Vertical Profiling of Velocity Microstructure

Thomas R. Osborn

Institute of Oceanography, University of British Columbia, Vancouver, Canada

(Manuscript received 2 July 1973, in revised form 28 August 1973)

ABSTRACT

A free-fall oceanographic instrument capable of producing direct estimates of the local rate of energy dissipation has been developed. The velocity sensor in an adaptation of the two-component airfoil probe to the oceanic environment. Spectra of the velocity data show that the instrument achieves complete spatial resolution of the vertical current shear and there is no apparent contamination of the signal from vibrations or body motions in the frequency range contributing to the variance of the shear. The energy dissipation is proportional to the variance of the vertical shear. Thus, it is possible to estimate the energy dissipation without comparing the velocity spectra to any "universal curve."

1. Introduction

As oceanographic instruments improved in the postwar period, large fluctuations in the vertical and horizontal distributions of temperature and salinity in the ocean were found. These fluctuations have come to be called fine-structure or microstructure.

The study of oceanic microstructure is really a study of oceanic turbulence and mixing. The source of the turbulent energy and the mechanisms of extracting the energy must be determined. It may then be possible to understand the effect of the turbulence on the temperature and salinity profiles.

Observations and photographs by Woods and Fosberry (1967) in the thermocline off Malta indicate that shear instability is a source of turbulent energy. A necessary criterion for the growth of an infinitesimal shear instability is

$$\mathrm{Ri}=-\frac{g}{\rho}\frac{\partial\rho}{\partial z}\Big/\left(\frac{\partial U}{\partial z}\right)^2<\frac{1}{4}. \qquad (1)$$

In order to evaluate the Richardson number it is necessary to know the vertical component of the density gradient and the vertical current shear. The vertical profile of the density can be calculated from vertical profiles of the temperature and electrical conductivity. Techniques for measuring these parameters are in the literature (e.g., Osborn and Cox, 1972; Gregg and Cox, 1972). Simpson (1972) describes a free-fall instrument which profiles the horizontal velocity fluctuations by sensing the motion of a neutrally buoyant vane. Neither the calibration technique nor the response of the vane to the fluctuations in the horizontal velocity were discussed, but the author states that the vertical resolution is on the order of the vane size, 30 cm. However, the dye studies of Woods and Fosberry (1967) indicate that the shear is concentrated into regions on the order of 10 cm thick.

A quantitative study of the roles of shear instability in generating oceanic microstructure requires detailed vertical profiles of the shear of the horizontal velocity. This paper describes an instrument capable of completely resolving a vertical profile of the vertical shear. From the variance of the vertical shear one can estimate the turbulent energy dissipation.

2. Instrument

As the instrument falls freely through the water at approximately 25 cm sec^{-1}, six signals are telemetered to the surface: temperature, its time derivative, pressure, rotation rate of the instrument, and two signals representing the horizontal velocity fluctuations. The electronics are mounted inside a 46-cm diameter polar access glass sphere produced by Corning Glass Works (Fig. 1). This sphere is mounted between two collars of 36 cm diameter polyvinyl chloride (PVC) pipe held together by ribs of PVC. On top of this somewhat cylindrical main body is attached a circular plate which holds the wings, flashing light, radio transmitter and expendable wire length (XWL). Below the glass sphere an aluminum tube 1 m long holds the velocity probe, thermistor, release mechanisms and weights. The top and bottom of the main body of the instrument are streamlined by plexiglas hemispheres 33 cm in diameter. The weight of the instrument is ~40 kg.

