A Technical Memorandum NOS 19

TEST RESULTS ON AN ELECTROMAGNETIC CURRENT SENSOR WITH AN "OPEN" DESIGN

Rockville Md.
August 1976

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NOS 14 Some Features of the Dynamic Structure of a Deep Estuary. Michael Devine, April 1974. (COM-74-10885)

NOS 15 An Average, Long-Period, Sea-Level Series for the United States. Steacy D. Hicks and James E. Crosby, September 1975. (COM-75-11463)

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DEPARTMENT OF COMMERCE
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TEST RESULTS ON AN ELECTROMAGNETIC CURRENT SENSOR WITH AN "OPEN" DESIGN

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ABSTRACT. An electromagnetic current sensor with a unique "open" design was developed by J. R. Olson of the Naval Undersea Center. It was tested for steady flow accuracy and cosine response in the horizontal and vertical planes. The sensor's configuration was designed to minimize hydrodynamic disturbances of the current flow and to offer good linearity and directivity response. Test data revealed the sensor's steady-flow measurement uncertainty to be ±2.5 percent of full scale. Horizontal directivity errors were less than ±4 cm/s and 5 cm/s for half- and one-knot test flows. The major contributor of error for the cosine response was determined to be an imbalance in amplifier gain between the sensor's two measuring axes. Vertical directivity results were too noisy for reliable analysis, and the problem was believed to be caused by a distortion of the sensor's magnetic field during testing.

INTRODUCTION

An electromagnetic (EM) current sensor with an "open" design was developed by J. R. Olson of the Naval Undersea Center, San Diego, California. The sensor is considered unique because of its physical configuration. Designed specifically for a turbulent, shallow water environment, the sensor measures mean stream velocity with a minimum of flow distortion created by the sensor's presence. Previous studies by NOIC[1] have indicated that a sensor's configuration directly influences the flow characteristics around the transducer and

[1]NOIC Technical Bulletin RN-1009, March 1974: Electromagnetic current meter evaluation. National Oceanographic Instrumentation Center, Washington, D.C., 11 pp.

thus affects its performance. For example, the local velocity variations around typical cylindrical EM sensors can range from zero to twice the free stream velocity. Under ideal flow conditions, measurements of the actual free stream velocity can be made (via calibration equations) provided the relative velocity variations from the surface of the sensor outward remain constant throughout the speed range of the sensor. NOIC has found, however, that the flow uniformity from the surface of EM sensors may vary as a function of the fluid velocity, attack angle, and fluid characteristics. The effects of this hydrodynamic behavior cause significant nonlinear calibration errors plus a loss of accuracy in the direction of sensed flow.

The Olson transducer configuration is designed to minimize boundary layer effects and accompanying velocity variations by allowing the fluid to flow through the "open" cage design, thereby making measurements directly related to the free stream velocity. Improved performance is expected for both the steady flow accuracy and directivity response.

CURRENT SENSOR DESIGN AND SIGNAL PROCESSING

This EM sensor was developed to measure shallow water currents in the presence of wave-induced orbital velocities.[2] The design of the sensor enables one to measure two orthogonal flow components simultaneously with minimum flow distortion. Theoretically, this type of sensor construction allows the output of each axis to follow a cosine relationship. Figure 1 shows the sensor and its associated signal processing unit. The arrows point to the two coils and one of the four electrodes.

The current sensor is a solid state electromagnetic transducer. The operating principle is based on Faraday's Law which states that electric potentials are induced in an electrical conductor (in this case, water) which moves through a magnetic field. The vector relationship is expressed as $\vec{E}=\vec{V} \times \vec{B}$ where $\vec{E}$ is the induced electric potential, $\vec{V}$ is the velocity of the conducting water, and $\vec{B}$ is the magnetic flux density generated by the sensor.

