COMPARISON OF VERTICAL-AXIS AND HORIZONTAL-AXIS CURRENT METERS

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ABSTRACT: The U.S. Geological Survey is studying the performance of vertical- and horizontal-axis current meters commonly used throughout the world. Laboratory and field testing of selected current meters have been done. The horizontal-axis current meters include the Ott C-31 (Germany) with four different impellers, Valeport BFM001 and BFM002 (United Kingdom), and PRC LS25-3A (Peoples Republic of China). The vertical-axis current meters (all from the United States) include the Price type-AA, winter Price type-AA and the Price pygmy. Summarized are laboratory test results for meter precision, linearity, and response to oblique flow angles and preliminary field testing results. Both horizontal- and vertical-axis current meters were found in laboratory tests to under- and over-register velocities with errors usually increasing as the velocity and angle of the flow increased. Precision and linearity of all meters tested were similar. When compared with the vertical-axis meters, horizontal-axis meters, except for the PRC LS25-3A, registered more velocity in the field tests.
KEY TERMS: current meters, velocity instrumentation, discharge measurement.

INTRODUCTION

All mechanical-current meters measure velocity by translating linear motion into angular motion. An ideal current meter should respond instantly and consistently to any changes in water velocity, and should accurately register the desired velocity component. Also, the meter should be durable, easily maintained, and simple to use under a variety of environmental conditions. Due to the fundamental difference in their axial alignment, vertical- and horizontal-axis meters differ in their maintenance requirements and performance. Meter performance depends on the inertia of the rotor, friction in the bearings, and the ease with which water moves the rotor.

Many studies of current-meter performance have been conducted and are summarized by Thibodeaux (1992). Yarnell and Nagler's (1931) study on current meters is one often referenced. However, no consensus has been reached as to whether vertical- or horizontal-axis meters perform best for stream gaging. Townsend and Blust (1960) compared vertical- and horizontal-axis meters and found that under favorable measuring conditions both types give virtually identical results. In highly turbulent flows, a less than favorable measurement condition, Groat(1913) found that vertical-axis meters over-register velocity and horizontal-axis meters under-register velocity. Most of the previous meter studies were published prior to 1960 and the tested meters have been subsequently modified. Recent laboratory (Fulford and others, 1993) and field testing has been completed by the U.S. Geological Survey on several horizontal- and vertical-axis current meters commonly used throughout the world. A comparison of the laboratory and field tests for thirteen of these meters are presented in this paper.

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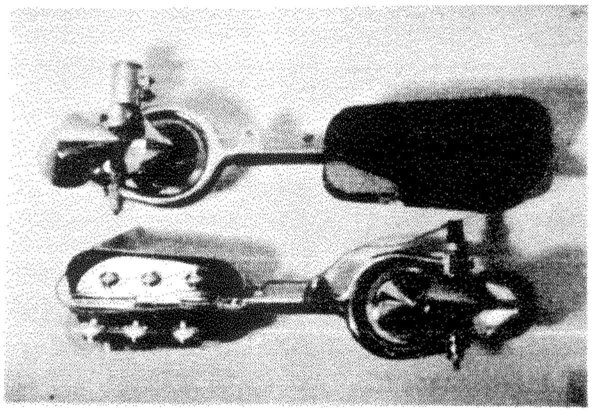
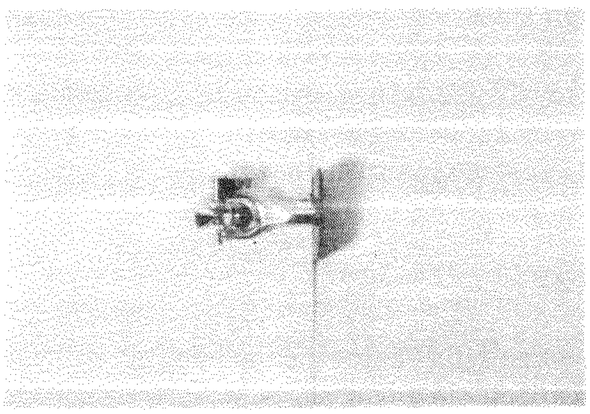
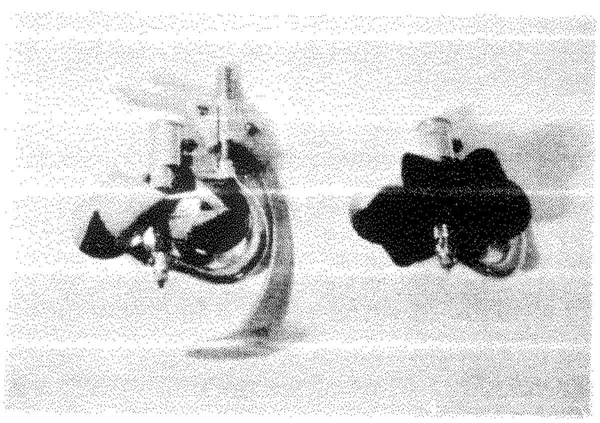