Variations in the horizontal velocity components are sensed with an airfoil type probe (Fig. 2) described by Siddon (1965, 1971a, b). The probe tip is an axisymmetric solid of revolution aligned with the axis of the freely falling body. Variations u' in the horizontal velocity represent a fluctuating angle of attack of the total velocity vector thereby causing a fluctuating lift

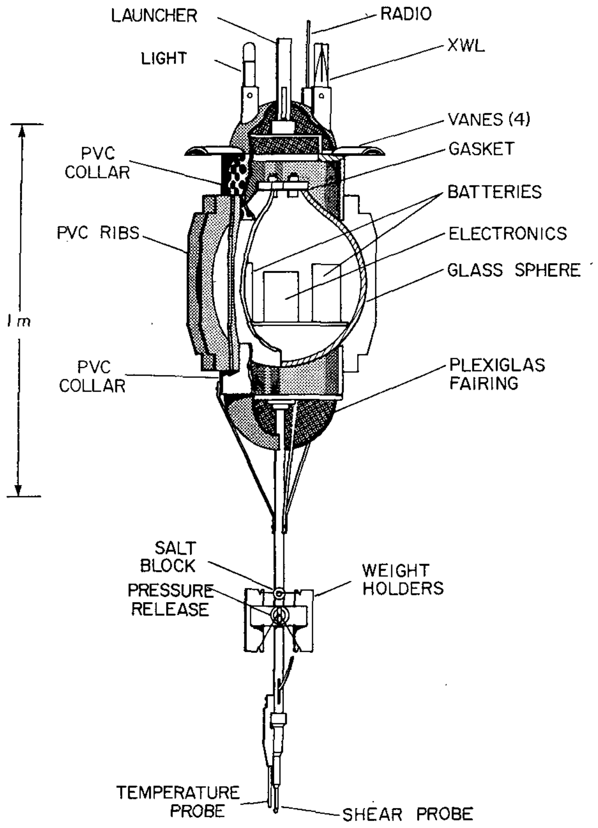

FIG. 1. Schematic diagram of temperature and velocity profiling instrument.

force on the probe tip. Embedded in the probe tip are two piezoceramic Bimorph beams from a ceramic phonograph cartridge which sense the components of the lift force into two perpendicular directions. To reduce the effect of the lead wires, two preamplifiers, one for each velocity component, are situated directly behind the probe in a small pressure case.

The oceanic measurements require an adaptation of Siddon's probe that has greater sensitivity and can operate at pressures on the order of 20 atm (=200 m depth). The probe, as far back as the preamplifier, is filled with epoxy. The epoxy tip is molded in place from the same epoxy, thereby waterproofing all the electrical contacts. We routinely operate to a depth of 230 m with no leakage. Tests in a pressure chamber showed the probe to be insensitive to changes in ambient pressure, even sudden changes on the order of 2 atm.

Sufficient sensitivity was finally achieved by using a urethene based epoxy with a hardness specification of 45 on the Shore A scale. An identical tip moulded from an epoxy with Shore A hardness of 70 is 60% less sensitive. Unfortunately, since most urethene based epoxies deteriorate in water, the probes have a lifetime in water on the order of 10 hr. Attempts to manufacture the probes with a urethane based epoxy that is insensitive to water look promising.

For calibration the probe is situated in the flow from a $\frac{1}{2}$ inch diameter nozzle inclined at an angle of 5° to the axis of rotation. The nozzle is rotated by a small motor and the output is displayed on an oscilloscope as a Lissajou figure to determine the sensitivity and to check the orthogonality of the two channels. On most probes the two channels are perpendicular to ±5° which is the limit at which we can judge the orthogonality. The beams are mounted in a jig while being epoxied to the support and wire leads in order to make the channels orthogonal and increase the reproducibility of the manufacturing process.

Since the device is responding to the lift force the output voltage is proportional to the angle of attack and the mean velocity squared, i.e.,

$$V \approx S(\tfrac{1}{2}\rho\bar{u}^2)\sin\alpha, \tag{2}$$

where V is the output voltage of the preamplifier, S a calibration constant, $\bar{u}$ the mean velocity along the central axis of the probe, and $\sin\alpha$ can be approximated by u'/u where u' is the fluctuating horizontal velocity. Calibrations of the instrument give a value of S as 4×10^{-3} V cm sec^2 gm^{-1}, with an estimated error of ±15%. The resolution is equivalent to 0.1 cm sec^{-1} at a fallspeed of 25 cm sec^{-1}.