The magnetic field is produced by driving two parallel coils (Helmholtz coils) with a 17 Hz sine wave signal. The two coils are separated by four

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[2]Olson, J. R., 1968: Component electromagnetic flowmeter. NUC TN193, Naval Undersea Center, San Diego, California, 29 pp.

evenly spaced Fiberglas rods. The Helmholtz coil construction provides a uniform magnetic field perpendicular to the electrodes, midway between the coils.[3] Voltages measured at the electrodes are on the order of 10 μV rms per meter per sec. A shielded input transformer in the signal processing unit is used to boost the measured voltage 12 times. The output of the sensor is composed of two 17 Hz sine wave signals with amplitudes proportional to the components of water current.

Lock-in amplifiers (Princeton Applied Research Model 120) are used to process the flow-related signal from the sensor. The amplifier is capable of detecting the fundamental frequency component of a noisy signal. The heart of the amplifier is a phase-sensitive, frequency-selective detector which locks in on the 17-Hz, flow-related signal amid the composite noise. The output of the amplifier is an analog voltage with a full scale reading of ±10 volts.

The electrode material for the sensor is a copper-nickel alloy (90% copper, 10% nickel) chosen to resist marine fouling. The electrodes and their leads are in the presence of the time-varying magnetic field which induces a quadrature voltage in addition to the desired flow-related signal. The quadrature voltage is caused by the fluctuating magnetic field cutting across these stationary conductors. This noise is at the same frequency but 90° out of phase with the desired signal and is considered the main disadvantage in using sine-wave-drive magnetic fields. Quadrature signals, if left unchecked, can cause a zero offset. In the Olson system, quadrature signals are reduced by an adjustable quadrature compensation voltage that is added into the secondary side of the input transformer. This voltage is 180° out of phase to the quadrature noise and nulls out the undesired noise level before it reaches the lock-in amplifiers.

TEST RESULTS

Accuracy Tests

Accuracy tests on this current meter were conducted on the No. 1 Tow Carriage of the Naval Ship Research and Development Center (NSRDC), Carderock,

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[3]Olson, J. R., 1972: Two component electromagnetic flowmeter. MTS Journal, 6 (1), 19-24.

Maryland. The tests conducted in freshwater were performed at carriage velocities between 0 and 100 cm/sec with the north-south axis (N-S axis) of the current meter aligned perpendicular to the flow. All data points are averages of 30 one-second samples of the lock-in amplifier output voltage. The carriage was run at several speeds along the length of the tow basin with a zero reading taken at each end after a suitable waiting period. Flow measurements were taken at each speed, and the residuals from least-squares, first-degree fit were plotted (figure 2). The nonlinearity error of the average positive N-S axis readings is less than ±1.5 cm/sec, and the nonrepeatability is less than ±1 cm/sec. All errrors indicate worst case conditions.

Horizontal Directivity Tests

Tests were performed to determine the directivity response to the sensor in its horizontal plane. Figures 3 through 6 represent data collected at 28.6 cm/sec and 52.6 cm/sec at NSRDC's Circulating Water Channel (CWC). The data collected for each axis are averages of 30 one-second samples of the analog output voltage at 10° increments of rotation. The resultant vector magnitude was computed as the square root of the sum of each orthogonal component squared, i.e., $(X^2 + Y^2)^{1/2}$. Figures 3 and 4 depict the resultant vector error as a function of azimuth angle for flows of 28.6 cm/sec and 52.6 cm/sec, respectively. Worst case errors are within ±4 cm/sec at 28.6 cm/sec and ±5 cm/sec at 52.6 cm/sec. The accuracy of the flow standard used in the CWC is ±0.5 cm/sec. Figures 3 and 4 reflect a distinct difference in gain (voltage output vs. flow) between the two measuring axes. This is characterized in the graphs by the sinusoidal variations in error, particularly when the vector magnitude is influenced by the measuring axis aligned into the flow (i.e., the 0°, 90°, 180°, and 270° points). Both figures indicate errors that are related to the signal processing circuits and not the transducer. The electronic gain for each channel should be balanced so that the output of each channel is identical under the same flow conditions, thus minimizing directivity error. The other major contributor of error in the directivity plots was the variation between the positive and negative readings of the N-S axis when aligned perpendicular to the flow. This is seen as a difference in vector error at 0° and at 180°.

