A Solid State Tilt Meter for Current Meter Attitude Determination

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Abstract - Earth coordinate determination of current requires measurement of heading and tilt of the sensor to rotate the instrument frame measurement of velocity into earth frame coordinates. Gimbaled magnetometer coils allow the magnetic heading to be determined but solid state three-axis magnetometers require tilt in addition to the earth's magnetic vector to resolve heading. A measure of tilt is also desirable if the current meter cannot be assured of a vertical orientation. Two-axis MEMS accelerometers by Analog Devices, Inc. are capable of providing this tilt measurement but require temperature correction to remove a significant error at zero tilt. The determination and application of this temperature coefficient to correct the error has enabled a versatile attitude sensor to be incorporated in the Modular Acoustic Velocity Sensor (MAVS) for conversion of flow measurements by the sensor into earth-coordinate currents. Residual tilt error is less than 0.3 degrees from 5˚C to 28˚C. Absolute accuracy of the sensor is better than 1˚ between -50˚ and +50˚ and is better than 3˚ between -70˚ and +70˚. Because the accelerometer works equally well inverted, the current meter can be mounted upside down to place the velocity sensor above instead of below the housing without opening the case. A second socket for the accelerometer at right angles to the first permits a horizontal mounting of the current meter with only minor internal rearrangement of a part.

INTRODUCTION

Attitude sensing in the context of current measurement means the determination of vertical and the determination of heading, two vector directions orthogonal to one another. There is no attempt to measure linear accelerations or rotational motion but only steady, fixed orientation (motion with accelerations less than 0.01 g can be neglected as can oscillatory motions with zero mean displacement). The direction of vertical is referenced to gravity. The heading is referenced to the projection of the earth's magnetic field on the horizontal plane, itself defined by local gravity. Attitude of the sensor is very important for current measurement to calculate the transport of water accurately. In fact, the direction of motion is at least as important as the speed of motion in open ocean transport measurements. One of the more limiting characteristics of mechanical current meters has been the vane and vane follower and the magnetic card compass required to determine the flow direction. In acoustic current meters, there are generally no vanes but a compass is still present whose output must be related to the instrument frame for determination of flow direction and the compass may have mechanical parts subject to friction or to stickiness that compromise the determination of heading. Flux gate sensors partly avoid the bearing problem of card or needle compasses but they too must have at least a pendulous component to resolve the horizontal components of the generally dipping earth's magnetic field. Solid state arrays of magnetic sensors, such as a three-axis magnetometer composed of orthogonal magneto-inductive sensors, entirely remove the need for the bearing or pivot. But this requires an independent measurement of vertical to resolve the magnetic vector into a horizontal direction. Such a vertical sensor may be a sensor of direction only but can also be a two-component accelerometer and avoid the bearing or pivot of a mechanical sensor. A two-axis accelerometer was selected to provide vertical orientation for a three-axis magnetometer compass in the Modular Acoustic Velocity Sensor (MAVS) current meter [1,2].

INSTRUMENTATION

A. ADXL202 Two-Axis Accelerometer

The Analog Devices, Inc. ADXL202, is a MEMS integrated circuit that measures two components of acceleration in the plane of the device with a range of plus and minus 2g or +/- 20 m/s^2[3]. The output is a duty-cycle modulated square wave. The ratio of the 'on' cycle to the full cycle can be used as a measure of the component of acceleration along the axis being measured. Alternatively, the average voltage produced by the fraction of the time the cycle is on can be measured. An integrator or a simple resistance/capacitor filter can be used to average a number of cycles of the square wave before digitizing the voltage from the device. This simple circuit provides a sensitive and accurate measure of the sine of the tilt angle of the device. The two channels correspond to two orthogonal components of tilt: pitch and roll.

