COMPARISON OF CURRENT METERS USED FOR STREAM GAGING

Janice M. Fulford[1], Kirk G. Thibodeaux[1], and William R. Kaehrle[1]

Abstract

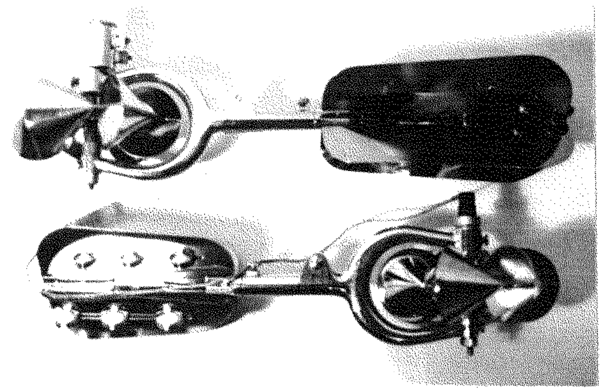
The U.S. Geological Survey (USGS) is field and laboratory testing the performance of several current meters used throughout the world for stream gaging. Meters tested include horizontal-axis current meters from Germany, the United Kingdom, and the People's Republic of China, and vertical-axis and electromagnetic current meters from the United States. Summarized are laboratory test results for meter repeatability, linearity, and response to oblique flow angles and preliminary field testing results. All current meters tested were found to under- and over-register velocities; errors usually increased as the velocity and angle of the flow increased. Repeatability and linearity of all meters tested were good. In the field tests, horizontal-axis meters, except for the two meters from the People's Republic of China, registered higher velocity than did the vertical-axis meters.

Introduction

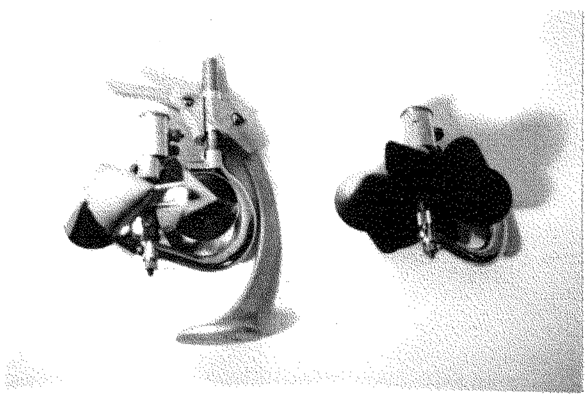
An ideal current meter, whether mechanical or electromagnetic, should respond instantly and consistently to any changes in water velocity, and should accurately register the desired velocity component. Additionally, the meter should be durable, easily maintained, and simple to use under a variety of environmental conditions. Mechanical-current meters measure velocity by translating linear motion into angular motion. The two types of mechanical current meters, vertical-axis and horizontal-axis, differ in their maintenance requirements and performance because of the difference in their axial alignment. Mechanical meter performance depends on the inertia of the rotor, friction in the bearings, and the ease with which water turns the rotor. Electromagnetic current meters measure velocity using Faraday's Law, which states that a conductor (water) moving in a magnetic field (generated by the probe) produces a voltage that varies linearly with the flow velocity. Electrodes in the probe detect the voltages generated by the flowing water. Performance for electromagnetic current meters depends on the probe shape, location of the electrodes on the probe, and the construction of the meter electronics.

Many studies of current-meter performance have been conducted by researchers (Thibodeaux, 1992). Most of these studies were published before 1960, prior to the development of electromagnetic current meters for stream gaging. Yarnell and Nagler's (1931) study on mechanical current meters is one often referenced. The previous studies used mechanical meters that have since been modified and rarely investigated the performance of electromagnetic current meters. Recent laboratory (Fulford and others,

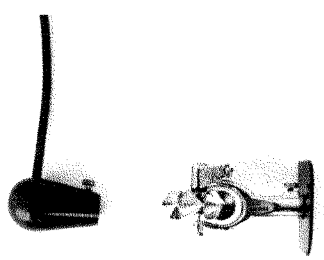
[1]Hydrologist, U.S. Geological Survey, Bldg. 2101, Stennis Space Center, MS 39529.



