Earth Coordinate 3-D Currents from a Modular Acoustic Velocity Sensor

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***Abstract* - MAVS, modular acoustic velocity sensor, measures 3-D flow components along four acoustic paths using differential travel-time techniques, removes the offset from each acoustic axis due to individual characteristics of the cabling and any electronic offsets, and rotates the corrected components into earth coordinates with a gimbaled two-axis magnetometer. In the present version of MAVS, the sensor is assumed to be aligned vertically to within 15°. Three requirements had to be met to allow the conversion of the three-axis current measurement into earth coordinates *in situ* without introducing non-removable bias. First, flow distortion by the sensor had to be reduced to an acceptable level so that a cosine response in elevation as well as azimuth could be applied. Second, the determination of offsets for zero flow had to be easily measured and compensated, and these offsets had to be stable. Third, the measurement of sensor-frame heading had to be accurate and tilt tolerant. Fairing of the transducer support rings achieved the first requirement. Enabling the sensor to be auto-zeroed and rigidly capturing the cables inside the transducer supports achieved the second. Rotating the precisely measured sensor-frame components of velocity into earth coordinates with the relatively imprecise magnetometer components and vector averaging the resultants achieved the third. That these can be done in a small instrument with low power permits a modular approach to current sensing. Direct reading, stand-alone logging, and modular component applications of a modular acoustic velocity sensor, MAVS, have been implemented.**

I. INTRODUCTION

Depending on the application, rotation of velocity measurements into earth coordinates may be important, may be convenient but not essential, or may be critical to remove current meter rotation. A single point measurement of stress or a measurement of turbulence in the inertial subrange of a bottom boundary layer may not require earth coordinates at all [1,2,3]. Velocity measurements from a fixed structure such as a piling or bottom tripod, while requiring rotation of velocities into earth coordinates, may not require continuous measurement of current meter orientation. In this case, earth coordinate output of velocity is a convenience but this rotation of coordinates could be done after the output of velocity in sensor-frame coordinates. A single orientation measurement could be made within the current meter, externally during installation, or during recovery. But a current meter that is not rigidly mounted, one free to rotate such as on a mooring or on a vehicle, must determine its orientation for every sample of velocity in sensor-frame coordinates to be useful. Vector averaging in earth coordinates requires this rotation before accumulation of vector components.

II. INSTRUMENTATION

A. Sensor Cosine Response

Before rotating from sensor-frame coordinates into earth coordinates, it is important to resolve the flow accurately into sensor-frame coordinates. This is the problem of cosine response. For largely horizontal flow, the horizontal cosine response is the important one. In flow near the air-sea surface, where wave orbits are circular, the vertical cosine response is also important. With poor vertical cosine response, vertical components of flow can reduce or augment the horizontal component in one horizontal direction more or less than that in the orthogonal horizontal direction. This can lead to an error in direction of the horizontal component of flow as well as the magnitude. In MAVS, the sensor used in this analysis, the horizontal cosine response is excellent due to symmetry and the vertical cosine response has been improved over previous designs by fairing the rings that support the transducers [4]. At the worst elevation of flow, 45°, the deviation from cosine response is less than 15% and is symmetrical so the horizontal response is not compromised.

B. Compasses

Small, low-power current meters depend on compasses or magnetometers to determine current orientation. Three-axis magnetometers with tilt sensors aid in accurately resolving the projection of the earth's magnetic field direction in the horizontal plane, especially valuable if the current meter is subject to tilt [5,6]. Errors in magnetic azimuth due to tilt, not corrected by either tilt measurements or pendulous alignment of two-axis sensors of magnetic field, can produce substantial error in direction. This results from the dip angle of the earth's magnetic field away from the magnetic equator, becoming vertical at the magnetic poles so that the measurement of direction there is indeterminate. At 45° magnetic latitude, the error in azimuth may be as much as three times the uncompensated tilt.

Magnetic compasses are low-power devices, at least the north seeking needle or card. Low-power optical readout (strobed LED and photodiode) or Hall-effect sensors are available with card or needle compasses. However, these are costly and large or are not precise. Fluid or magnetic damping, available with compasses, is troublesome at certain

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rotational frequencies of the current meter. Magnetometers are small and inexpensive but draw more power and add noise to the measurement. Three-axis magnetometers with tilt are not inexpensive and consume an order of magnitude more power than the two-axis compasses without tilt. However, two and three-axis magnetometers are an enabling technology for small, low-power current meters.

Individual measurements of direction with the Precision Navigation V2XG [7], a gimbaled two-axis magnetometer, were observed to have a standard deviation of 5° in azimuth. Individual measurements give two 16-bit values for the two orthogonal components of the projection of the earth's field onto the horizontal plane. The magnitude from these two components is about 400 bits from which it can be seen that the 30 bits of noise observed is 5° of noise in direction. Each strobed measurement of the V2XG requires 140 ms so averaging to reduce the noise is only realistic for stationary applications, those for which earth coordinates are a convenience but not essential to prevent an error in a vector averaged result.