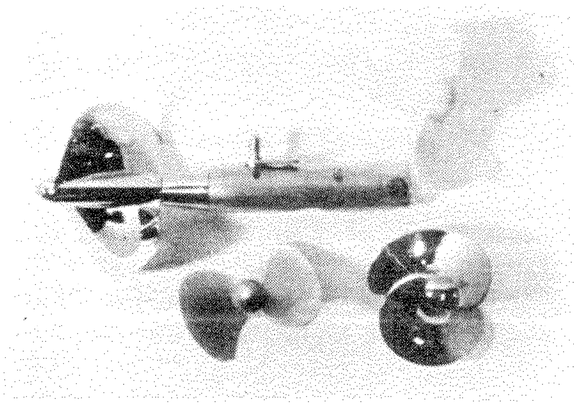
a) Upper meter, Price type-AA; lower meter optic Price type-AA



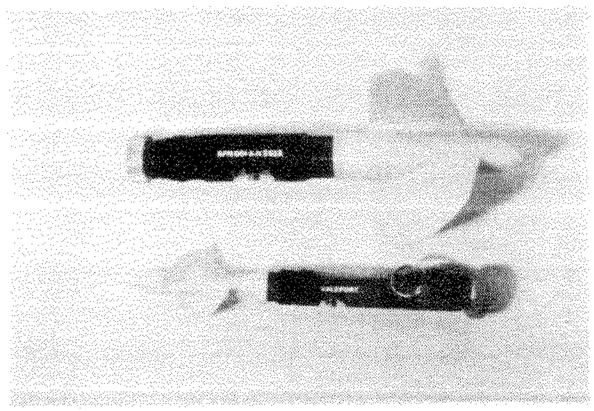
b) Price pygmy



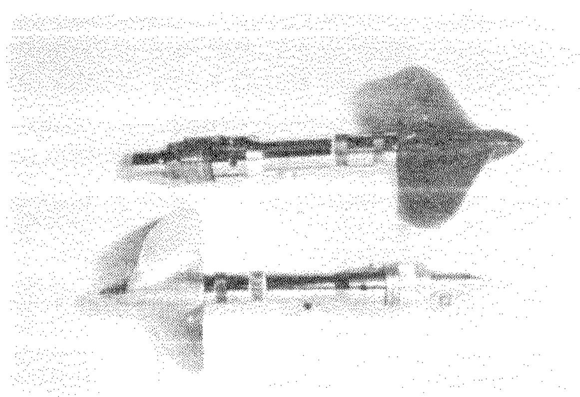
c) Left to right, winter Price type-AA, metal; winter Price type-AA, polymer



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 (PRC, People's Republic of China).

METERS TESTED

Comparisons are presented for five vertical-axis meters; Price type-AA, optic Price type-AA, Price pygmy, winter Price type-AA, and winter Price type-AA with polymer rotor; and eight horizontal-axis meters, Ott C-31 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 (any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government). These meters are shown in figure 1.

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 silt and sediment from contaminating the bearings. Disassembly for cleaning requires the removal of the shaft and rotor assembly from the yoke. Cleaning and oiling is recommended for vertical-axis meters after each discharge measurement.

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 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 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.