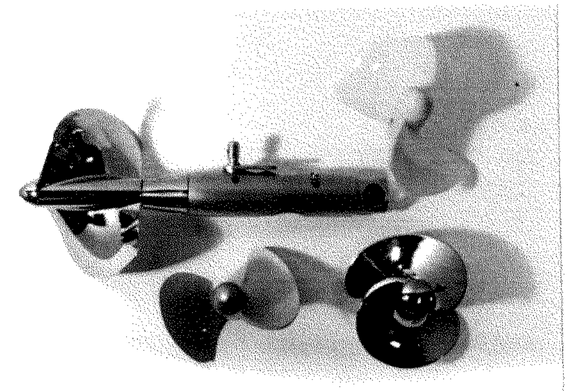
a) Upper meter, Price type-AA; lower meter optic Price type-AA



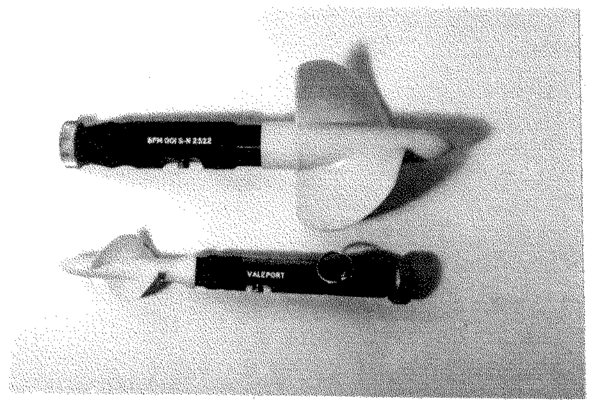
b) Left to right, winter Price type-AA, metal; winter Price type-AA, polymer



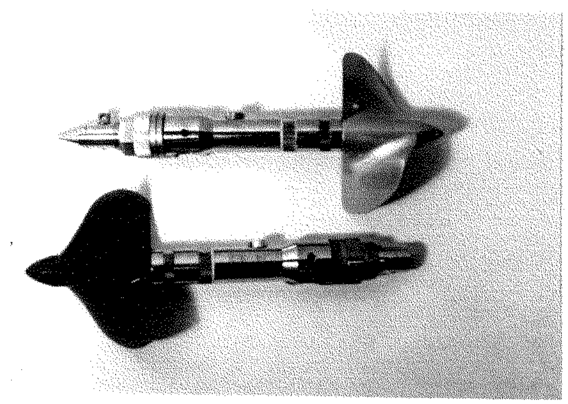
c) Left to right, Marsh McBirney 2000; Price pygmy



d) Ott C-31, standard impeller; impellers clockwise from top, plastic, A, and R.



e) Top, Valeport BFM001; bottom, Valeport BFM002.



f) Top, PRC LS25-3A, metal; bottom, PRC LS25-3A, plastic

Figure 1. Photographs of tested meters. Vertical-axis meters a,b, horizontal-axis meters d-f and vertical-axis and electromagnetic meter c.

1993) and field testing has been completed by the U.S. Geological Survey (USGS) on several current meters. A comparison of the laboratory and field tests for fourteen of these meters is presented in this paper.

Meters Tested

All meters tested measure one component of flow velocity for a small volume of the total flow measuring section. Total flow or discharge is determined with these meters by making multiple velocity measurements in the section and multiplying each measured velocity by its contributing flow area. Comparisons are presented for five mechanical vertical-axis meters, Price type-AA, optic Price type-AA, Price pygmy, winter Price type-AA, and winter Price type-AA with polymer rotor; eight mechanical horizontal-axis meters, Ott C-31[2] with metal, plastic, A, and R impellers, Valeport BFM001 and BFM002, and People's Republic of China (PRC) LS25-3A with metal and plastic impellers; and one electromagnetic meter, the Marsh McBirney 2000. These meters are shown in figure 1. All meters tested use battery powered electronic devices to either count the meter revolutions or to measure the voltage. Maintenance of the electronic devices consists of checking batteries for proper voltages and replacing or recharging when needed.

The vertical-axis meters tested have six conical cups fixed to a hub that rotates a vertical shaft. Vertical-axis meters do not present a symmetrical profile to flow velocities. Velocities angled in the vertical plane impinge on a meter profile that is very different from the meter’s horizontal profile. These meters have few parts and are relatively easy to maintain and clean. The bearings are located in an air pocket to prevent contamination from silt and sediment. Disassembly for cleaning requires the removal of the shaft and rotor assembly from the yoke. Daily cleaning and oiling is recommended for vertical-axis meters.

The horizontal-axis meters tested all have screw type impellers that rotate about a horizontal axis. Unlike the vertical-axis meters, the horizontal-axis meters present a symmetrical profile to velocities in the measurement section. Maintenance requirements vary widely among the horizontal-axis meters. The Ott C-31 and the PRC meters require disassembly of numerous parts, cleaning, and oiling between discharge measurements. Both of these meters have a complex ball bearing assembly that is sealed in oil to provide lubrication and exclude sediment. The PRC meter is similar in construction to the Ott, but has three times the number of internal parts. In contrast to the Ott and PRC meters, the Valeport is simpler and has fewer parts. Cleaning is recommended with clean water between discharge measurements. The Valeport meters’ bearing surface is inside the impeller nose and uses water as the lubricant.

