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Albert J. Williams, 3rd

Eulerian Current Measurements and the Acoustic Current Meter

Eulerian current measurements are those made from a fixed array. They represent the flow field rather than particle trajectories. Fluid mechanics is formulated as a field theory so Eulerian measurements are natural to it. However it is not possible to measure the flow field continuously in space or time and one must be wise in sampling the physical variable, the current field. Even not counting deviations of the sensor from ideal behavior, variability in the flow due to waves and eddies, and spatial structure due to fronts can alias the measurements if they are not frequent enough or close enough together.

In the 1960's, the moored current meter array program got underway to measure transport in the Gulf Stream and other major water movements. Savonius rotors for speed and vanes for direction were used to sense the current and the number of revolutions and the vane direction with respect to the case. These measurements and the case direction with respect to north were recorded every 15 minutes. Surface floats were used because acoustic command releases were unreliable and subsurface moorings would have been hard to recover. By the end of the decade, two problems were discovered: the currents varied too much to trust the spot direction measurement to be representative and the surface float introduced motion to the mooring that the Savonius rotor rectified and over-read. Near the surface, the inability of the vane to follow wave reversals led to large errors in measurement. However these problems went away when the moorings went subsurface in the 1970's with improved releases.

At the end of the 1960's, it was recognized that the new low power digital integrated circuits would permit vector averaging wherein the vane and compass would be read every time a rotor turned a fixed distance. The motion could than be decomposed into north and east flows.

Toward the end of the 1970's, interest turned to the surface layer where air-sea interaction is important. To correctly average wave motions, the Davis-Weller fan blade current meter was developed. This instrument had a good cosine response, low inertia, and linear response. Thus it could even track reversing flows in waves. Two pairs of fans at right angles to one another are mounted with their axes of rotation perpendicular to a shaft extending from one endcap. They are far from the disturbance of the instrument case and sufficiently separated to avoid disturbing one another. Each pair of fans has a good cosine response (the ability to respond to the component of flow along the rotation axis) and is linear to a low threshold.

The VMCM, as the fan current meter is called, has replaced the older VACM, the vector averaging Savonius rotor current meter, for all mechanical flow measurements where there is vertical motion. However for measurements near the bottom boundary, the electromagnetic current meter, or EMCM, is sometimes used. This sensor depends on the electric field induced in a conductor moving in a magnetic field. The electric field is mutually perpendicular to the magnetic field and the current. A coil in a sphere or oblate spheroid produces the magnetic field used in the measurement. There are sets of electrodes to sense the electric field around the equator of the shape. Two components of flow can be measured with a single coil and three can be measured with a second coil at right angles to the first. The magnetic field is chopped and the electric potential is synchronously detected. Large potential offsets occur with even the best electrodes and a DC measurement is impossible. Even with a chopped technique, asymmetries in the field or electrodes produce a slight zero offset, the error in defining zero flow. Perhaps more importantly, the sensed volume of EM sensor is within the boundary layer of the sphere or spheroid, a complicated region to measure flow and one with hysteresis if the flow is accelerated.

The coil takes a lot of power compared to the mechanical current meters and efforts to reduce the power degrade the sensitivity. However the freedom from moving parts and the small size of the sensor recommend it and it is the commercial sensor of choice for boundary layer measurements and measurements in heavy fouling environments.

All the current sensors mentioned are physically intrusive and must disturb the flow. It would be better to measure the flow remotely, particularly if the flow might reverse and sweep back over the sensor after being disturbed. Acoustic and optical sensors permit more or less unobstructed flow measurements. There has also been one EM measurement with a Helmoltz coil to generate the field that is less obstructing to the flow but uses a lot of power. The remote measurements fall into two classes, scattering and transmission.

Scattering sensors, the acoustic Doppler current meter and the laser Doppler velocimeter, depend on scatterers naturally occurring in the water, unlike the case for laboratory instruments which depend on artificial seeding of the flow with latex spheres. These scatterers can be a troublesome part of the problem. In the case of acoustic Doppler current meters, the scatterers appear to be small bubbles, thermal inhomogenieties, and small organisms. The LDV depends on mineral or organic particles with a size of 10 to 20 microns. If there is no scatterer of the right size in the volume, the signal drops out and this is a serious problem for a frequency tracker. While this is a dominant problem for the LDV, the opposite problem occurs for the acoustic Doppler velocimeter. There, the scattering volume is so large that many different velocities may be present at once, giving a spread of frequencies in the received signal.