The sensitivity of the two orthogonal beams is within a few percent and the value of S varies less than 3% for mean velocities of 100 and 145 cm sec^{-1}. Although the instrument falls at about 25 cm sec^{-1}, calibrations are performed at these high speeds because the present calibrating device will not operate properly with the slower water velocities.

The piezoceramic beams are inherently ac devices: with the present preamplifier design the low-frequency cutoff (3-db point) is 5.6×10^{-2} Hz. The value is determined from measured values of the circuit elements. The signals from the preamplifiers go to the glass sphere where, due to low-frequency drift in the preamplifiers, there is another low-frequency filter (3-db point at 5×10^{-2} Hz) before the final amplification. With the present calibrating device we have found that the frequency response of the probe is uniform from below 2 Hz to 30 Hz. The present calibrator will not operate properly outside this frequency range. The probe response is assumed to be uniform from 2 Hz down to the point where the aforementioned high-pass filters affect the response. The response above 30 Hz is believed to be uniform to beyond 100 Hz, since the resonant frequency of the tip is between 1 and 2 kHz. The resonance is well damped. A new calibrator is being designed which will permit calibration at lower water speeds and over a greater frequency range. The initial response of the probe to a step change in temperature at a fallspeed of 25 cm sec^{-1} is a drift of 6 cm sec^{-1} (C°)$^{-1}$ in about 3 sec. The response is slow due to the large thermal mass of the nosepiece.

Temperature is sensed with a Veco 43A401C microbead thermistor which is glass coated and has a nominal diameter of 0.013 cm. It is mounted 2 cm from the velocity probe and maximum exposure to the flow is achieved by suspending the bead from its 0.0018 cm diameter wire leads which extend on opposite sides of the bead.

The thermistor bead, wire leads and mounts are coated with 0.0016 cm of Paralene-C to provide electrical insulation from the sea water. The effect of the coating can be estimated from the data of Balko and Berger (1968) which indicates that the response time (50% amplitude response) of a 0.0005-cm thick copper-constantan thermocouple would be increased from 0.2 msec to 4 msec when coated with 0.0016 cm of Paralene-C. Comparison tests of these coated micro-beads with a platinum film indicate a time constant on the order of 15 msec. Plate thermistors, 1 mm square and 0.004 mm thick, coated with Paralene-C but not coated with glass, were also tested. The plates had a slower response than the micro-beads, probably due to the difference in the boundary layers.

The micro-bead thermistor forms one arm of a resistance bridge. A multiple pole switch in another arm of the bridge is used to set the resistance of the null point. The signal from the bridge is amplified to provide the temperature data. Gain of the temperature amplifier is selected with another switch so that seasonal changes in the total temperature range can be accommodated easily. This circuit is calibrated by substituting a series of known resistances for the thermistor and noting the output voltage.

The signal from the bridge is also differentiated. The differentiation extends to 35 Hz, higher frequencies being suppressed to reduce noise. The differentiation circuit is calibrated using the analytical expression for their response. The calculated response to a step change in input resistance as well as calculated gain vs frequency values compare favorably to the measured values. Resolution is on the order of 4×10^{-4}C cm^{-1} and the error is estimated at ±10%.

The thermistors are assumed to have the same functional response to small changes in temperature as they do to large temperature changes. Thus, the resistance vs temperature properties of the thermistors are known from water bath calibrations in which their resistance is determined for five temperatures between 6 and 15C.

The fallspeed is determined from a record of pressure vs time sensed with a 0–500 psia vibrotron pressure transducer mounted inside the glass sphere. Values for the fallspeed are usually in the 20–25 cm sec^{-1} range.