The electromagnetic meter tested has no moving parts and presents a symmetrical tear drop shape to the velocities in the measurement section. Cleaning is recommended with clean water and mild soap to remove dirt and nonconductive grease and oil from the probe's electrodes and surface. The zero reading should be checked periodically in still water. In contrast to the mechanical meters, rinsing the probe with clean water after a measurement is usually the only maintenance needed.

[2]Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

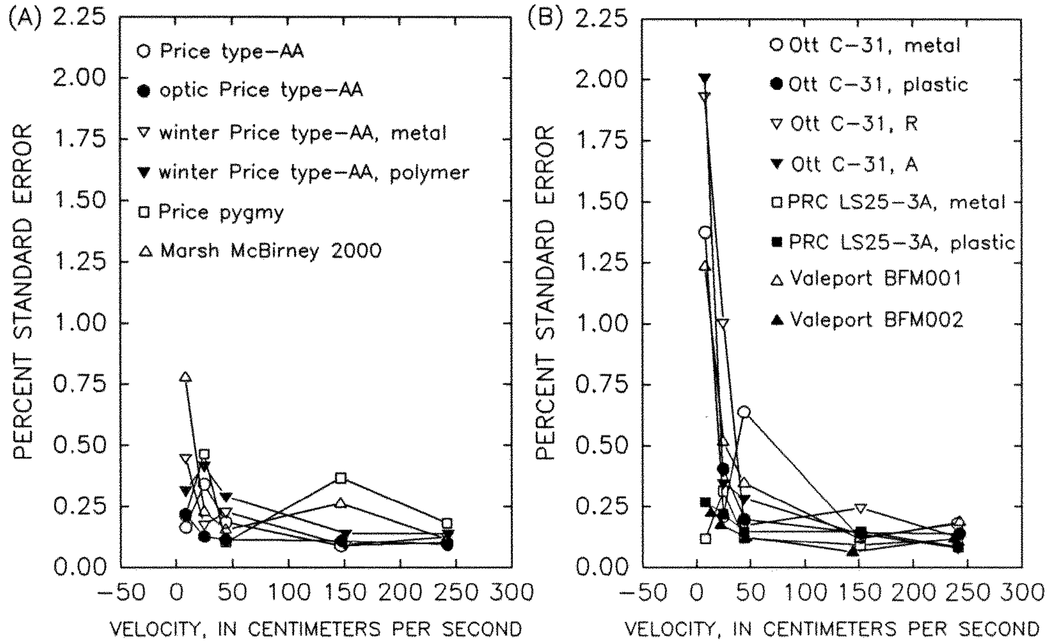


Figure 2. Percent standard error computed by velocity for (A) vertical-axis and electromagnetic meters and for (B) horizontal axis meters.

Laboratory Tests

Laboratory testing of the meters included repeatability testing and oblique flow response testing and was conducted in the jet tank at the USGS Hydraulic Laboratory Facility, at Stennis Space Center, Mississippi. The laboratory testing for the mechanical meters has been previously described by Fulford and others (1993) in a paper comparing vertical- and horizontal-axis current meters. Parts of this previous work are presented here with the addition of the tests for the electromagnetic meter. Test results for the electromagnetic meter are included in the vertical-axis meter figures. The repeatability test measures how repeatable or consistently a meter measures velocity. For each meter, ten measurements were made at each of five velocities, 7.62, 24.38, 45.72, 152.46 and 243.84 cm/s. Standard errors for each test velocity were computed for the mechanical meters from the meter revolutions per second (r/s) and for the electromagnetic meter from the readings displayed on its electronic readout device. Percent standard errors were computed at a test velocity by dividing the standard errors by the mean and multiplying by 100. Plots of percent standard error versus the test velocity are shown in fig. 2. For all meters except the Price pygmy and Marsh McBirney, percent standard errors decrease with increasing velocity. The vertical-axis meters have the most consistent response of the meters tested. For the five velocities tested the percent standard errors for the vertical-axis meters are less than 0.5% and for the horizontal-axis current meters are less than 0.75% for velocities greater than 24.38 cm/s. The Marsh McBirney meter has percent standard errors less than 0.5% except for the lowest velocity tested (7.62 cm/s) where the percent standard error is 0.78%. At the lowest test velocity (7.62 cm/s) the metal Ott, Ott A, Ott R, and Valeport BFM001 had percent standard errors from 1.2 to 2.0% and the PRC meters , the plastic impeller Ott, and the Valeport BFM002 had percent standard errors less than 0.5%.