It is difficult to determine the exact cause of this behavior, but it is assumed to be in the DC-amplifier section of the N-S lock-in amplifier.

Figures 5 and 6 illustrate the angular error of the resultant velocity calculated from the measured orthogonal components. This error is calculated using the equation $E = TAN^{-1} \frac{Y}{X} - \phi$ where E is the calculated error in degrees, X and Y are the average N-S and E-W readings, and ϕ is the sensor geometric angle of rotation relative to the flow direction. Nonlinearity error is ±5.9° at 28.6 cm/sec and ±6.4° at 52.6 cm/sec. The error associated with figures 5 and 6 is influenced by the differences in gain between the measuring axes and could be considerably reduced with properly adjusted gain.

Vertical Directivity Tests

Attempts to obtain vertical directivity (tilt) data yielded results considered too noisy for reliable analysis. The test was conducted on the NSRDC tow carriage with the sensor secured to a right-angle pipe added at the bottom of the test fixture. One axis was aligned into the flow, and the test fixture was rotated in 12° increments to measure the desired cosine response. The data yielded noise levels greater than 100% of signal, and it is believed that the sensor's magnetic field was distorted due to the position of the sensor relative to the water surface.

Testing Summary

Accuracy tests on one sensor axis show a steady-flow uncertainty of less than 2.5 cm/sec on a fixed orientation related to flow direction. The deviations from the least-square equation are not believed to be flow related but rather systematic errors of the processing electronics. The open design concept of this solid state sensor is considered effective in reducing hydrodynamic distortion of the flow within the testing range.

The vector magnitude error as seen in the horizontal directivity test results is a function of the individual gain of each measuring axis and could be reduced with ideally balanced circuitry or application of correction factors.

Testing proceeded slowly because of the difficulty experienced in overcoming noise sources and electronic problems. Noise resulted from ground loops, extraneous signals, magnetic field distortion, and a signal cable sensitivity to shock or vibration. Zero drift problems attributed to quadrature signals also caused difficulties in the accumulation of reliable data.

DISCUSSION

J. R. Olson has developed an improved second generation current meter with the same open design transducer, but it is now battery-operated. The major design changes of the signal processing electronics include a square-wave coil drive with appropriate sample and hold techniques. An inert material (carbon) is now used for the electrode. Square-wave drive with the sample and hold capability eliminates the quadrature voltage on the electrodes and leads induced by the magnetic field reversals. This is accomplished when the measurement of the electrode potential is delayed until the field stabilizes. NOIC tests of the sensor design have been suspended because of the aforementioned electronic problems. The Evaluation Program will continue in the fall of 1976 with the improved current measuring system. Tests of vertical directivity and dynamic response will be included in the Evaluation Program for the new system.