Table I shows the results of tests made to select the appropriate number of digitizations required to reduce the variability below an acceptable threshold. With too few measurements, the electronic noise and the bit noise of the digitizer (12 bit A/D in the Tattletale 8 single board computer that is the controller for MAVS) give an unacceptable uncertainty in tilt angle. Too many measurements increase the time required obtaining an angle and the power consumed in its determination is excessive for the purposes of the current measurement. Based on a statistical test of standard deviation and of the range of measurements with a single digitization, 10 digitizations, and 100 digitizations, an optimum of five digitizations was selected. Five measurements takes about 25 ms. This ensured that variations from noise and digitization granularity were less than 0.5º of tilt.

Using the 5-digitization measurement of angle, the linearity of the tilt measurement was checked and is shown in Fig. 1. Tilt was set with a machinist protractor and bubble level with an expected error of about 0.3º.

Since the output of the accelerometer is proportional to the sine of the tilt angle, this is converted to an angle by forming the arcsine of the reading, suitably scaled. This presents two issues: first, the scale factor must be determined in calibrations, and second the absolute value of the argument of the arcsine must not exceed 1.000. In the example shown, as well as in the standard calibration procedure, the tilt is set first to 0º and the offset noted. Then the tilt is set to about 45º and the reading is compared to that at 0º. This difference is divided by the sine of the tilt angle and is the scale factor for this sensor. For all subsequent tilt measurements, the reading of the sensor is corrected for zero tilt offset (the offset value is subtracted from the reading) and that result is divided by the scale factor. This is the argument for the arcsine that gives the tilt angle.

TABLE I
SAMPLE AVERAGING FOR TILT

Pitch for Single Measurement	STD 0.289º	Range 1.4º
Roll for Single Measurement	STD 0.447º	Range 1.8º
Pitch for 10 Measurements	STD 0.111º	Range 0.5º
Roll for 10 Measurements	STD 0.134º	Range 0.5º
Pitch for 100 Measurements	STD 0.050º	Range 0.3º
Roll for 100 Measurements	STD 0.097º	Range 0.2º

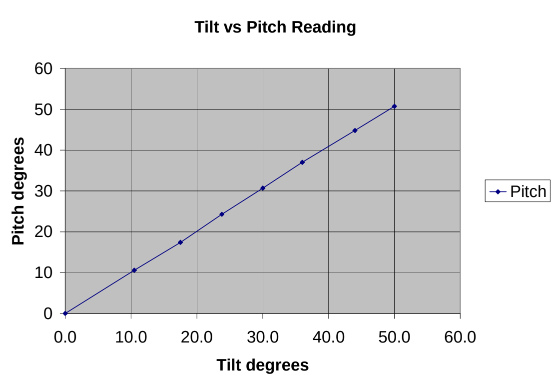

Fig. 1. Applied tilt angle and measured pitch derived from 5 digitizations of the ADXL202 duty cycle output. The scale factor was chosen for a best fit.

The second concern is that the calibration procedure may give a reasonable fit to the tilt over the range +/-70º but when the tilt approaches 90º the argument approaches 1.000 and may exceed it because of noise or slight error in the scale factor or even from instantaneous accelerations due to instrument motion. This will cause an error in the arcsine routine. Either this condition must be computationally trapped before the arcsine routine is implemented or the result of such an error must be acceptable.

B. ADXL202 Temperature Coefficient

The stability of the ADXL202 over voltage fluctuations is acceptable if the A/D converter reference voltage is used to power the ADXL202. This is true since the duty cycle modulation is insensitive to the voltage driving the circuit. And the amplitude of the average of the modulated square wave is proportional to the supply voltage. But there is a characteristic of the ADXL202 that is not acceptable without correction, the temperature coefficient of the zero offset. In the technical specification sheet this offset is graphically presented as an uncertainty in the zero g offset as a function of temperature away from 25ºC that is as great as 0.1g at the freezing point of water, a temperature that is likely to be encountered in an oceanographic instrument. This would result in an error of more than 5º tilt. Such an error would be unacceptable. A simple calibration run with a heat gun on an ADXL202 clamped in a horizontal orientation shows the uncompensated temperature offset. An example can be seen in Fig. 2. Note that the temperature offset of the roll axis is unrelated to that of the pitch axis. To make this measurement, a copper bar with a thermistor mounted to it was clamped to the tilt sensor and the bar was heated with a heat gun over a period of a minute and then allowed to cool down. The heat was applied to the end of the bar closer to the tilt sensor than the thermistor and the temperature gradient along the bar produced the hysteresis in tilt that is visible at the high temperature end of the plot.

