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An oceanographic in situ Laser Doppler Anemometer

by

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INTRODUCTION

An in situ Laser Doppler Anemometer is described. The instrument is capable of measuring high frequency fluctuations, as occurring in surface wave motion, and low velocities, of the order of magnitude ± 2 mm/sec. The spatial resolution is very high, the measuring volume being of the order 0.5 mm^3. The range can be varied from ± 2 cm/sec to ± 5 m/sec over full scale, and the calibration of the instrument is extremely simple. Furthermore, no disturbances, i.e. artificial sensors, are placed in the flow field since the naturally occurring particles in the water are used as measuring units.

In this note the oceanographic background for the development of the instrument is discussed and the measuring principle, the electronic equipment, and the field test carried out so far are presented. The project is a joint project between DISA Elektronik and the Institute of Physical Oceanography and has been sponsored by the Nordic University Group for Physical Oceanography and the Danish Natural Science Council.

OCEANOGRAPHIC BACKGROUND

In recent years a large interest in physical oceanography has focussed on the surface boundary layer, the benthic boundary layer, and internal mixing processes, in particular the mechanisms responsible for the vertical transfer of matter and momentums. Regions where vertical motion plays an important role, such as upwelling areas, are also being studied intensively. In all these areas of research the motion is highly complicated and there is a great need for instruments capable of measuring high frequency fluctuations, low velocities and with good spatial resolution.

Modern instrumentation has revealed that the motion as well as the temperature and salinity distributions in the sea are a great deal more complicated than was earlier expected. Especially the small-scale or even micro-scale vertical layering of the T, S-fields seems to be present in most areas of the sea beneath the near-surface region (e.g. Woods and Wiley 1972). It is quite clear from recent studies that the vertical mixing can be very weak, and that high-frequency, small-scale motion can play an important role in generating the mixing (e.g. Woods and Wiley 1972, Kullenberg 1971, 1974).

The few existing observations of the motion in the benthic boundary layer show that the motion there can be weak and of an intermittent nature (Wimbush and Munk 1968). Likewise the motion in the surface boundary layer can vary over a large range as regards velocity and turbulence intensity.

It is evident that not only the mean motion but in particular the fluctuations of all frequencies need to be observed together with the small-scale spatial variations of the motion, especially in the vertical direction. As a consequence great efforts have been devoted to the development of flow meters with the required properties. The conventional current meters are not capable of the required resolution and do not have the sensitivity and fast response. The most promising attempt so far appears to be the Acoustic Doppler current meter (Gytre 1971). The high potential of the Laser Doppler Anemometry technique used with great success in many laboratory studies and applications is evident. This technique relies on the Doppler shift of the frequency of the light scattered by particles in the flow. These particles can be naturally occurring or they can be injected on purpose in the stream. It is possible to utilize either the forward scattered or the backward scattered light. The primary problem in connection with an oceanographic application of this technique relates to the light scattering in the sea.

The light scattering in the sea is caused by the water itself, by the dissolved salts, and by the suspended matter. The particle scattering is by far the most important part of the total scattering. Only in very clear waters, as in the Sargasso Sea, is the molecular scattering important and then only for large scattering angles. The major part of the scattering is caused by particles larger than the wavelength of the scattered light, as is evident from the asymetrical form of the scattering function $\beta(\theta)$ (θ is the scattering angle measured from the incident beam; Jerlov 1968). About 50-60 % of the total scattering is found in the angular interval $0^{\circ} < \theta \leq 5^{\circ}$, and the ratio

$\beta(\theta)/\beta(90^\circ)$ covers a range of 10^4 (Kullenberg 1974a). The $\beta(\theta)$-function has a broad minimum around 100° scattering angle, and the scattering increases only slightly for larger angles. The scattering at an angle of 5° is 10^3–10^4 times stronger than the scattering at an angle of 170°–180°. This suggests that it is most promising to use the forward scattering mode in the Laser Doppler Anemometer. The solution using the backward scattered light is, however, more attractive from a practical point of view. Accordingly the present instrument is equipped with a detector unit for both forward and backward scattered light. The laser, a Spectra Physics He-Ne laser, is placed in the backward scattering unit. Both units are attached to a tube so that the whole system is very rigid.

MEASURING PRINCIPLE AND OPTICAL SYSTEM

The project was undertaken partly to test the feasibility of using the LDA-principle for the measurement of the small scale properties of sea currents. Therefore, we have stressed flexibility and interchangeability in the construction of the system in order to be able to test various LDA-modes as well as both back-scattering and forward scattering simultaneously.