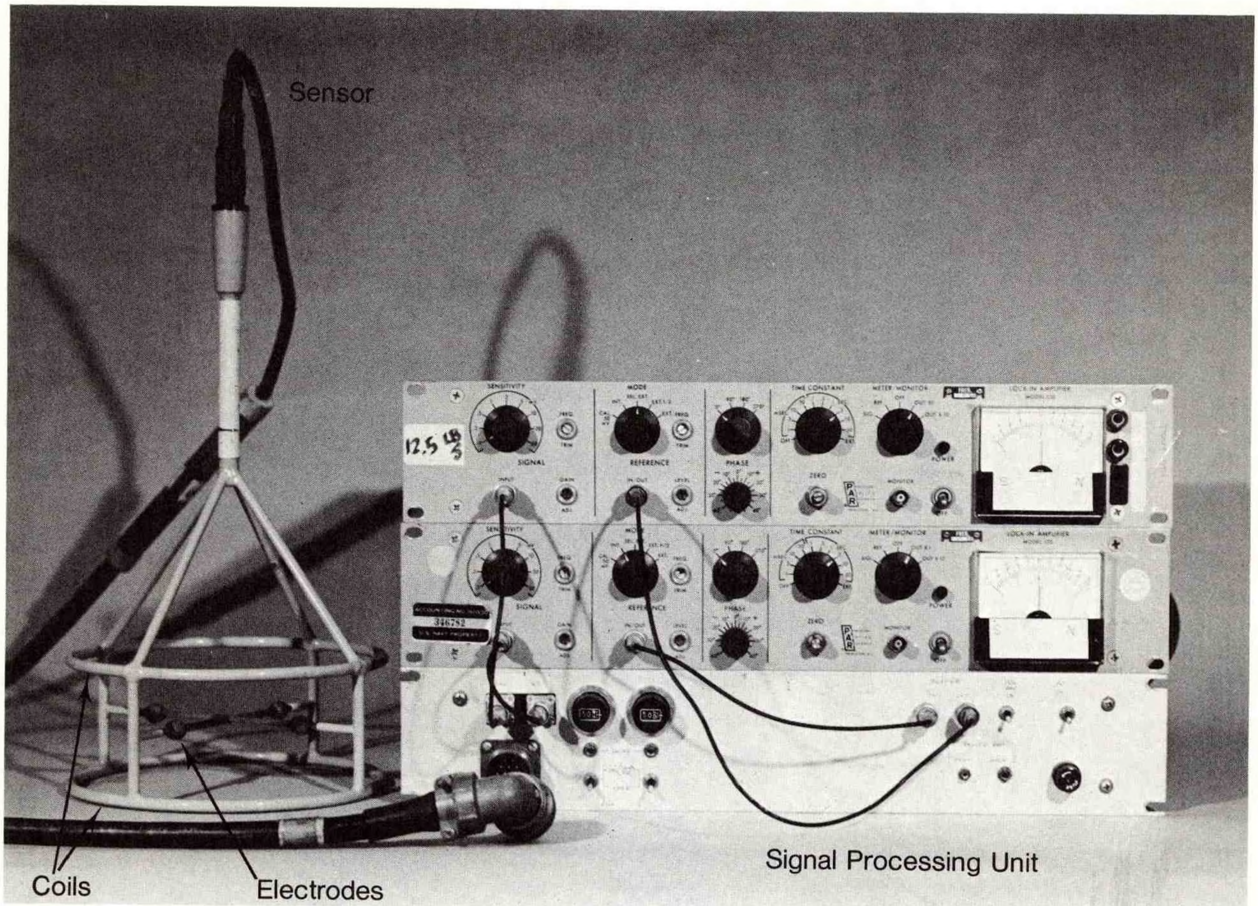

Figure 1.--The "open" design current sensor and signal processing unit.