The instrument rotates as it descends through the water column. In the initial design the rotation was necessary to produce a lift force. It was desirable to have a slow rate of descent for the sensors to give maximum resolution and a large excess weight so that changes in water density and displaced volume of the instrument body made little difference on the fallspeed. Also, as the instrument body rotated, a thermistor mounted off the central axis had a horizontal component of velocity thus sampling the horizontal as well as the vertical microstructure. This instrument has been operated with an outboard thermistor but for the operation described in this paper the mount was removed to make the instrument more symmetrical and therefore less likely to wobble.

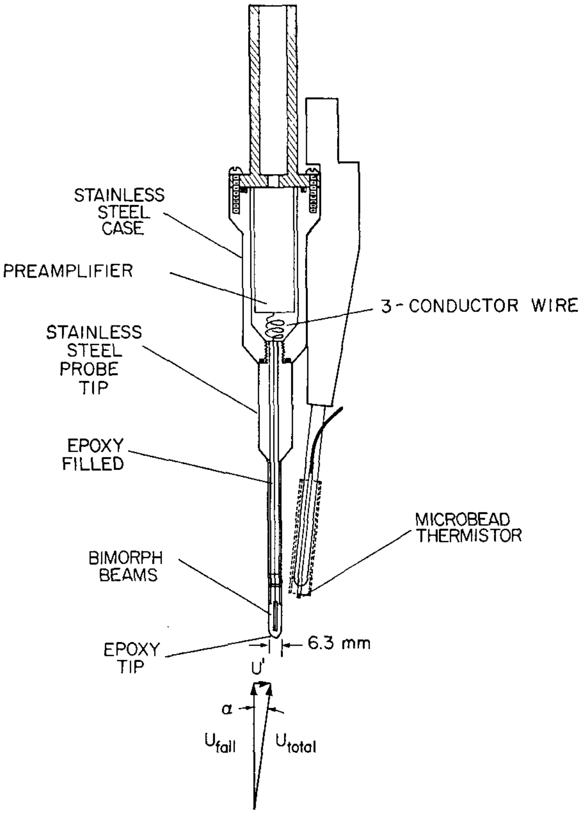

FIG. 2. Diagram of velocity and temperature probes. Vectors show that a change in the horizontal velocity relative to the probe tip appears as a change in the angle of attack of the overall velocity vector.

Experience had shown that the instrument must rotate very slowly, with a period of about ~20 sec per revolution, for the velocity data to be interpretable. With the short wings used the lift force is small, so the instrument is adjusted to be only slightly heavier (500 gm) than the displaced water.

It is still desirable to rotate the instrument in order to determine the orientation of the velocity sensors. Rotation is monitored as a function of the time with a 3000 turn coil wrapped around a permeable iron core, the coil producing a sinusoidal voltage as the instrument rotates through the earth's magnetic field. The orientation of the coil relative to the Bimorph beams is determined in the laboratory.

The temperature, its time derivatives, and the two velocity signals are converted from voltages to FM signals using voltage-controlled oscillators operating on four standard IRIG frequencies. The vibrotron is