The LDA is based on the detection of the Doppler shift of light scattered from small particles moving with the medium. This method has become feasible with the emergence of the laser as a practical and reliable light source. The good temporal and spatial coherence of the laser light allows the concentration of the light in a small volume, the measuring volume, and the subsequent detection of very small Doppler shifts relative to the original light frequency.

In the light detection itself we take advantage of the properties of optical heterodyne detection, in which two parallel beams of light are mixed on the photodetector. This way we are able to suppress beat signals from light scattered from regions outside the measuring volume. The detector current contains an a.c. component, which is the difference between the frequency of the two light beams entering the detector, i.e. the Doppler shift caused by the motion of the particles. We distinguish between different LDA-modes according to how we select the two beam entering the detector (Durst, Whitelaw 1971). In the present system we consider only the reference beam mode and the differential or fringe mode. In both cases the laser beam is split into two parallel beams in the transmitter section and focussed into a common focal volume. In the reference beam mode the photodetector is placed in one of the beams, the reference beam, and the mixing takes place between that beam and light scattered from the other beam in the direction of the reference beam. This mode gives high insensitivity to background light and allows the use of PIN-photo diodes.

In the differential or fringe mode the photodetector (which must be a photomultiplier due to a lower level of light) is placed symmetrically between the incident beams. This mode gives a superior signal-to-noise ratio in the case of only few scattering particles in the measuring volume at one time, and is the mode we have chosen for the field tests reported here. The frequency of the a.c. component from the detector is in both modes $f_D = (2|Vx|/\lambda)\sin(\theta/2)$, where λ is the wave length of the laser light in the water and θ is the angle in water between the two incident beams. Vx is the component of the velocity vector on a direction perpendicular to the bisector between the two incident beams and in the plane of the two beams. The numerical sign indicates that the sign of the velocity component is lost at the detection.

Since we are expecting to measure highly fluctuating and reversing flows, an initial frequency difference has been introduced between the two beams by means of a Bragg cell placed in each beam. Each Bragg cell shifts the laser beam frequency upwards by the amount $fo \pm fs/2)$, where fo= 40 MHz and fs = 250 kHz in this case. The result is a difference in frequency between the two beams entering the measuring volume of fs = 250 kHz. The detector current frequency is now $fd = |fs + fD|$,) where fD is now taken with the sign. Thus as long as $|fD| < fs$, we are able to measure the velocity component Vx with the sign.

The instrument consists of a transmitter-receiver section containing a spectra-Physics model 120 5 mW He-Ne laser, two Zenith model 40 Bragg cells, and for each beam lenses and prisms for directing and focusing the beams into the measuring volume. In addition the transmitter-receiver section contains an optical system, which through a 90 mm d. aperture collects the light back-scattered from the measuring volume, and an RCA model 70040 K photo-multiplier behind an adjustable pin-hole.

The module also contains laser power supply, PM power supply and a pre-amplifier, which matches the PM output to the land based electronics. Thus the transmitter-receiver section makes a complete submersible backscatter LDA-system only requiring a 12 V supply current and a signal cable.

By means of a rigid 90 mm d. by 2.50 m long boom the system may be extended with a forward scatter unit containing light collecting optics, pin-hole, and a photo-multiplier tube in a water tight housing.

In the present configuration, the distance between the measuring volume and the forward or back-scattered section is about 50 cm, the size of the measuring volume is about 0.5 mm diam. and 2 mm long, and the conversion factor between velocity and the Doppler frequency is 170 kHz per m/sec.

ELECTRONIC SIGNAL PROCESSING

Two methods have been considered for the signal processing of the Doppler signal: the frequency tracker if a continuos signal from many small particles is available and the LDA-counter if only distinct bursts generated by individual particles passing through the measuring volume are available.

The frequency tracker is essentially a servo-controlled narrowband filter, which tracks the instantaneous frequency of the Doppler signal (Deighton Sayle 1971). Although most frequency trackers today are protected against short "drop-out" periods of the input signal, they will not work well if on the average less than one particle is present in the measuring volume at a time. The advantage of the frequency tracker is its ability to detect signals of very low signal-to-noise ratio by using a very narrow filter. On the other hand there is a trade-off between filter bandwidth and speed of response (slew-rate).

The LDA-counter on the other hand is based on the detection of the frequency of an individual "Doppler burst". The bandwidth of this instrument may be high, but the signal-to-noise ratio of the burst must be high. This may mean a rather low data rate in systems using low power lasers, since many detected bursts may have too low signal-to-noise ratio to be accepted as a valid measurement by the counter validation circuit.