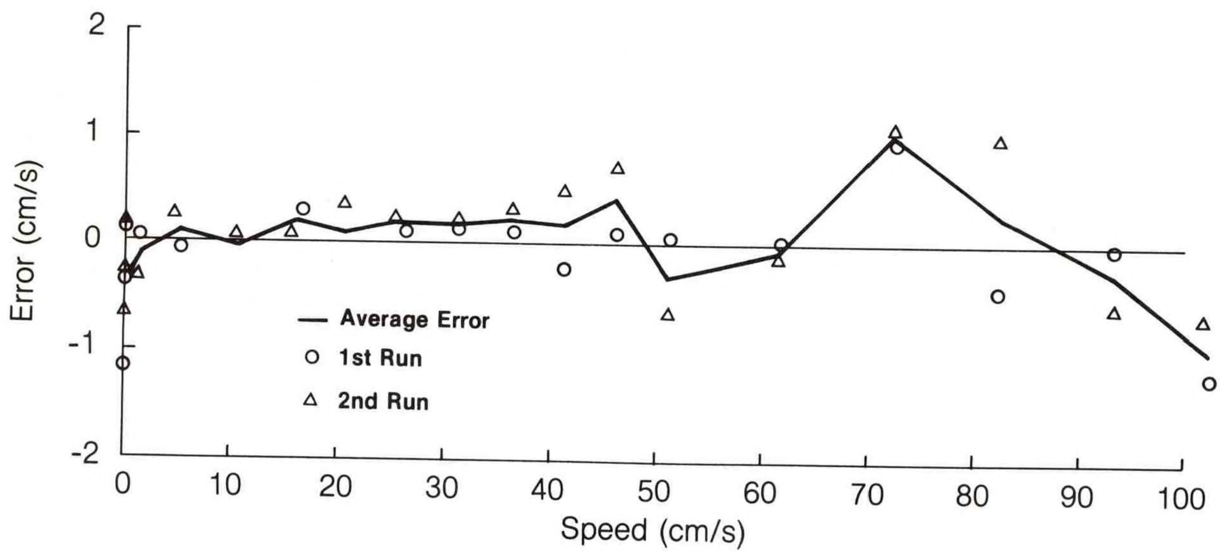

Figure 2.--Calibration error, N-S axis. Speed (cm/s) = 10.747 (volts) + 0.014

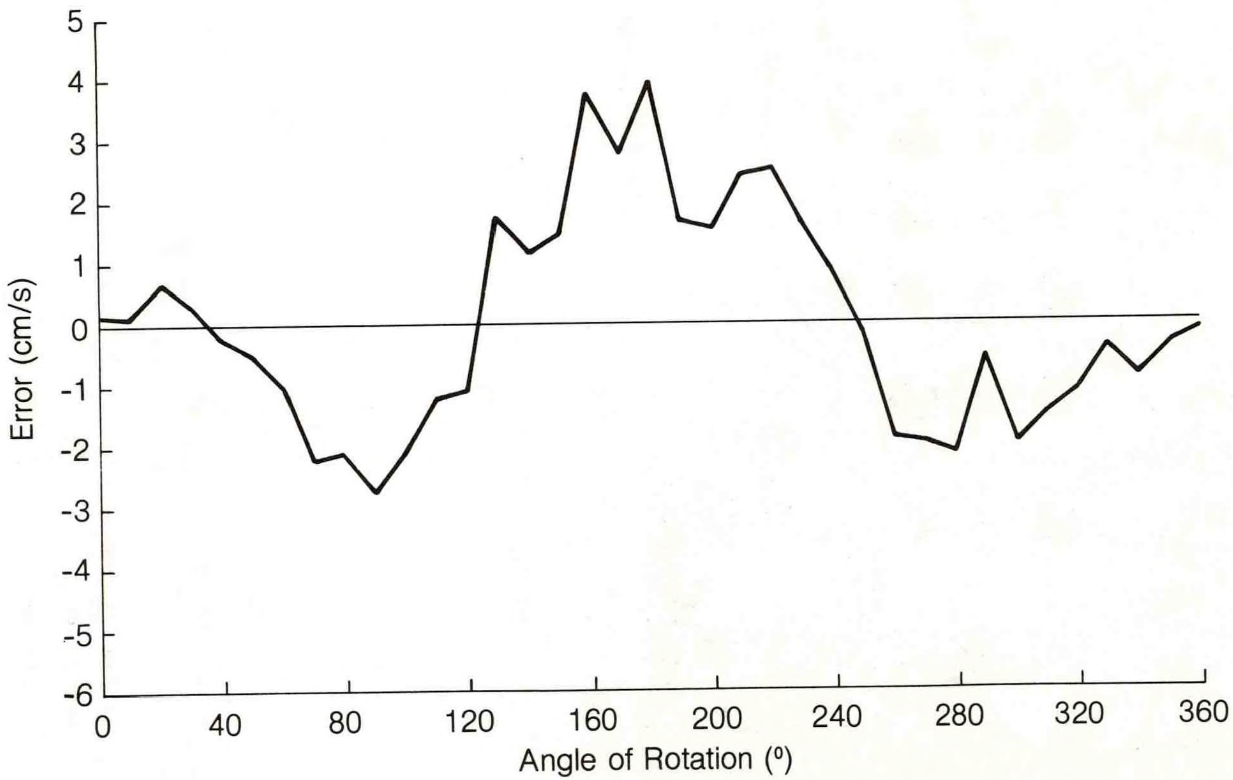

Figure 3.--Horizontal directivity test, resultant vector error at 28.6 cm/s. NSRDC circulating water channel (CWC), 5-15-75.

