HORIZONTAL RESPONSE OF THE NBIS ACOUSTIC CURRENT METER

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ABSTRACT

The Neil Brown Instrument System Acoustic Current Meter (ACM) is one of the most advanced current meters available. This meter is an excellent instrument for research purposes, but is limited by its horizontal response. This paper concerns the errors due to non-cosine response in the horizontal plane.

By towing the NBIS ACM at known speeds at various angles to the direction of tow, the responses of both axes of the current meter were determined. Calibration runs were performed on three current meters at a nominal speed of 10 cm/s and on one current meter at 12 cm/s and 31 cm/s.

The error induced by the wakes of the supporting rods can reach ±8% of the flow speed. By using a least squares Fourier series to correct the outputs, the error may be reduced to 1 - 2%.

INTRODUCTION

In December 1979, a densely instrumented array of current meters were deployed in the Gulf of Mexico. The experiment was designed to investigate high-vertical wavenumber processes and to evaluate the benefits of tracking mooring motions for improved S/N in measurement at the upper end of the internal gravity wave spectrum in the upper ocean. To accomplish this investigation a current sensor capable of high accuracy was required. At the time the experiment was designed it appeared that the Neil Brown Instrument Systems Acoustic Current Meter (ACM) was the best commercially available instrument, and this conclusion is consistent with results to date.

According to the manufacturer's specifications, the overall accuracy of the vector magnitude of the current is ± 0.5 cm/s or 3%, whichever is greater. The direction accuracy was given as ±5° for currents greater than 10 cm/s (1). At a current speed of 50 cm/s the vector magnitude should be accurate to about ± 1.5 cm/s. The manufacturer specifies horizontal cosine response error of ± 2° of the vector magnitude over a 360° rotation.

A typical variance spectrum of ocean currents is shown in Figure 1.

ROTOR AUTO-SPECTRA

Energy Density

![Rotary Auto-Spectra](image)

Figure 1. Example of a rotary spectrum of open ocean currents observed in the Gulf of Mexico in the winter 1979-80.

In order that high frequency processes be resolved by ACM, it is necessary that any noise contamination be significantly less than any point on the spectrum. If we assume that noise appears in the same form as digitizing noise the noise level is given by:

\[
N = \frac{2\tau (\Delta u)^2}{3}
\]

where \( N \) = noise level of the spectrum
\( \tau \) = sampling interval
\( \Delta u \) = peak error in the current measurement (or \( \frac{1}{2} \) digitizing error).

The digitizing error due to the ACM is about

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0.15 cm/s ($\Delta u = 0.075$ cm/s) and the sampling time is 60 seconds. This leads to a digitizing error of $N = 6.25 \times 10^{-5}$ (cm$^2$/s$^2$)/cph. If the specified overall accuracy for 50 cm/s mean current is applied, $\Delta u = 1.5$ cm/s and $N = 2.5 \times 10^{-2}$ (cm$^2$/s$^2$)/cph. Suppose, on the other hand that the error was, in fact, 10% of the mean speed ($\Delta u = 5$ cm/s). Then the noise level would be 0.28 (cm$^2$/s$^2$)/cph. It may be seen that the first noise spectrum is much less than the observed spectrum. The second case would begin to contaminate data at frequencies above 3cph while the last case would contaminate any process occurring at 0.9 cph or greater.

It is known that the horizontal error in the VACM can be as great as 5% in magnitude (2). This effect is due to the presence of the support rods on the rotor cage of the VACM.

From the outline diagram of the ACM (Figure 2) it can be seen that there are four support rods.

Figure 2. Outline Diagram of the Neil Brown Instrument Systems ACM - 1.

The relatively large magnitude of the departure from a "cosine response" of the VACM led naturally to a concern that a similar effect due to the support rod could be the primary source of error in this current meter. This source was confirmed by tests of the horizontal response of an earlier model of the NBIS ACM by Appell (3) and McCullough (4). As the geometry of our ACM model differed from that previously studied it was necessary to perform tests on the horizontal response of the ACM to determine the magnitude of the error and, if possible, to obtain a calibration curve which might be used to correct horizontal response errors.