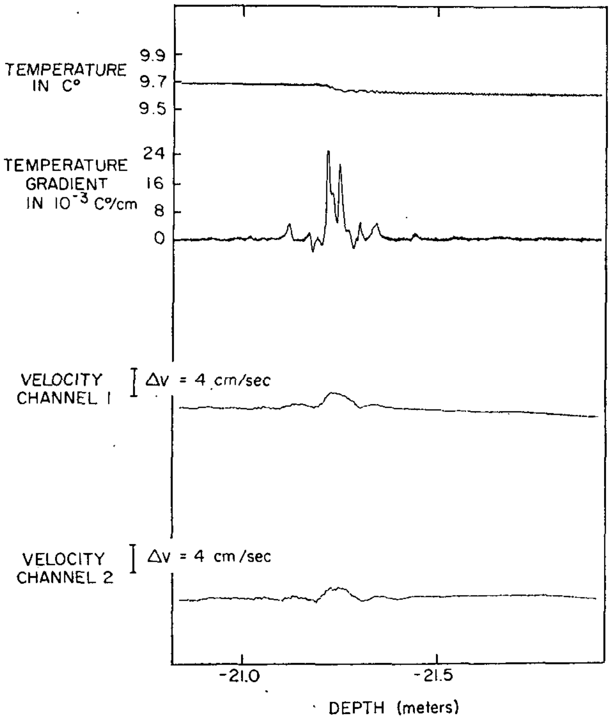

FIG. 3. Data collected on 5 July 1972 in Howe Sound near Vancouver, British Columbia.

an FM device operating on a standard IRIG channel. The five FM signals are multiplexed together and transmitted from the instrument to the support vessel along a Sippican Expendable Wire Length.

The Sippican Expendable Wire Length is essentially a Sippican Expendable Bathythermograph without a thermistor or nose weight. It consists of two spools of very fine two-conductor wire (39 gauge), one spool being attached to the instrument and the other remaining on the support vessel. The wire is free spooling, i.e., it comes off the spool like line off a spinning reel, and causes essentially no drag on the instrument as it falls through the water. In the frequency range we use, there is large capacitive coupling between the two conductors so sea water is used as the signal return path.

The rotation rate is telemetered directly up the wire as a slow variation on the offset voltage of the wire. An operational amplifier on the surface ship presents a high impedance load on the wire. The FM signals are recorded directly following a high-pass filter on one channel of a Hewlett Packard 3960 B tape recorder while the rotation rate passes via a low pass filter to be recorded on another channel, and a stable 14.5 kHz signal is recorded on a third channel to provide tape speed compensation.

To operate the instrument, the temperature bridge is adjusted for the expected temperature range as observed by an STD. The instrument is assembled as seen in Fig. 1. The probe cover on the thermistors is removed and the instrument lowered into the water. It is held at the surface while the output is examined. During operation, the signals are decoded by a set of discriminators and displayed on a 6-channel recorder in real time. As soon as the instrument appears to be operating properly it is released. The advantage of telemetering the data to the ship, as opposed to recording the data inside the instrument, is the real-time presentation of the data. When something goes wrong—the instrument hits bottom or becomes neutrally buoyant—we can diagnose the problem quickly. Since the wire usually remains connected while the instrument surfaces, we can tell when it is on the surface in the event of a radio failure.

The instrument descends until the weights are released by a Richardson-type, stretched-pin release or by the dissolving of a salt block which acts as a backup release. Upon return to the surface, the instrument is located with the aid of the flashing light and radio transmitter. An STD profile is taken immediately after each successful drop.

3. Example of measurements

Fig. 3 shows temperature, temperature gradient and velocity data from the instrument. The interface revealed by the data is sufficiently thin that we can neglect the rotation of the instrument for the following discussion. One second of time represents 23 cm in depth. The interface consists of a temperature change of 0.06C. The temperature gradient profile shows the temperature decrease to be concentrated into two thin regions with gradients three times larger than the mean gradient for the interface and much larger than the mean gradient for the region. The velocity component profiles show a bulge at the interface indicating a 9-cm thick layer of water moving at a maximum velocity of 2.8 cm sec^{-1} relative to the instrument. The velocity relative to each of the two perpendicular sensing elements has a maximum value of 2 cm sec^{-1}. Due to the size and time scale of these velocity profiles, the contribution to the signal from the thermal "shock" of the airfoil probe is less than 10% of the peak amplitude. The maximum value of the shear is 0.7 sec^{-1}, considerably larger than values reported by Simpson (1972) or Woods and Fosberry (1967).

