acoustic current meters is recorded along with the voltage output from the LDV on an instrumentation recorder. After separate processing of the time series from each instrument, the velocity records can be aligned in time and the phase information from the acoustic sensors can be used to determine the direction associated with the speed measured by the LDV. Figure 4 shows a drawing of the wave boundary layer system. Note that the LDV can be profiled from the bed to the lowest acoustic sensor using a diver-operated crank.

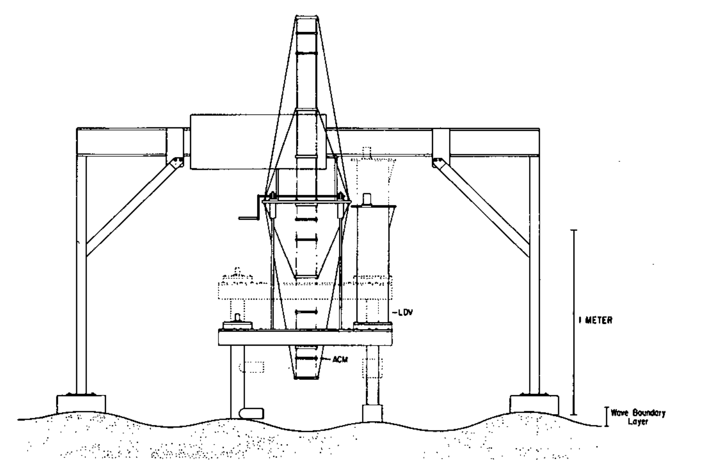

Figure 4. Laser Doppler Velocimeter (LDV) for profiling velocity within the wave boundary layer. Scale of boundary layer for typical wind wave conditions is 5-10 centimeters. Measurement volume of LDV is approximately .75 millimeters[3]

allowing us sufficient resolution. Sets of parallel rings above the LDV are acoustic current meters (ACM) used to obtain velocity profiles over the rest of the water column and to keep track of wave phase.

SUMMARY

In summary, a low cost prototype single-axis forward scatter LDV has been described and its application to two important coastal problems has been described. The results of these experiments are encouraging and demonstrate that more advanced two-axis and three-axis LDV systems are justified. Moreover, the advent of such advanced LDV systems will provide boundary layer and sediment transport researchers with the ability to make undisturbed small scale, high frequency flow measurements extending down to the sea bed of a quality not presently available with more conventional methods such as hot films.

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