DATA COLLECTION

Four current meters were tested. The first (serial #08-2296-028) cited was tested by personnel from NOAA's Test and Evaluation Laboratory, using the towing facilities of the No. 1 tow carriage at David Taylor Naval Ship Research and Development Center (DTNSRDC). The direct voltage outputs from both axes of the current meter were fed to digital volt meters operating on an IEEE-488 data bus. The speed of the carriage was determined by a counter (also on the IEEE-488 data bus) driven by a magnetic pickoff on a gear attached to the carriage. The data were fed into an HP9825A calculator and the observed speed and ACM voltages were averaged over 1 minute intervals. The angular increment for these data was 15°. Two runs were made, the first at 12.7 cm/s (nominal) and the second at 31.1 cm/s (nominal).

The other three current meters (serial numbers 08-2296-031, -032 and -33) were tested by the author at the tow facility at the National Space Technology Laboratories. The data collection method was essentially the same as that used at DTNSRDC. The runs were made at a tow speed of 10 cm/s (nominal) and at an angular resolution of 2° (later runs were made with a 5° step.)

DISCUSSION

As the carriage speed cannot be held exactly constant, the output of each axis was normalized by the carriage speed. This quantity will be designated the "gain" of each axis. The units of the gain are in mV/(cm/sec). From the equations used in the NBIS ACM operating manual the nominal gain for such a current meter is about 7.0 mV/(cm/sec). In general this value will vary slightly with the current meter, the axis under consideration and the case orientation. In addition, it may be expected due to the modification of the wake structure behind the support rods and the transducer supports that the gain will also be a weak function of speed.

Only one current meter will be discussed in detail as the properties are similar for all meters. The details of the response of each current meter will appear in a technical report.

The gain functions for each axis are plotted in Figure 3. For comparison, the theoretical gain curves assuming a maximum gain of 7 mV/(cm/sec) are plotted for comparison. Certain deviations from the theoretical cosine and sine curves are apparent, but in general, the observed points seem to fit the theoretical curves rather well.
In order to emphasize the deviations from the theoretical curves, some new variables are introduced. The relative gain amplitude error $e(\theta)$ is defined by:

$$e(\theta) = \frac{\sqrt{G^2_x(\theta) + G^2_y(\theta)} - \bar{G}}{\bar{G}}$$

where $G_x(\theta)$ and $G_y(\theta)$ are the gains at case orientation $\theta$ and $G = \frac{1}{N} \sum_{i=1}^{N} \left( G^2_x(\theta_i) + G^2_y(\theta_i) \right)^{\frac{1}{2}}$

where $\theta_i$, $i = 1, \ldots, N$ are all the case orientations for which the gains were measured. The direction error $\phi(\theta)$ is defined as:

$$\phi(\theta) = \theta - \tan^{-1}\left( \frac{G_y(\theta)}{G_x(\theta)} \right)$$

The relative gain amplitude error is a measure of fractional error in speed when the case is oriented at an angle $\theta$ while the direction error is the error in direction that will be made when the case is oriented at the angle $\theta$. These parameters will approximate the error when it is assumed the case is oriented at the angle defined by $\tan^{-1} \left( \frac{G_y}{G_x} \right)$ providing $|\phi| << 1$.

The values of $e(\theta)$ and $\phi(\theta)$ are plotted in Figure 4 as a function of $\theta$.

Figure 3. Horizontal Cosine Response of ACM.(S/N 08-2296-033). The x and y axis gains are plotted versus the angle of the x-axis to the flow. The data are plotted as letters indicating which axis is sampled and, for comparison, the theoretical gain functions are plotted as solid curves.

Figure 4. The Relative gain amplitude error and angular error are plotted versus angle.

It should be noted that $e$ achieves local maxima at odd multiples of 45° and minima near the multiples of 90°. The maximum deviations of $e$ are of the order of ± 6-8% while the maximum direction errors are of the order of ± 5°.

In order to analyze the causes of the variation, the separate gain function $G_x(\theta)$ and $G_y(\theta)$ were subjected to a Fourier decomposition over $\theta = 0$ to 360°, i.e., $G_x$ and $G_y$ are approximated by $G_x$ and $G_y$ where

$$G_x(\theta) = \sum_{n=0}^{N} a_n \cos n\theta + b_n \sin n\theta$$

where $\xi$ may represent $x$ or $y$. The coefficients for current meter 33 are summarized in Table 1 for $N = 10$. If the meters exhibited a perfect horizontal "cosine" response the only non-zero coefficients would be $a_1$ and $b_1$ and these would be equal to each other and to the theoretical gain. It is apparent this is not true and there are strong effects which appear in the third harmonic coefficients and to a lesser degree in the seventh harmonic coefficients.