Fig. 4 displays the data for an 8 m thick region. The fallspeed was 20.7 ± 0.5 cm sec^{-1} and the rotation period 26 ± 0.3 sec. There is a turbulent region 5 m thick wherein both the velocity traces and the temperature gradient show intense activity. Some activity is seen in the water above and below. These data show a very complicated situation, the understanding of which would require some information about the horizontal extent of the turbulent region. Note that the instrument makes more than one complete rotation while traversing the region shown.

Fig. 5 shows the spectrum of the data from velocity channel 1 in Fig. 4. Temporal frequency times the

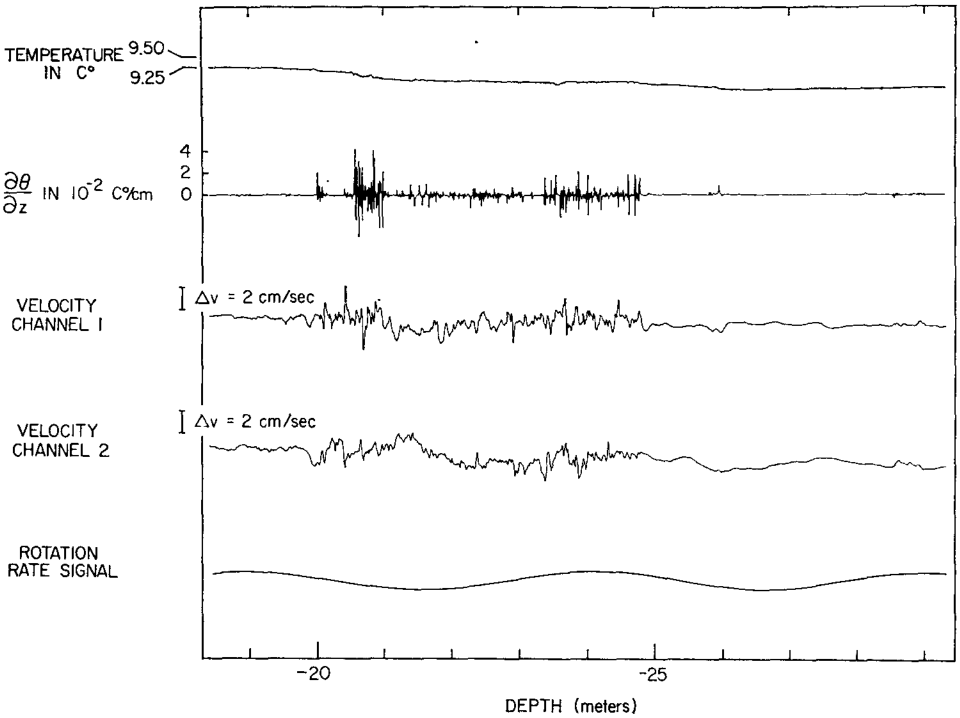

Fig. 4. Data collected 2 August 1972 in Howe Sound.

spectral density of velocity is plotted against the logarithm of the temporal frequency. The plot is variance-preserving in the sense that the areas under the curve are proportional to the variance. Frequency times the spectral density of the vertical current shear, which is frequency squared times the velocity spectrum, is also plotted. The rise in the shear spectrum above 14 Hz is due to noise.

The velocity data are subject to low-frequency contamination due to pendulum-like oscillations of the instrument body. Examination of many spectra and the original data traces indicate that some of the energy in the frequency bands below 0.1 Hz is from body motions. If all of the energy below 0.1 Hz in Fig. 5 were due to oscillations of the instrument housing, the amplitude of the oscillation would be on the