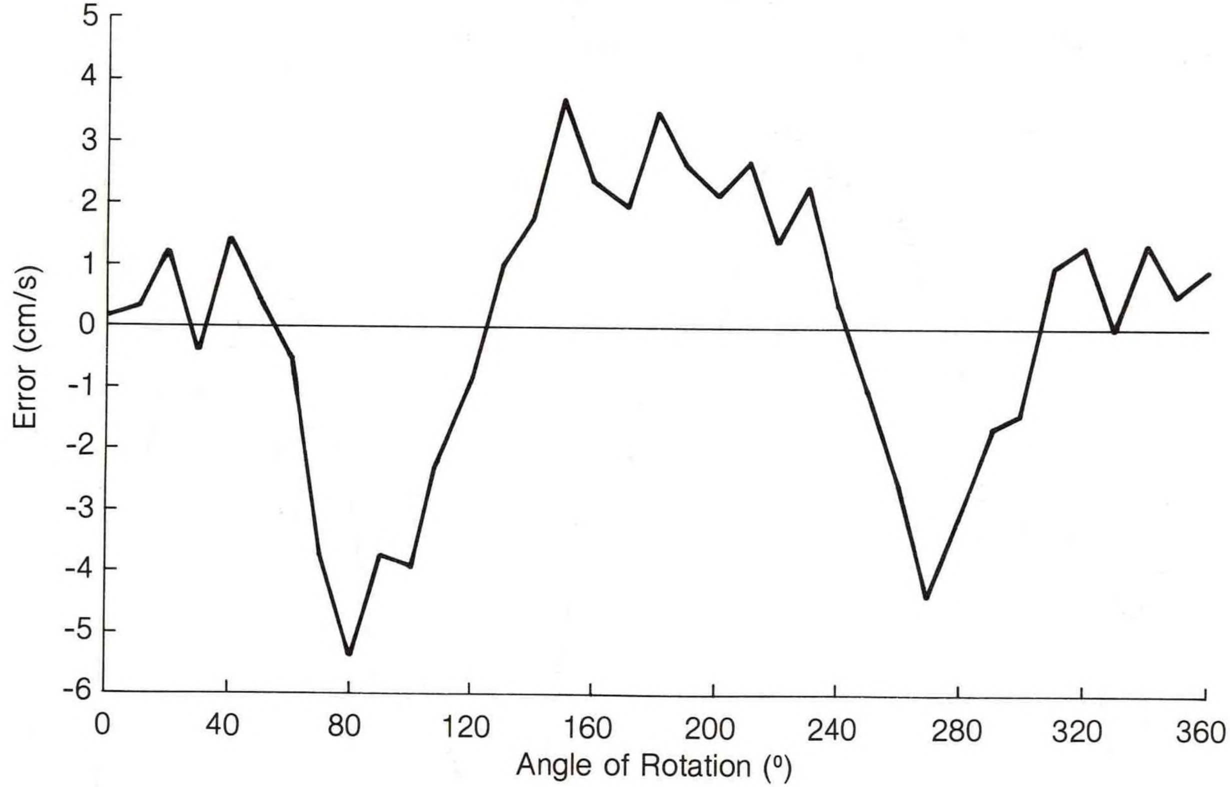

Figure 4.--Horizontal directivity test, resultant vector error at 52.6 cm/s. NSRDC circulating water channel (CWC), 5-15-75.