As expected, the largest contribution is the "cosine" response of the first harmonic. The third harmonic coefficient may be qualitatively accounted for by the wake structure of the support rods. Figure 5 illustrates the situation when the current is approaching from the -x axis.
Fourier Coefficients for both axes responses of ACM S/N 08-2296-033. (10th Order fit).

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Figure 5. Conceptual diagram showing the effect of the wakes from the tension rods on the acoustic sampling volume for two orientations of the case with respect to the flow.

In this case, the observed current speed will be higher than for a pure cosine response due to the acceleration of the flow between the wakes from the support rods. When the case is rotated 45° (Figure 5b), the wake from the support rod directly crosses the acoustic sensing volume, thus indicating a speed deficit.

The third harmonic contribution is illustrated schematically in Figure 6 for the x-axis response.

Figure 6. Effect of the third and seventh harmonics in distorting the theoretical cosine response. The effects have been exaggerated for clarity.

At $\theta = 0°$, the 3rd harmonic contribution is positive (enhanced observed speed). By the time $\theta = 30°$ there is no contribution as the effects of the wake deficit and streamline compression cancel one another. From 30° to 90° the wake effect dominates producing the speed deficit (part of the apparent deficit is purely mathematical as the contribution from the third harmonic must go to zero at 90°; this is probably why the 7th harmonic and 1st sine harmonic contribution are still large). The same description applies to the other quadrants. Another expected effect is due to the wakes of the transponder support struts.

In order to estimate the reduction in error possible using a fitted curve defined by the coefficients in Table 1, the relative gain amplitude error was computed using

$$\epsilon(\theta) = \frac{\sqrt{a_x^2(\theta) + a_y^2(\theta) - G_y(\theta)}}{G_y(\theta)}$$

where $\hat{G}_y(\theta) = \sqrt{a_x^2(\theta) + a_y^2(\theta)}$. The values for $\hat{G}(\theta)$ are plotted in Figure 7. The improvement is good. Instead of relative errors of ±8%, the relative errors have been reduced to about ±1-2% and the direction errors have been reduced from about ±5° to about ±1°.

Thus, it appears that if the case orientation relative to the current is known throughout the sampling period, it may be possible to correct for the imperfect horizontal response of the current meter. As the case orientation is obtained only once every eight samples, the above requirement necessitates that the case orientation and the current direction both be slowly varying functions of time with respect to an 8 minute time scale. In general, however, this situation will not probably exist except for mooring in rather weak flows far from surface. Figure 8 shows a one day record of case orientation obtained from NBI ACM moored in deep water in a strong (0.5m/s) current. From this example it is clear that the orientation is not a slowly varying function of time with respect to the sampling interval, however it is conceivable that sufficiently smooth conditions may be more common.
Four instruments were tested in the course of this work. Only one of the four was tested at more than one nominal speed. By comparing the Fourier decompositions between current meters it was clear that if a calibration is to be used to correct for case orientation effects, a separate calibration must be used for each current meter. In the case where one current meter was studied at two different nominal speeds there is an indication that the horizontal response may be speed dependent as well as instrument dependent. More work remains to be done to either verify or reject this indication.

CONCLUSION

The major source of error in horizontal current measurements utilizing the NBIS Acoustic Current Meter appears to be due to the imperfect horizontal response of the instrument. If the torsional motion of the instrument is absent or varies slowly enough, the amplitude error due to the horizontal response could be reduced by about a factor of 5 and the directional error reduced by a factor of 2.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the contributions of the following individuals to this study and to thank them for their help. A. W. Green, R. L. Zalkan and H.T. Perkins provided helpful conversations and comments of the paper. G. Appell and T. Mero are to be thanked for obtaining the horizontal response data at DYNSEDC. H. Cole, D. Burns, M. Bergin and L. Banchero provided great assistance in collecting data at NSTL. M. Knott typed the manuscript.

REFERENCES