Since 1990, the Acoustic Doppler Current Profiler (ADCP) has become a dominant current meter in coastal and even deep-sea moorings. First used on ships in a downward looking mode, it now is bottom mounted in trawler proof cages and on subsurface moorings looking nearly to the surface. A recent modification has permitted the ADCP looking up to measure wave directional spectra. The range is order 100 meters at 300 kHz acoustic pulse frequency with 1-meter resolution and order 300-meter range at 150 kHz. In 1994, broadband ADCPs became available with coded transmissions that permitted more than one pulse to be in the water at a time, breaking a previous range-repetition rate limitation. Now a number of manufacturers are producing competing ADCPs, generally broadband, to capture the mass market of current profiling.

The acoustic Doppler technique has also been adapted to compete with a former LDV niche as the Acoustic Doppler Velocimeter (ADV). This instrument is bistatic, meaning the transmitting beam is crossed with a receiving beam and the measurement volume is defined by the beam intersections. There is no range ambiguity (unless a reflection from a surface puts acoustic energy back in the measurement volume) so the velocity acquisitions can be made very rapidly, giving many measurements that can be averaged to bring the velocity uncertainty down to an acceptable value, even for turbulence measurements.

In 2003, there are several serious contenders for a moored acoustic Doppler current meter. The Aanderaa RCM9 and RCM11 use four beams from a small diameter cylinder in line with the mooring looking out in four horizontal directions. The RCM11 rejects the downstream axis in determining the 2-D flow. SonTek and Nortek also produce a moored version of their ADV for replacement of the VACM and RCM5 rotor vane instruments. These are being tested and have acquired a small following.

Acoustic travel time current meters depend on the difference in travel time for propagation of sound in opposite directions to measure the component of flow along the acoustic axis. The group velocity of sound through the water plus the speed of the water with respect to the sensors determines the travel time of the pulse.

$$t_1=d/c-v$$
$$t_2=d/c+v$$
$$dt=2dv/c^2$$

where d=distance between transducers,
c=phase speed of sound in water, equal to group velocity because water is non-dispersive for sound,
$v=\mathbf{v}*\mathbf{d}/d$, the component of velocity along the path.

Eddies smaller than the sensor volume are averaged over because the effect of one side of the eddy is canceled by that of the other side.

The sample rate of the volume-averaging sensor is set by the need to sample twice for the shortest time an eddy with the characteristic size of the sensor is advected through the sensor volume. We make the frozen field hypothesis in which the changes in the turbulent eddies are assumed to be small in the time it takes to advect them past a point. The smallest eddy that can be resolved by the sensor has a diameter d and at an advection velocity V, a transit time d/V, requiring a minimum sample rate 2V/d where V is the maximum expected velocity. The penalty for failing to do this is that spatially resolved but under sampled eddies will contribute energy to a lower wave number part of the spectrum and alias the true spectrum. If there is no interest in eddies at that small a scale, a larger sensor volume could be used or extra samples could be taken and averaged before recording.

A puzzle concerns the averaging length of the acoustic travel-time sensor. The turbulence spectrum would be expected to start to fall faster than -5/3 at the wavenumber equivalent to the pathlength. A slope of -3 is predicted by one model after the wavenumber exceeds the reciprocal of the pathlength. However the observation is that the spectrum continues to fall at -5/3 at least out to the scale of the beam width and possibly even beyond. In fact, acoustic travel-time current sensors seem to resolve as high a wavenumber in turbulent flow as any sensor including LDV.

Either pulses or continuous wave signals can be used to measure the travel time. If continuous waves are used, phase measurements rather than pulse arrival times are used. The measurement of phase can be done quite precisely and at lower power because it is inherently a slower measurement, averaged over many cycles. This is the technique used in the FSI acoustic current meter (Neil Brown design). If the velocity is great enough to shift the phase more than 180^o an ambiguity arises which can be removed by trading an infinite wave train for a short burst and getting close to the right answer from the travel time of the burst. The advantages of the cw burst phase measurement are lower power and lower impedance resulting from transformer coupling.

Power however is less important than the total energy needed to make a measurement and the more power hungry technique of determining the arrival time of a pulse precisely can be traded off with the very short time required to make the measurement. For example, fifty measurements can be made with the pulse detection method in the time it takes to make one phase measurement. Since each measurement stands alone and no history of phase is used in the measurement, each sensor can be multiplexed for only a brief time to the detector and many acoustic axes can be measured with no more energy than a single-phase measurement. The benefit can only be realized if there are many axes to measure, otherwise all the energy saved will be lost in turning the detector on and off.