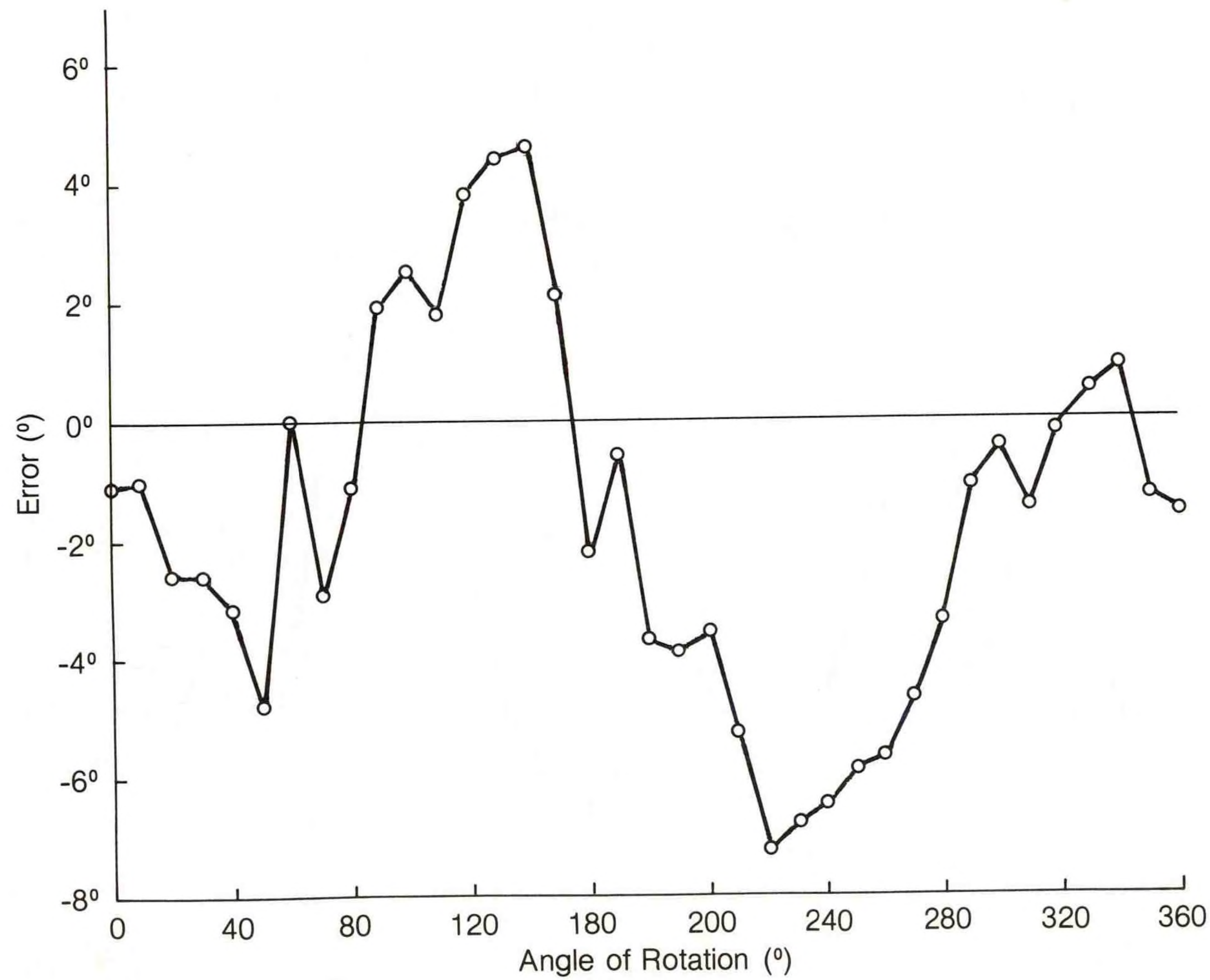

Figure 5.--Directivity response at 28.6 cm/s, NSRDC CWC, 5-15-75.