Table 1.-Linear response of meters; root mean squared (RMS) errors and regression coefficients determined from repeatability data.
[cm/s, centimeters per second; cm/rev, centimeters per revolution]

Meter	RMS error (cm/s)	slope (cm/rev)	intercept (cm/s)	meter type
Optic Price type-AA	0.524	67.391	-0.427	vertical
Price type-AA	1.067	68.976	-0.579	vertical
Winter Price type-AA/metal	0.622	69.921	-0.122	vertical
Winter Price type-AA/polymer	1.716	79.004	1.707	vertical
Price pygmy	1.634	32.034	-1.676	vertical
PRC LS25-3A /metal	0.567	19.934	0.274	horizontal
PRC LS25-3A /plastic	0.527	19.903	-0.061	horizontal
Valeport BFM001	1.234	26.518	-0.061	horizontal
Valeport BFM002	0.735	11.003	1.737	horizontal
Ott C-31 /metal	1.545	25.603	2.652	horizontal
Ott C-31 /plastic	1.372	25.451	0.213	horizontal
Ott C-31 /R impeller	1.402	25.085	2.316	horizontal
Ott C-31 /A impeller	1.999	12.834	3.871	horizontal
Marsh McBirney 2000	0.875	30.450	1.341	electromagnetic

Repeatability data were also fitted using linear regression to determine a meter's linear response. For each meter, the 50 repeatability measurements (velocities of 7.62, 24.38, 45.72, 152.46 and 243.84 cm/s) were regressed against the reference velocity. The root mean squared errors (RMS) and computed regression coefficients are listed by meter in table 1. RMS ranged from 1.999 cm/s for the Ott with A impeller to 0.524 cm/s for the optic Price type-AA. The Marsh McBirney meter RMS (0.875 cm/s) was larger than the two PRC meters, the optic Price type-AA, metal winter Price type-AA and the Valeport BFM002. All meters had RMS less than 2.000 cm/s and for velocities less than 7.62 cm/s percent standard errors smaller than 0.75%. However, the vertical-axis and electromagnetic meters had better repeatability and smaller standard errors at velocities less than or equal to 45.72 cm/s.

The oblique flow response test is a measure of how accurately a meter measures the appropriate vector component of the flow. This test is also known as the cosine response because an ideal meter would register the cosine component of an angled flow. Each meter was tested at speeds of 7.62, 24.38, 45.72, 152.46 and 243.84 cm/s and at flow angles ranging from 90° to -90° in increments of 10°. Positive angles were flows directed downward onto the vertical-axis meters or from center to right side for horizontal-axis meters. At each combination of velocity and angle, two velocity measurements were made with each meter. Because only the meter and not the actual flow could be angled, the vertical-axis meters were positioned with the axis perpendicular to the force of gravity when testing for response to vertical angles of flow. This insured a consistent loading of the meter bearings throughout the oblique flow tests. Tilting the vertical-axis meters in the vertical plane would load the meter bearings differently for each angle tested and produce a varying error in the test.

Percent error was computed as $100 \times [\text{revs/sec}_\alpha \div (\cos\alpha \times \text{revs/sec}_0) - 1]$ for the mechanical meters. Subscripts α denotes the angle of flow and 0 straight flow. The electromagnetic meter percent error was computed using the display device reading instead