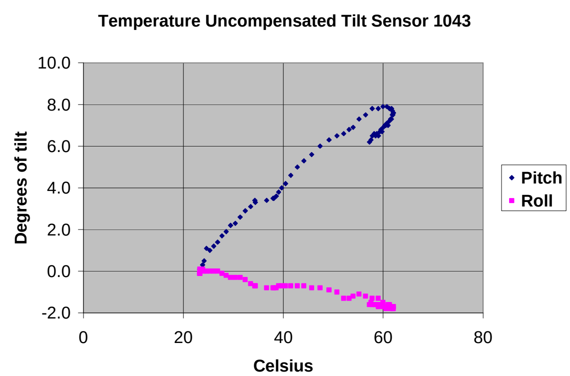

Fig. 2. Tilt appears to increase as much 8º with an increase in temperature from 25ºC to 60ºC from an uncompensated tilt sensor. Heat was applied with a heat gun while the sensor was clamped in a horizontal orientation. Hysteresis in the tilt measurement, when the heating stopped, results from the separation of the thermistor from the tilt sensor causing a temperature tracking error during rapid heating.

C. Temperature Compensation of the ADXL202

Temperature changes are relatively easy to implement in the positive direction from room temperature to 40ºC or higher but are not particularly relevant to oceanic conditions. Likewise, temperature excursions below freezing are easy to implement with circuit cooler (a Freon spray that boils about -50ºC) but when the temperature rises to between freezing and room temperature, condensation of water vapor onto the circuit makes measurements ineffective. Fig. 3 shows an example of the lower and the higher temperature range where the output is the sum of five digitizations in millivolts.

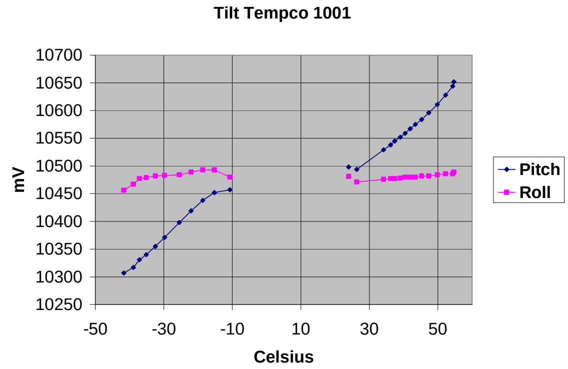

Fig. 3. Temperature coefficient measurements made with heat gun and circuit cooler. The region of oceanic interest is inaccessible due to condensation of moisture on the circuit.

To obtain measurements in this missing range, a thermoelectric cooler was employed, which in the cool-down mode collected moisture on the cooling fins inside the chamber, keeping it off the circuit, and permitted coefficients to be determined between 24ºC and 6ºC, more representative of the oceanic range. Fig. 4 shows a machinists vise in a thermoelectric cooler holding a circuit board with six ADXL202 sensors and a thermistor clamped under a copper bar. The cooler is closed at an elevated temperature to ensure that all the surfaces are dry. Then measurements of millivolt output readings are made for each of the six sensors, for both pitch and roll axes, and the thermoelectric cooler is run overnight to lower the temperature below 6ºC after which the readings are made again. From these two readings the temperature coefficients (tempco readings) are calculated.

For each measurement taken in the MAVS current meter, this temperature coefficient is used to reference the millivolt reading from the ADXL202 sensor to what it would be at 0ºC. The zero tilt offset referenced to 0ºC is subtracted from the measurement, also referenced to 0ºC, to obtain a reading. Then the scale factor is applied and the arcsine run to yield the tilt. Fig. 5 shows the temperature compensated tilt measurement in a descending temperature run that was made inside the thermoelectric cooler. The temperature compensation coefficients were determined from the measurements made at 16ºC and 5.5ºC and at these temperatures the offset in tilt in Fig. 5 is the same. Because the zero was set at 48ºC there is an offset at the coefficient-determining temperatures of -1.7ºC that would normally be absent if the zero-tilt offset had been obtained at room temperature.