The velocity sensor used in the current meter, MAVS, has a standard deviation in velocity measurement of 0.5 mm/s [8]. Thus for a current speed of 10 cm/s, the error in current direction due to velocity noise is 2.5° and less than 1° for current speed greater than 25 cm/s. Velocity measurements take only 20 ms and consume only 25 millijoule so directional precision is limited by the magnetometer for current speeds above 10m cm/s based upon power consumption and sample frequency. The problem then is how to combine magnetometer measurements with velocity measurements to get velocities in earth coordinates.

III. COMPUTATIONS

A. Direction Cosines

To rotate a vector in one coordinate system into a second coordinate system in two dimensions, the components of the unit vector of the earth coordinate system projected on the sensor-frame are used. These are the direction cosines and are the x component of magnetic field and the y component of magnetic field normalized by the magnitude of the magnetic field (the horizontal magnitude). There is no benefit in converting to angle when Cartesian components are the output of the magnetometer. Cartesian components are also the output of the velocity sensor so the transformation to earth coordinate velocity east (V_e) and velocity north (V_n) is:

$$V_e = V_X Y - V_Y X$$
$$V_n = V_Y Y + V_X X$$

where V_X is the x component of velocity, V_Y is the y component of velocity, X and Y are the direction cosines of the horizontal component of the earth's magnetic field along the x-axis and y-axis, respectively. Note that this transform involves four products and two additions, an inconsequential manipulation where it might be done as a matrix operation on a PC, but an 18 ms process in Tattletale BASIC on a low-power, single board computer [9].

To generate the direction cosines X and Y from the magnetometer values M_X and M_Y, compute

$$X = M_X \Big/ \sqrt{M_X^{\,2} + M_Y^{\,2}}$$
$$Y = M_Y \Big/ \sqrt{M_X^{\,2} + M_Y^{\,2}} \bullet$$

The magnitude involves two products, a sum, and a square root, which takes 13 ms in Tattletale BASIC. The division takes an additional 4 ms so the calculation of the two direction cosines takes 21 ms (the magnitude is only calculated once). This calculation need not be repeated for each sample in stationary installations and, of greater import, the compass need not even be read. Thus, the conversion from velocity measured in sensor-frame coordinates to earth coordinates for a fixed instrument takes 18 ms in MAVS using Tattletale BASIC.

It is important to note that the velocity is measured twice for each axis, once with transducers connected normally to the measurement circuit, once with the transducers connected reversed. Each measurement is stored in a data file as it is measured and then subtracted pair-wise in MAVS to remove electronic bias. The measurement, storage and subtraction process takes 26 ms but leaves four values in storage. Checking these for error, combining them into Cartesian coordinates, and removing zero error, requires an additional 46 ms. Then the time to rotate into earth coordinates does not seem excessive

B. Auto-Zero

The rotation of velocity measured in sensor-frame coordinates into earth coordinates illustrates a potential problem if there is an offset in sensor-frame coordinate velocity. The problem is even more severe if the instrument rotates, which makes removal of velocity offsets impossible after the fact. In acoustic travel-time current sensing, the zero point is not inherent to the sensor and must be determined by calibration in still fluid. This is an important but troublesome chore in the cable connected sensors of BASS in which flexure of the cables when dressed on the BASS tripod changes their capacitance [10]. In BASS, after assembling the tower of 2 to 7 sensors, the urethane-jacketed coaxial cables are tie wrapped to wire guys and the legs of the tripod. Only then can the zeros be measured. These values are determined by casting the sensors in carrageenan gel or by bagging them in plastic film and deploying the tripod while measuring the flow inside the bags [11]. In MAVS, the cables are inside a rigid stainless tube, filled with urethane. A single zero calibration should suffice barring dimensional changes with temperature and age. In any case, MAVS is relatively easy to zero since the sensor is at the end of a tube and can be immersed in a bucket of still water or a pot of hot carrageenan which is allowed to cool and gel. If MAVS is powered up while so immersed, it automatically obtains an average of 16 measurements of velocity and stores them in an array for subtraction from subsequent measurements. This is essential for doing earth coordinate rotations with an acoustic travel-time current meter.

Clearly it is important to retain the auto-zero when the MAVS is next powered. The test for subsequent power ups is that the sensor is not immersed. This disables the auto-zero routine and retains the previously determined zero. For tripod work, the instrument is generally powered on deck, then deployed. Similarly, for moored deployments the instruments are powered before being deployed. The exception is when MAVS is used in a direct reading mode, as when cable lowered or powered from shore in observatory applications. For these, a menu permits auto zeroing but does not do an auto-zero unless commands are entered within a short interval. Without these responses, the previous zero is retained.