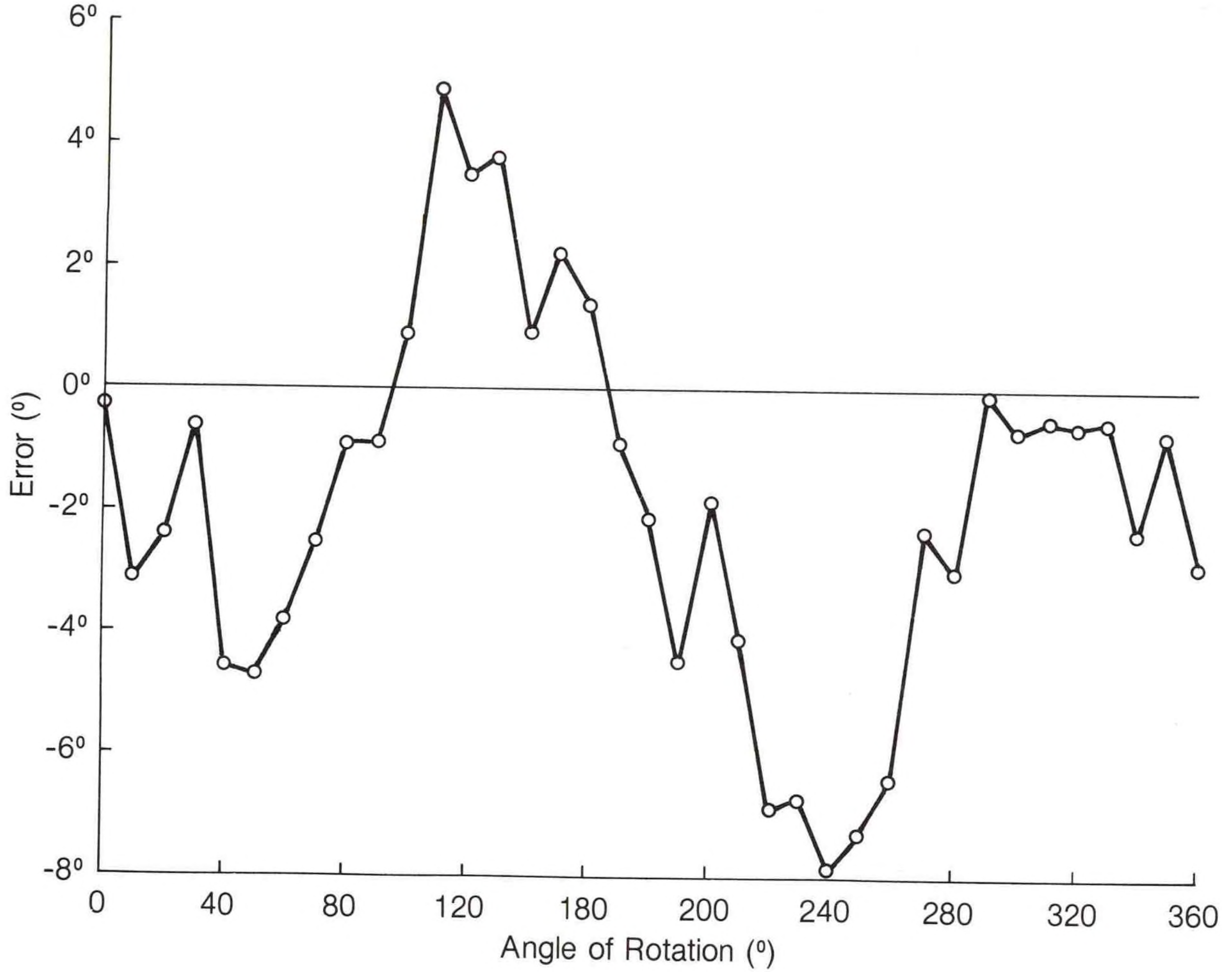

Figure 6.--Directivity response at 52.6 cm/s, NSRDC CWC, 5-15-75.

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NOS 16 Deep Sea Tide and Current Observations in the Gulf of Alaska and Northeast Pacific. Carl A. Pearson, December 1975.

NOS 17 Deep Sea Tide Observations Off the Southeastern United States. Carl A. Pearson, December 1975.

NOS 18 Performance Evaluation of Guildline Model 8400 Laboratory Salinometer. James E. Boyd. In press, 1976.