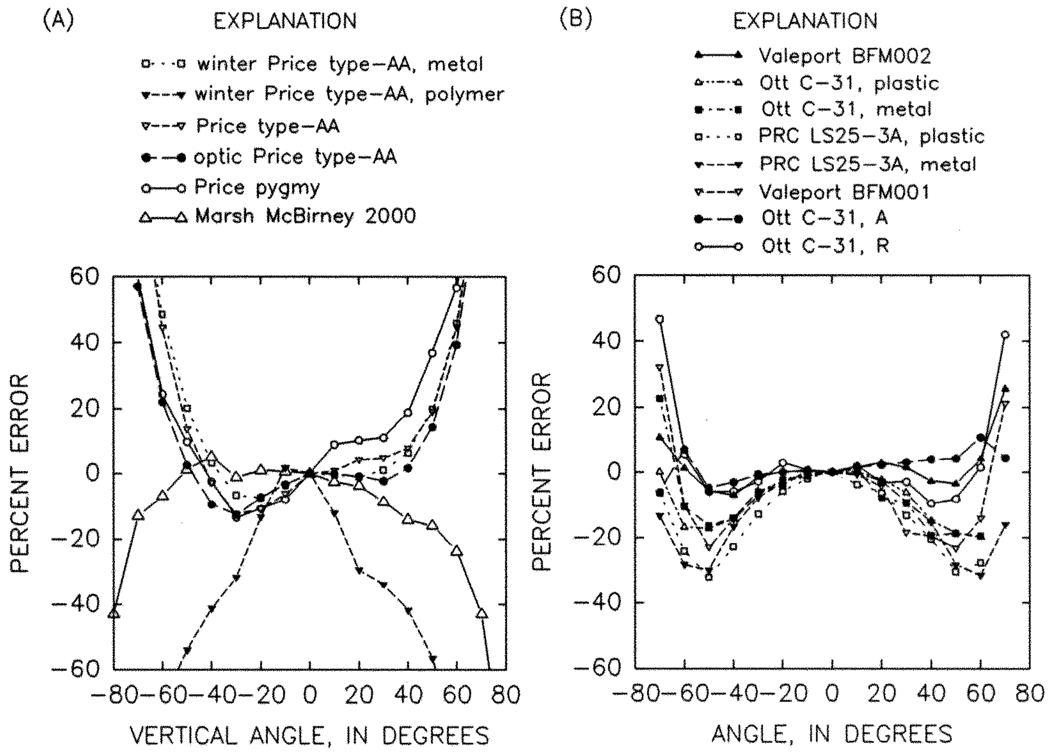


Figure 3. Average response for oblique flows for (A) vertical-axis and electromagnetic meters and for (B) horizontal-axis meters.

of r/s. Vertical-axis and electromagnetic meters were tested for response to vertical and horizontal angles of flow. Due to limited length of this paper, only the results of vertical-angle testing are shown. Stream gagers are unable to correct for errors due to vertically angled flow during field use of meters.

All tested meters under-registered and over-registered velocity depending on the angle and flow speed. In figure 3 are plots of average percent error for the five test velocities versus angle. Only the angles between ±80° are shown in figure 3 because any registration of velocity at ±90° results in a large error. The winter Price type-AA meter with polymer rotor under-registered for all angles tested. The other vertical-axis meters over-registered for positive angles and under-registered for angles between -40° and 0° the flow velocity. The electromagnetic meter over-registered for angles of -50°, -40°, -20°, and -10°, and under-registered for all other angles. All horizontal-axis meters stalled for flow angles greater than 70° and except for the Ott with the A or R impeller and the Valeport BFM002, tended to under-register the velocity for most angles. At angles between ±10° the vertical-axis meter errors range from -3.30% to -0.17% for the optic Price type-AA and from -7.87% to 8.92% for the Price pygmy. At angles between ±10° errors for horizontal-axis meters range from 0.58% to 0.91% for the Ott with plastic impeller and from -2.02% to -3.77% for the PRC meter with plastic impeller. The electromagnetic meter errors range from -2.565% to 0.699% at angles between ±10°. At larger angles of ±30° the vertical-axis meter errors range from -6.71% to 1.01% for the winter Price type-AA with metal rotor and from −31.83% to -33.97% for the winter Price type-AA with polymer rotor. For the horizontal-axis meters the errors range from -0.68% to 2.95% for the Ott with A