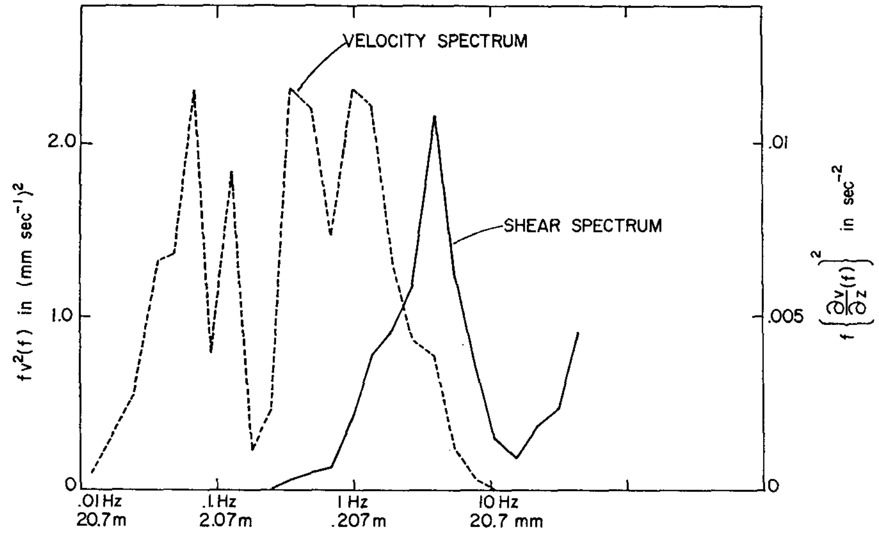

Fig. 5. Spectrum of data from velocity channel 1 shown in Fig. 4 taken at a fall-speed of 20.7 cm sec^{-1}. The spectrum of the shear is frequency squared times the velocity spectrum.

order of 0.5°. That value is comparable to the tilt one would calculate for the instrument situated in a shear layer with a velocity change of 10 cm sec^{-1}. The spectrum of the shear shows that this low-frequency energy does not contribute to the estimate of the variances of the vertical current shear.

High-frequency contamination of the velocity data can come from the acceleration sensitivity of the probe. Vibration of the probe tip places an inertial load on the Bimorph beams which is proportional to the amplitude and frequency of the vibration and the mass of the epoxy tip. For this particular instrument housing the vibrations are between 15.8 and 23.7 Hz with the peak at 19 Hz. Since the vertical shear is the time derivative of the horizontal velocity as seen by the falling probe tip, these high-frequency vibrations can contribute significantly to an estimate of the variance of the vertical shear. However, the bulk of the variance in this spectrum and other spectra is between 1 and 10 Hz, with the peak near 5 Hz well away from the natural modes of vibration in the body.

A new instrument body has been built to ameliorate many of the difficulties found in the present design. The instrument housing is a long aluminum tube [similar to that of Simpson (1972)], in order to increase the stability of the free-fall body, to reduce oscillation of the body due to the eddies that are shed off the uppermost part of the housing, and to provide sufficient buoyancy. Using an inclinometer produced by J. Filloux, an aluminum cylinder 14 cm in diameter, 1.5 m in length with an excess weight of 300 gm and falling at 30 cm sec^{-1} was seen to deviate from the vertical by less than 0.25° with flat and caps. When the ends of the tube were faired with plastic ellipsoids the maximum deviation from the vertical decreased to below 0.1°. The velocity data are differentiated in the instrument thus giving the velocity shear directly and reducing the noise level in the shear spectra at high frequencies.

To determine if the present instrument has completely resolved the vertical current shear we must be sure the response has not been limited. From the calibration data we know the temporal response of the probe extends at least to 30 Hz which is well beyond the 5-Hz peak of the oceanic current shear. There is also a spatial limitation of the probe. From Siddon's (1971a) work it appears that the response starts to fall off slowly at a wavelength four times the size of the probe. The lift force is concentrated in the region where the probe is changing cross sectional area, which, for this probe, is at a length of about one diameter. For the spectra shown in Fig. 5 the sensitivity of the probe tip starts to fall off above 8 Hz but the spectral level of the shear is already down by a factor of 4; thus, the loss in sensitivity would not appear to have a large effect upon the estimate of the variance.