LABORATORY TESTS

Laboratory testing of the meters included precision testing and oblique flow response testing. All laboratory tests were conducted in the submerged-jet tank at the U.S. Geological Survey's Hydraulic Laboratory at Stennis Space Center in Mississippi. The jet tank is 120 feet long with a 12 X 12 feet cross section and can provide constant "live" velocities from 0.25 to 10 feet per second (ft/s). Velocity is determined by timed volumetric measurement and the 2 feet diameter area of the jet orifice. Meter angular velocity in revolutions per second (rev/s) is determined by counting and timing revolutions.

The precision test is a measure of meter precision and measures how repeatable or consistently a meter measures velocity. For each meter ten measurements were made at each of five velocities, 0.25, 0.8, 1.5, 5 and 8 ft/s. Meters were positioned pointing into the flow at the center of the jet. For each of the five velocities, standard errors were computed. Percent standard errors were computed from the meter revolutions per second at a jet velocity by dividing the standard errors by the mean and multiplying by 100. Plots of percent standard error versus jet velocity are shown in figure 2. For all meters, percent standard errors decrease with increasing jet velocity. The vertical-axis meters have a more consistent response than do the horizontal-axis meters. For the five velocities tested the vertical-axis meters have percent standard errors of less than 0.5%. The Price-pygmy meter has the largest

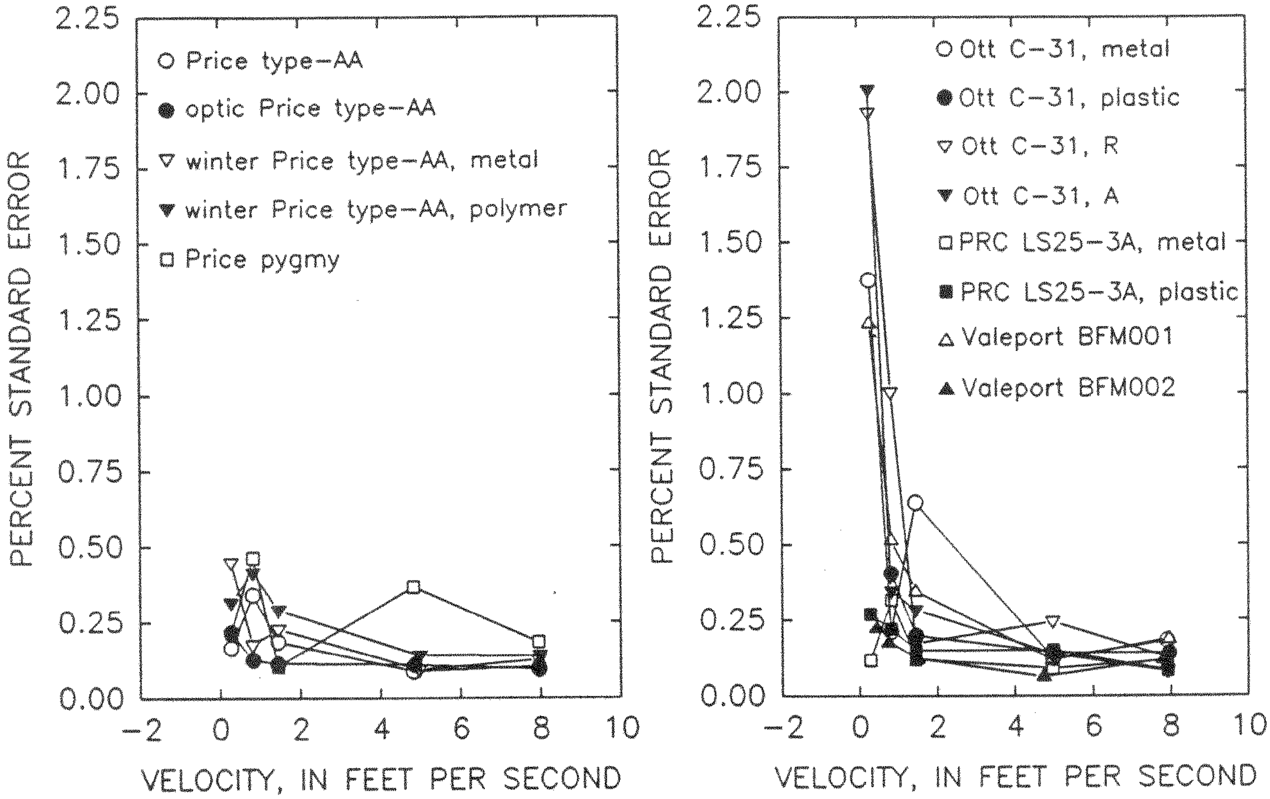


Figure 2. Precision tests. Percent standard error computed by velocity for (A) vertical-axis meters and for (B) horizontal axis meters (PRC, People's Republic of China).