A final question remained about the temperature coefficient effect on scale. To test this, the machinist level was set to 45º tilt and a temperature run was made in the thermoelectric cooler. This is illustrated in Fig. 6.

Fig. 4. The thermoelectric cooler with temperature calibrating board contains six ADXL202 tilt sensors under a copper bar held in close contact with clamps. A thermistor is inserted into a hole in the bar and coupled to it with heat sink grease. The machinist vise is set to hold the tilt sensors horizontal during the calibration. For descending temperature, the cooling fins sequester moisture so the circuits remain dry.

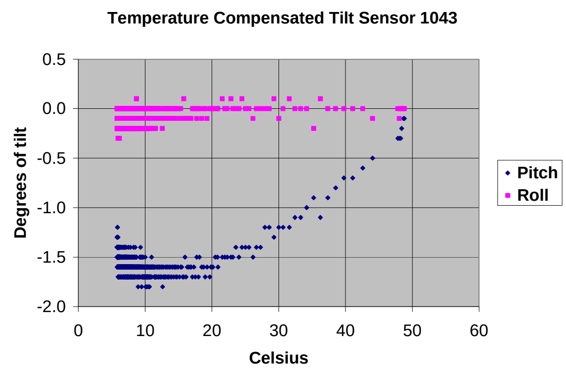

Fig. 5. Tilt was zeroed at 48ºC and the temperature was reduced to 5ºC in the thermoelectric cooler. Between 24ºC and 5ºC the pitch and roll readings were within 0.3º tilt angle of the coefficient-determining settings at 16ºC and 5.5ºC.

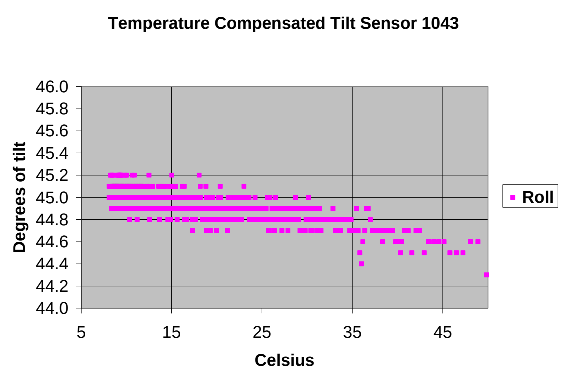

Fig. 6. There is negligible effect of temperature coefficient on the scale factor. This tilted temperature run shows less than 0.3º of tilt uncompensated between 30ºC and 8ºC.

No single temperature coefficient will suffice for all ADXL202 devices. As Fig. 7 shows, the distribution of temperature coefficients for twenty units that have been calibrated extend from 10 mV/ºC to -2 mV/ºC. The pitch coefficients are consistently more positive than the roll coefficients but each axis of each device must go through a temperature cycle for determination of the temperature coefficients. Only a single coefficient is determined however, a linear fit to two points on the curve, at about room temperature and as cold as the thermoelectric cooler can take it, typically 24ºC and 5.5ºC.

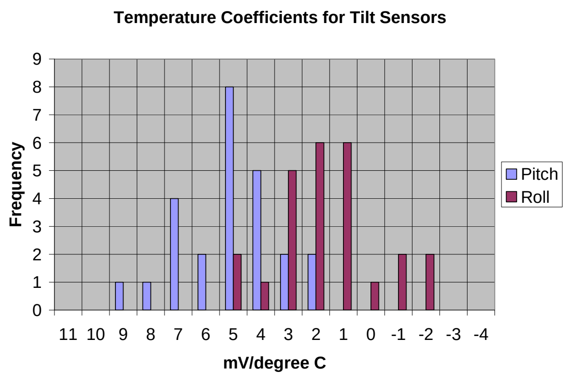

Fig. 7. Temperature coefficients for twenty ADXL202 devices show a spread of values. No single coefficient can be used and pitch and roll for each device must be obtained.