There are two solutions to this problem. The first is to make smaller probes; the second is to determine the detailed nature of the probe's response to fluctuations that are of comparable size to the probe. As mentioned before, Siddon did not find a rapid loss in sensitivity but his work was at frequencies approaching the resonant frequency and there may have been an amplification of the response due to the nearby resonance.

In isotropic turbulence the energy dissipated by viscosity can be estimated (Hinze, 1959) from

$$\epsilon=\frac{15}{2}\nu\left(\frac{\partial u}{\partial z}\right)^2, \qquad (3)$$

where ν is the coefficient of kinematic viscosity, ϵ the viscous energy dissipation, and u is one horizontal component of the velocity. Using this formula the energy dissipation for the shear spectrum if Fig. 5 is 3×10^{-4} erg cm^{-3} sec^{-1}.

There is evidence that the turbulence in the ocean is not generally isotropic (Grant *et al.*, 1968: Nasmyth, 1970) and much work must be done to determine the three-dimensional nature of oceanic turbulence. One can argue that the vertical shears are a significant part of the energy dissipation and if the turbulence is not isotropic it will change the numerical coefficient from 7.5 to a lower value which will still be greater than 2. The turbulence is more likely to be isotropic where ϵ is large, on the order of 10^{-3} erg cm^{-3} sec^{-1} or more, in which case the rms shear is $\sim10^{-1}$ sec^{-1}. When the energy dissipation is low the isotropic formula probably overestimates the dissipation rate. It might, therefore, be appropriate to change the factor 7.5 to 5±2.5. There is an increasing belief that it is the catastrophic events and not the mean situation that are important in turbulent transfer in the ocean. Therefore, we are more interested in the regions with high values of ϵ than low values.

In conclusion, the airfoil probe combined with a free-fall instrument housing is ideal for studying the vertical current shear in the ocean. The resolution and sensitivity are sufficient to provide estimates of the energy dissipation directly.

Acknowledgments. I am grateful to R. Wards for his work on the electronics and D. English for making the probes. I would also like to thank Dr. T. Siddon for his generous help and Dr. P. Nasmyth for providing facilities to test the thermistors. This work was supported by the North Atlantic Treaty Organization, Defence Research Board of Canada, and the Department of the Environment through the Marine Sciences Directorate Pacific Region, and the Marine Ecology Laboratory, Bedford Institute of Oceanography.

REFERENCES

Balko, Bohdan, and Robert L. Berger, 1968: Measurements and computation of thermojunction response times in the submillisecond range. *Rev. Sci. Instr.*, **39**, 498–503.

Grant, H. L., B. A. Hughes, W. M. Vogeland and A. Molliet, 1968: The spectrum of temperature fluctuations in turbulent flow. *J. Fluid. Mech.*, **34**, 423–442.

Gregg, M. C., and C. S. Cox, 1972: The vertical microstructure of temperature and salinity. *Deep-Sea Res.*, **19**, 355–376.

Hinze, J. O., 1959: *Turbulence*. New York, McGraw-Hill, 586 pp.

Nasmyth, P. W., 1970: Oceanic turbulence. PhD. disseration, University of British Columbia.

Osborn, T. R., and C. S. Cox, 1972: Oceanic fine-structure. *Geophys. Fluid Dyn.*, **3**, 321–345.

Siddon, Thomas E., 1965: A turbulence probe using aerodynamic lift. Tech. Note 88, Institute for Aerospace Studies, University of Toronto, 14 pp.

——, 1971a: A minature turbulence gauge utilizing aerodynamic life. *Rev. Sci. Instr.*, **42**, 653–656.

——, 1971b: A new type of turbulence gauge for use in liquids. Preprint of paper presented Symposium on Flow, Pittsburgh, Inst. Soc. Amer., 11 pp.

Simpson, J. H., 1972: A free-fall probe for the measurement of velocity microstructure. *Deep-Sea Res.*, **19**, 331–336.

Woods, J. D., and G. G. Fosberry, 1967: The structure of the thermocline. Report 1966–1967, Underwater Association, 5–18.