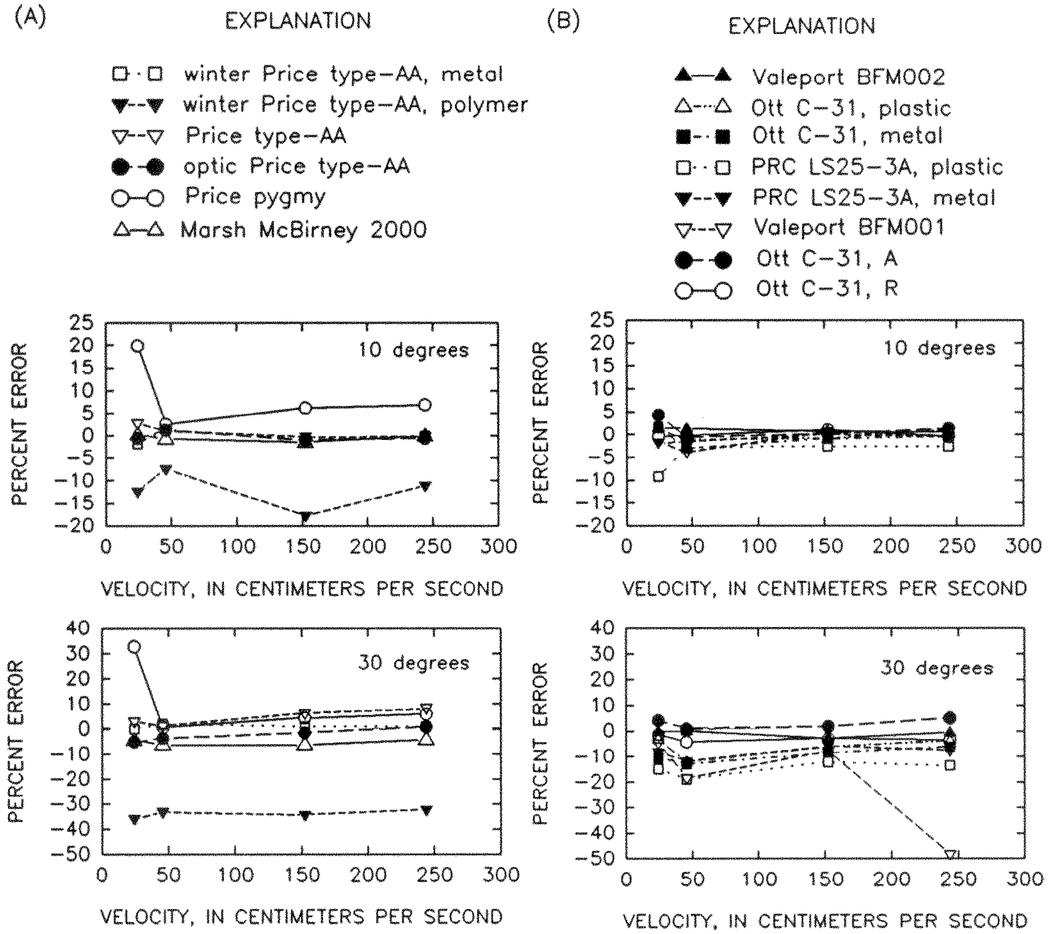


Figure 4. Response for 10° and 30° oblique flows for (A) vertical-axis and electromagnetic meters and for (B) horizontal-axis meters.

impeller and from -12.87% to -13.19% for the PRC meter with plastic impeller. The electromagnetic meter errors are -1.24% at -30°and -8.68% at 30°.

Error due to oblique flows increases slightly with velocity, except at the lowest velocity tested. At the lowest velocity tested, errors are larger than or nearly equal to the errors found for the highest velocity tested. In fig. 4 are plots of percent error versus jet velocity for 10° and 30° flows. Because the horizontal-axis meters stalled at low velocities in oblique flows, test results for 7.62 cm/s are omitted from the plot. All meters tested have larger errors at larger angles of flow. The Ott meters, equipped with component impellers (A and R) designed to register the cosine component of angled flow, have the smallest errors and the Price pygmy and the winter Price type-AA with polymer cup have the largest errors in oblique flow. The electromagnetic meter has smaller errors than the vertical-axis meters for most angles tested. Unlike the horizontal-axis meters, the vertical-axis and electromagnetic meters have an obvious asymmetrical response to vertical angles of flow. The asymmetrical responses are probably caused by flow disturbances that result from the contact chamber at the top of the vertical-axis meters and from the signal cable exiting the top of the electromagnetic meter probe.

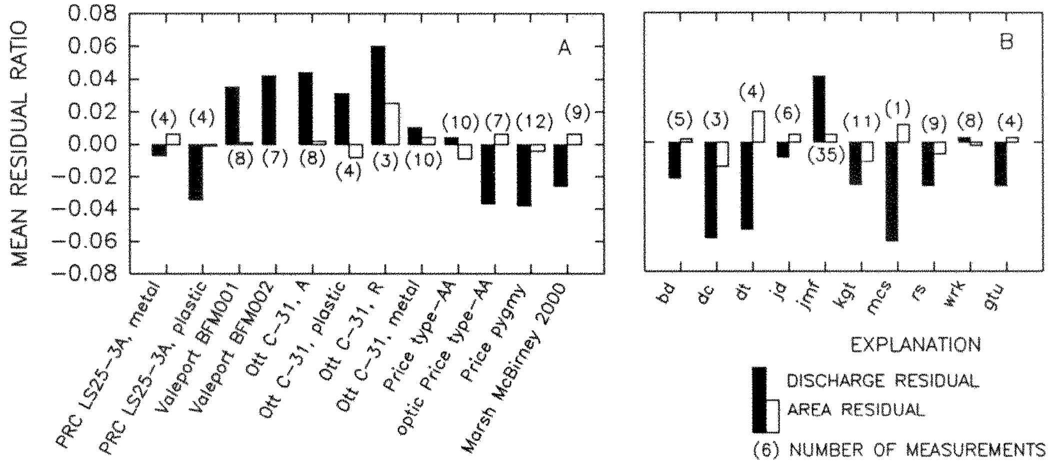


Figure 5. Mean percent residual grouped by (A) meter and by (B) stream gager.