As an aside, it can be noted that the reason fast things take more power all other things being equal is that capacitance in circuits is approximately fixed by the physical dimensions of semiconductor junctions and the only way to charge them rapidly is to lower the resistance of the series gates and circuits and increase the current. Improvements in solid state devices include decreasing the size of junctions, which improves their frequency response at a given power.

While acoustic travel time devices to measure current have the advantages of physical averaging, continuous signals not subject to dropout, and reduced flow disturbance due to their minimum structure, they have the problem of uncertain zero point calibration. Being linear through zero velocity, nothing distinguishes the origin. Instead, the zero point must be determined by lab calibration. Offsets in measurements can best be determined and corrected for by the method of reversals. Ideally, the acoustic current meter could be rotated 180^o in the flow and the measurement repeated. Subtracting the two would cancel the offset and double the signal. This is impractical to do in most cases but it is possible to electrically reverse the connection of the transducers to the rest of the circuit by multiplexing them with a reversing connection.

This brings us to BASS, an acoustic current meter array for measuring turbulent fluctuations in the boundary layer. The benthic acoustic stress sensor multiplexes four acoustic axes on each of six sensors to a single pair of time delay detectors. Each pair of axes is swapped to minimize sensitivity to zero point drift. Incidentally the board count and power are also reduced. The only penalty is difficulty in keeping the impedance low through the multiplexors. BASS illustrates the parameters of an instrument design fairly well. The volume of the acoustic current sensor is the first filter on the physical environment and restricts both the scale of the physical variable that can be studied and the wave number that must be sampled to avoid aliasing. Second, the sample rate can be chosen to prevent under sampling with an assumed maximum current. Third, substitution (in this case reversal) is used to minimize the effects of zero point drift. Finally, limitations of electrical energy and data storage capacity are present to make the choice of data rates and speed of measurement critical.

BASS has seen a diversity of its uses to include an acoustic vorticity meter and a wave boundary layer sensor named the BASS Rake from its tines. The vorticity meter was first thought of to measure the shear in the surface boundary layer in the presence of waves. The large velocity of waves makes small errors leak into apparent shear. But the waves in an unstratified region, the surface mixed layer, are irrotational so have zero vorticity. The three-axis measurement of vorticity can theoretically reject wave velocities retaining only true shear. The BASS Rake concentrates the acoustic axes of a BASS current meter array into horizontal planes very near the bottom, the region where the wave boundary layer may exist. Ultimately the number of transducers in this region may become very large while the transducer size becomes quite small to resolve velocity variations over millimeters. This requires a different switching scheme with low impedance switches to multiplex the receiver to many transducers.

A single sensor BASS has been designed to fill the low cost requirement for a moored current meter that could be deployed in a large array, up to 100 instruments to study for example, benthic weather. Originally conceived as a modular sensor for inclusion in other instrument suites, it is named MAVS for Modular Acoustic Velocity Sensor. It is a three axis acoustic travel-time sensor with integral microprocessor and battery. Normally it includes a compass to rotate the velocities into earth coordinates and often it includes a tilt meter to erect the currents if the meter is tilted. In its 2004 version, solid state three-axis magnetometers coupled with solid state two-axis accelerometers both resolve the horizontal magnetic field direction and tilt. It can also measure other environmental variables including temperature, pressure, conductivity, turbidity, and analog voltages generated by external modular sensors. Thus MAVS has become a generalized data system as well as a 3-D current meter. The critical part of MAVS is the sensor head for current measurement. This is a pair of injection molded rings supporting eight transducers that define the velocity sensing volume. Each acoustic axis is inclined 45° to the horizontal and spaced 90° in azimuth but the transducers are paired in each ring so the axes form a closed, bent contour. Also, there are spokes supporting the rings from a central tube that carries the wires from the transducers to the electronics case but the transducers are not at the ends of the spokes. The offset of the acoustic axes from the straight structural elements avoids any acoustic path being in the plane of a wake, no matter what the direction. Finally, the rings are faired in the direction of the acoustic path so that when the flow is instantaneously along a path, the wake is minimum. This has resulted in a nearly perfect horizontal cosine response (horizontal being the plane of the rings) and a very good vertical cosine response. There is a cost of this performance in that the turbulence shed by the more bulky faired rings is about four times that in BASS, where the transducers alone have significant bulk. The wires being inside the support tube makes them rigid and reduces offsets in zero point due to motion of the cables as in BASS. There is however a pressure compensation problem in which the urethane that encapsulates the wires in the tube compresses with hydrostatic pressure and must be allowed to move as it gets smaller. In the present design, a urethane tube open at one end to seawater allows expansion internally to compensate for the shrinkage of the potting.