D. Compass/Tilt Attitude Sensor in MAVS

The combination of the three-axis magnetometer compass with the two-axis accelerometer in an attitude sensor for MAVS is illustrated in Fig. 8. The calibrated ADXL202 on a DIP adapter is plugged into a 14 pin DIP socket on the board. While there may be as much as a 2º variation in alignment each time this is plugged into the socket, the calibration of level made before a deployment determines the correct offset. There is a right angle DIP socket also on the board to allow the tilt sensor to be moved for applications where the current meter is to be mounted horizontally. This keeps the normal reading of the tilt sensor near 0º where it is sensitive and well away from the arcsine error condition of 90º. The same temperature coefficients and scale factors that were determined during calibration are appropriate for the new orientation and no change need be made except to indicate in the MAVS setup menu that the orientation of the current meter is now horizontal. The saving of a second calibration was sufficient motivation for moving the sensor rather than installing two sensors and allowing software to select the orientation. It is not necessary to even move the tilt sensor to the other socket if the current meter is inverted. The orientation change need only be entered in the setup menu of MAVS. Fig. 9 shows the temperature compensation behavior of the inverted sensor.

SUMMARY

A solid state tilt meter, the ADXL202 two-axis accelerometer, can resolve the earth's magnetic field vector measured by a three-axis magnetometer onto the horizontal plane to obtain a magnetic heading. The two-axis accelerometer can also remove residual tilt in the orientation of the current meter. The package is small, low power, fast, accurate, and easy to interface to the MAVS controller. The process of obtaining the temperature coefficients of each sensor is not overly complex and the scale factor is similarly easily determined. However, these four coefficients must be determined for each tilt sensor.

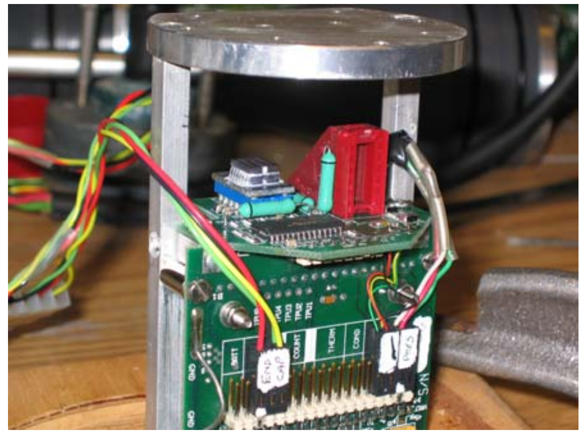

Fig. 8. Attitude module with the three-axis magnetometer compass and the two-axis tilt sensor. There is a right angle DIP socket to mount the ADXL202 circuit into if the MAVS current meter is to be deployed horizontally.

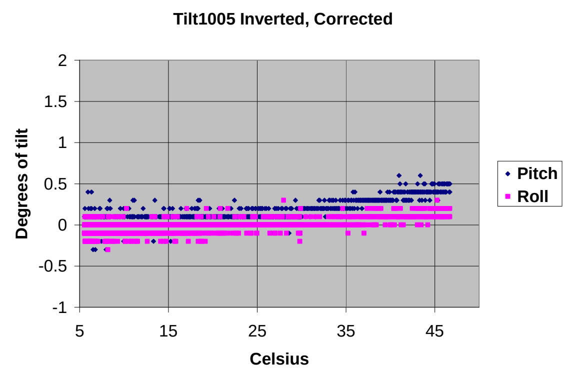

Fig. 9. Temperature compensation is effective with the sensor inverted as can be seen with the temperature run of tilt sensor 1005.

ACKNOWLEDGEMENT

This work was made possible by the Woods Hole Oceanographic Institution and Nobska Development, Inc. WHOI Contribution number 11222

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