Field Tests

Laboratory testing approximates and does not duplicate the field conditions in which current meters are used. In the field, meters are subjected to changing velocities and to an unknown range of flow angles. Meters in the field may not be subjected to the entire range of flow angles tested in the laboratory. Field testing is necessary to help interpret the importance of the laboratory findings. Field testing was done in 4 sections at the floodplain facility at the Stennis Space Center in Mississippi, and at five USGS gaging locations in Colorado and Wyoming. Three floodplain sections were located along a grassed half-trapezoid channel section. The fourth section was in the riprap bottomed exit channel of the facility. The locations in Colorado and Wyoming were mountainous streams with sand, gravel, and cobble bottoms. Discharge measurements were made using USGS stream-gaging procedures (Rantz, 1982). Winter Price meters were not used during field testing. Due to time constraints every meter was not used at every location. The Ott C-31 with metal impeller, Price type-AA, Price pygmy, Marsh McBirney, and Valeport BFM001 were used at every location except for the fourth floodplain section where the Valeport BFM002 was used instead of the BFM001. The remaining meters were used whenever possible. Although multiple stream gagers used various meters to measure the discharge, only three stream gagers (the authors) made discharge measurements at each of the sites. Usually a current meter was used once to measure discharge at a site. Meters were not rotated among gagers intentionally and some meters were used by only one stream gager throughout the field tests. All measurements were made by wading and meters were positioned in the water using the USGS top-setting wading rod. For the horizontal-axis meters, adapters were fabricated to allow their use with the top setting rod.

Discharge was not determined at any of the sites by means other than current meter measurements. As a result, meter performance can only be compared relative to the other meters. Of the total 86 discharge measurements, 41 were made in the floodplain and 45 were made in Colorado and Wyoming. Mean flow depths ranged from approximately 30.48 to 60.96 centimeters. Discharges ranged from 0.765 to 6.003 cubic meters per second (m^3/s) for the sites in Colorado and Wyoming and from 1.841 to 2.124 m^3/s for the floodplain sites in Mississippi. All fourteen meters operated satisfactorily during the

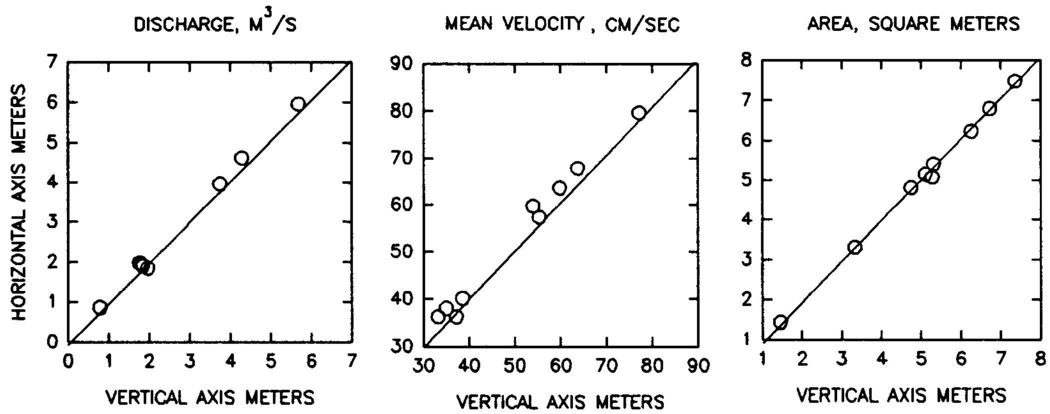


Figure 6. Test location averages of discharge, mean velocity, and area for horizontal-axis meters plotted versus averages for vertical-axis meters.

field tests and functioned in the 110°F water of the Hot River in Wyoming. However, the Valeport BFM001 nose cone unscrewed during measurements and had to be tightened in midstream. It was observed that the horizontal-axis meter impellers shed grass and other vegetation somewhat better than the vertical-axis meters and that grass did not prevent the electromagnetic meter from registering velocity.