The equipment used for signal processing during the first field test was a DISA model 55L20 Doppler Signal Processor and a prototype DISA model 55L95 LDA-counter. The results of the test indicate that the signal-to-noise ratio of the back-scatter module may indeed be too low for the operation of either the tracker or the counter in a real-time mode. However, the counting system was able to give the mean value of the velocity by integrating over a period of several minutes. In the forward scatter operation both the frequency tracker and the LDA-counter would operate well. The tracker was operating with a bandwidth of 10 kHz corresponding to a small signal frequency response of about 180 Hz. Under the same conditions(a mean velocity of .1 - .2 m/sec) the counter was operating with a data rate of about 100 - 200 measurements per sec. Thus the scattering properties of costal seawater as we have encountered here are such that LDA-measurements are indeed feasible.

FIELD TEST

Apart from laboratory tests the instrument has been tested in a series of measurements at the Bornö Station in the Gullmar fjord. The Laser Doppler Anemometer (LDA) was suspended directly from the pier at Bornö. This arrangement was made so as to avoid disturbances from a moving platform. The depth which could be reached was, however, only 5 m. The primary objective of the field test was to investigate the feasibility of the instrument in coastal water with a fairly high content of particulate matter. The measurements should also be compared with conventional oceanographic observations.

It was established that the forward scattering mode is working excellently with an observation frequency in the range 10^2-10^3 Hz, making it possible to detect high frequency fluctuations. The mean velocity can also be obtained very accurately by integration over an optional number of measurements. Observations made close to the surface displayed quite clearly the oscillatory motion due to the action of small surface waves. The periods of the waves estimated from direct observations conform with the periods displayed in the registrations.

Several comparative measurements were made at depths of 1-3 m, integrating the data over a 2-minute period using both the LDA and a conventional propeller current meter (a Braystoke meter). The agreement between the two instruments is good. The difference, of the order 10 % for a mean current about 10 cm/sec, can probably be ascribed to the calibration uncertainties for the Braystoke meter.

The backward scattering signal was much more intermittent than the forward scattering signal. The measuring frequency was only of the order 1 Hz, implying that the high-frequency fluctuations of the motion could not be resolved. The mean current velocity could, however, be obtained satisfactorily.

CONCLUSIONS

It can be concluded that the Laser Doppler Anemometer can be used for oceanographic purposes, employing the forward scattering mode. The advantages with the LDA are primarily:

large velocity range, high sensitivity and quick response no calibration problems

no disturbances are introduced into the measuring volume of the flow

very high spatial resolution

These properties are of great interest in many important research applications.

The background scattering mode does not appear to be feasible at the present stage. More powerful lasers are required for this mode.

The technique needs to be tested in clear oceanic waters where the particle content is less than in the fjord water. The present results suggest, however, that the LDA can be used without loss of its required properties in most oceanic regions.

An important shortcoming of the present instrument is that only one component of the flow can be resolved. The next stage of the development is to include a second component and eventually it is hoped that a three-component instrument can be produced.

References

DURST, F. and J. H. WHITELAW (1971). Integrated optical units for Laser Anemometry. Joun.Phys.E: Scientific Instruments, 4, pp 804-808.

DEIGHTON, M. D. and E. A. SAYLE (1971). An electronic tracker for the continuous measurement of Doppler frequency from a Laser Anemometer. DISA Information, 12, pp 5-10.

GYTRE, T. (1971). An ultrasonic current meter. ICES, C.M.1971/C:24.

JERLOV, N. G. (1968). Optical Oceanography. Elsevier Oceanography Series, 194pp.

KULLENBERG, G. E. B. (1971). Vertical diffusion in shallow waters. Tellus 23, p 129.

KULLENBERG, G. E. B. (1974). An experimental and theoretical investigation of the turbulent diffusion in the upper regions of the sea. Rep.Inst.Phys.Oceanogr. 25, U. of Copenhagen, 250pp.

KULLENBERG, G. E. B. (1974a). Observed and computed scattering functions. In Optical Aspects of Oceanography, eds. Jerlov, N. G. and Steeman Nielsen, E., Academic Press, London and New York 1974.

WIMBUSH, M. and W. H. MUNK (1968). The benthic boundary layer. In The Sea IV, ed. A. Maxwell, p 731, McGraw Hill, London 1972.

WOODS, J. D. and R. L. Wiley (1972). Billow turbulence and ocean microstructure. Deep-Sea Res. 19, p 87.