C. Vector Averaging

If MAVS is moored or lowered on a cable it can rotate. In this case, the compass must be read every time the velocity is sampled to correctly rotate into earth coordinates. Since the measurement of velocity takes 20 ms, the measurement of the compass requires 140 ms, and the coordinate rotation adds 64 ms, with the output overhead the maximum sample rate is about 3.7 Hz. The sample sequence is designed to minimize the interval between measuring the current in sensor-frame coordinates and measuring the sensor-frame orientation. Stabilization of the voltages before the current measurement takes 6 ms. Immediately after the 8 velocity values are stored (four normal and reversed components), the compass is powered. 10 ms are required for the start of conversion and 100 ms for the conversion within the compass. An additional 30 ms is required to complete the measurement and shift the data out but the interval between the velocity determination and the orientation determination is nominally 60 ms. Then the subtractions and rotations are performed. These do not affect the interval between the velocity determination and the orientation. Typically, the velocity and orientation are measured every 500 ms and converted to earth coordinates. It is at this point that vector averaging is an option.

Averaging reduces the amount of data that must be stored or transmitted. Velocities at 2 Hz from a mooring do not necessarily contain important information at the sample frequency. Mooring motion is often not of interest to the user so it may be removed by averaging for 1 second or longer. This raises the possibility of further contaminating the recorded or transmitted measurements by including bad velocities in the average.

The main error in velocity measurement is loss of a received acoustic pulse. An acoustic reflector such as a large air bubble or a bone can block an acoustic path and prevent one or more components of the velocity from being measured. This is detected by requiring that both transducers defining an acoustic path have received signals by the end of the measurement interval. If either or both have not received signals, a flag word is stored in place of the velocity. This word is detected when the normal and reversed measurements are subtracted. If either the normal or the reversed measurement contains the flag word, the flag word replaces the result of the subtraction. When the velocities in the sensor-frame are rotated into earth coordinates, the presence of a flag word is checked for each component of the velocity and if present, the earth coordinate velocities are all replaced by flag words.

When the samples are being accumulated for the average, the flag word must be checked again and the flawed measurement removed from the average or the average must be flagged. This is easy to implement in a recursive filter type of average but the recursive filter has undesirable attributes.

D. Recursive Filter

If each new earth coordinate velocity component is weighted and combined with the previous average of that component, a simple recursive filter results. For example, a new measurement of V_e, v_e, can be combined with an old value of V_e, $V_{e\,old}$, to obtain a new averaged $V_e, V_{e\,new}$. If the weighting is 25% and the sample rate is 2 Hz, a recursive filter with a 2-second response time is formed.

$$V_{e\,new} = (3 * V_{e\,old} + v_e)/4$$

In such a filter, a single bad value can be ignored; the filter simply repeats the last value for the flawed sample. This filter retains some memory of large events for a long time. For example, it is important to start it with a reasonable Ve old or it will take a long time to converge. The first measurement can be loaded in as $V_{e\,old}$ before filtering to minimize settling time.

This filter is the digital equivalent of an RC filter in analog electronics with the 3 dB point at the response time of the filter. Higher frequencies are attenuated and lower frequencies are preserved. It does not have a sharp cut-off, which is undesirable for some purposes.

The recursive filter has a problem peculiar to BASIC integer arithmetic. BASIC integer division truncates, dropping the remainder. In the recursive filter, truncation gives a new average biased ½ bit lower than it should be on the average. Since the new average is used for the next determination of the average, the bias accumulates and drives the filtered output towards zero. The least bit scales the problem so it is not noticeable when the velocities are large or the averaging interval is short. The repair is not easy to implement. So the recursive filter has been abandoned in favor of the boxcar filter.

E. Boxcar Filter

If the average is stored or transmitted only at an interval that is used for the boxcar filter, this filter is easy to implement. Accumulators are zeroed at the beginning of the averaging period. The earth coordinate components are added for the duration of the averaging period. The number of samples divides the sum in the averaging period and the quotient is stored or transmitted as the boxcar average. Each sample is weighted equally. The boxcar filter has sidebands so it must be used cautiously. However, its ease of implementation makes it attractive for low-power, small current meters. A bad measurement is not so easily accommodated, however. If a flagged measurement is not to be used in the average, the divisor must be reduced each time a sample is not accumulated. While this could be done, it is a burden for a small system. Instead, the entire average may be replaced by a flag word. The incidence of a bad measurement is infrequent unless the environment has degraded or the sensor is failing. If either of the last two is occurring, the loss of averaged data is unavoidable. If the former, loss of data is so infrequent that it is not a problem as long as it is detected in subsequent processing.

IV. Summary

Rotation of current measurements to earth coordinates requires a compass or magnetometer but compromises speed of measurement unless used appropriately. For turbulence measurements where speed is important, fixed mountings allow the orientation to be measured outside the period of rapid sampling. Then the transformation to earth coordinates can be performed rapidly using the direction cosines of the sensor-frame orientation. For cable lowered or moored measurements, such high speed is not possible and the compass or magnetometer must be measured for each sample. In this case, averaging is often required. In either case, current meter zeros must be determined and subtracted from each measurement to avoid contaminating the rotated results. Bad measurements must be flagged and not used in forming the averages.

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