Residual ratios were computed for discharge and area for each measurement location as residual ratio = (measured value$_i$ - mean value$_i$) ÷ mean value$_i$, where i is a location and the mean value$_i$ is computed from all the measurements at location i. Mean residual ratios of discharge and area were computed for each of the meters tested and for each stream gager. Bar charts of the mean residual ratio of discharge and area computed for the meters tested and for the stream gagers are in figure 5. Because discharge is the product of velocity and area, area is a possible source of error and was included in the analysis. Also included in figure 5 is the number of measurements made with each meter and by each stream gager.

Because all depths were measured using a top setting rod, small mean area residual ratios were computed for the meters (fig. 5A) and for the stream gagers (fig. 5B). Mean area residual ratios ranged from -0.008 to 0.025 for the meters and from -0.015 to 0.019 for the gagers. The mean discharge residual ratios for most meters and stream gagers are at least twice as large as the mean area residual ratios. Mean discharge residual ratios ranged from -0.038 to 0.060 for the meters and from -0.061 to 0.041 for the gagers. Except for the PRC meters(-0.007 metal, -0.034 plastic), horizontal-axis meters have positive mean discharge residual ratios. The vertical-axis meters, except for the Price type-AA(0.004), have negative residual ratios. The Marsh McBirney electromagnetic meter has a negative residual ratio of -0.026. The Ott C-31 and Price type-AA had the smallest discharge residual ratios. Because each gager did not use every meter at each measurement location, the mean residual ratios represent not only meter bias in discharge measurements but stream gager bias as well. Conversely, because some meters were used by one gager, gager bias is represented in the chart for the meters.

Groat(1918) found that vertical-axis meters over-register velocity and horizontal-axis meters under-register. However, for the field test data, most of the horizontal-axis meters over-registered the flows and most of the vertical-axis meters under-registered the flows.

The two PRC meters under-registered and the Price type-AA over-registered. Averages of discharge, mean velocity, and area for the horizontal-axis meter measurements are plotted versus the averages for the vertical-axis meters measurements in figure 6. The average areas are distributed about the line of perfect agreement between the meters in figure 6. The discharge and mean velocity are distributed above the line of agreement in figure 6 because horizontal-axis meters usually measured more velocity than the vertical-axis meters.

Summary

All meters tested had good repeatability (small percent standard errors) and similar linearity of response (RMS < 2.000 cm/s). For all meters tested, repeatability and response to oblique flow is poorest at the lowest test speed of 7.62 cm/s. Two horizontal-axis meters with component impellers, the Ott C-31 meter with A and R impellers had the smallest error in oblique flows. Except for the winter Price type-AA with the polymer rotor, the vertical-axis meters over- and under-register oblique flows with angles between $\pm 40°$. The Marsh McBirney electromagnetic meter also over and under-registers oblique flows with angles between $\pm 40°$. Horizontal-axis meters tended to under register oblique flows with angles between $\pm 40°$. The magnitude of error for horizontal-axis meters and the electromagnetic meter is usually smaller than those for vertical-axis meters in oblique flows. All meters tested, except for the Price type-AA, Price pygmy, and the winter Price type-AA polymer, had absolute meter errors less than 5% for flow angles between $\pm 10°$. Of the remaining meters, only the pygmy (-7.9% to 8.9%) did not have absolute errors less than 6% for flow angles between $\pm 10°$.

In previous literature it had been concluded that vertical-axis meters over register in "turbulent" flows in comparison to horizontal-axis meters. However, for the field data collected the vertical-axis meters and electromagnetic meters registered less velocity when compared with most of the horizontal-axis meters. The exceptions were the PRC meters, which registered lower velocity in comparison to the Price type-AA and greater velocity in comparison to the optic Price type-AA and the Price pygmy. The Marsh McBirney registered lower velocity in comparison to the Price type-AA and the PRC meter with plastic impeller.

References

Fulford, Janice M., Thibodeaux, Kirk G., and Kaehrle, William R. (1993)."Repeatability and oblique flow response characteristics of current meters," Proc. of 1993 Hydraulic Engineering Conference 1993, ASCE, New York, 1452-1457p.

Groat, B.F.(1918)."Characteristics of cup and screw current meters; performance of these meters in tail-races and large mountain streams",Transactions of American Society of Civil Engineers, New York, 819-870p.

Rantz, S.E. and others (1982)."Measurement and computation of streamflow: volume1. measurement of stage and discharge, USGS Water Supply Paper 2175, 79-183p.

Thibodeaux, Kirk G. (1992). "A brief literature review of open-channel current meter testing," Proc. of Hydraulic Engineering Conference 1992, ASCE, New York, NY, 458-463p.

Yarnell, David L. and Nagler, Floyd A. (1931). "Effect of turbulence on the registration of current meters." Trans. of the ASCE, 766-860p.