percent standard errors of the vertical-axis meters. Horizontal-axis meters have percent standard errors of less than 0.75% for velocities greater than 0.8 ft/s. At the lowest test velocity (0.25 ft/s) the metal Ott, Ott A, Ott R, and Valeport BFM001 had percent standard errors from 1.2 to 2.0%. The PRC meters, plastic impeller Ott, and Valeport BFM002 had percent standard errors of less than 0.5%.

Precision test data were also fitted by a straight line using linear regression to determine their linear response. For each meter, the 50 measurements from the precision test (velocities of 0.25, 0.8 1.5, 5 and 8 ft/s) were regressed against the measured jet velocity. The root mean squared errors (RMS) and computed regression coefficients are listed by meter in table 1. Both horizontal- and vertical-axis meters generally have a similar range of RMS. The two PRC meters and the optic Price type-AA have the smallest RMS (about 0.018 ft/s) of the tested meters. The largest RMS is for the Ott with the A impeller (0.0656 ft/s). All meters had RMS less than 0.066 ft/s and for velocities less than 0.25 ft/s percent standard errors smaller than 0.75%. However, the vertical-axis meters had better precision and smaller standard errors at velocities less than or equal to 1.5 ft/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 0.25, 0.8, 1.5, 5, and 8 ft/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-

Table 1.-Root mean squared errors and regression coefficients for precision data.
[ft/s, feet per second; ft/rev, feet per revolution; PRC, People's Republic of China]

Meter	RMS error (ft/s)	slope (ft/rev)	intercept (ft/s)	axis type
optic Price type-AA	0.0172	2.211	-0.014	vertical
Price type-AA	0.0350	2.263	-0.019	vertical
winter Price type-AA/metal	0.0204	2.294	-0.004	vertical
winter Price type-AA/polymer	0.0563	2.592	0.056	vertical
Price pygmy	0.0536	1.051	-0.055	vertical
PRC LS25-3A /metal	0.0186	0.654	0.009	horizontal
PRC LS25-3A /plastic	0.0173	0.653	-0.002	horizontal
Valeport BFM001	0.0405	0.870	-0.002	horizontal
Valeport BFM002	0.0241	0.361	0.057	horizontal
Ott C-31 /metal	0.0507	0.840	0.087	horizontal
Ott C-31 /plastic	0.0450	0.835	0.007	horizontal
Ott C-31 /R impeller	0.0460	0.823	0.076	horizontal
Ott C-31 /A impeller	0.0656	0.421	0.127	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. 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. Positioning the axis perpendicular to gravity insured a consistent loading of the meter bearings throughout the oblique flow tests.

Percent error for all types of meters was computed as $100 \times [\text{revs/sec}_\alpha \div (\cos\alpha \times \text{revs/sec}_0) - 1]$ where the subscripts, α, denote the angle of flow and 0 straight flow. Vertical-axis meters were tested for response to vertical and horizontal angles of flow. Due to the limited length of this paper and because stream gagers are unable to correct for errors due to vertically angled flow during field use of meters, only the results of vertical-angle testing for the vertical-axis meters are shown with the angle testing for the horizontal-axis meters.

Both the vertical- and horizontal-axis meters under-register and over-register 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 meter rotation at ±90° results in a large error. Most vertical-axis meters over-register for positive angles and under-register for angles between -40° and 0° the flow velocity. The winter Price type-AA meter with polymer rotor under-registered for all angles tested. Horizontal-axis meters, except for the Ott with either the A or R impeller and the Valeport BFM002, tended to under-register the velocity for most angles. For flow angles greater than 70°, all horizontal meters stalled. 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. At 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 impeller and from -12.87% to -13.19% for the PRC meter with plastic impeller.

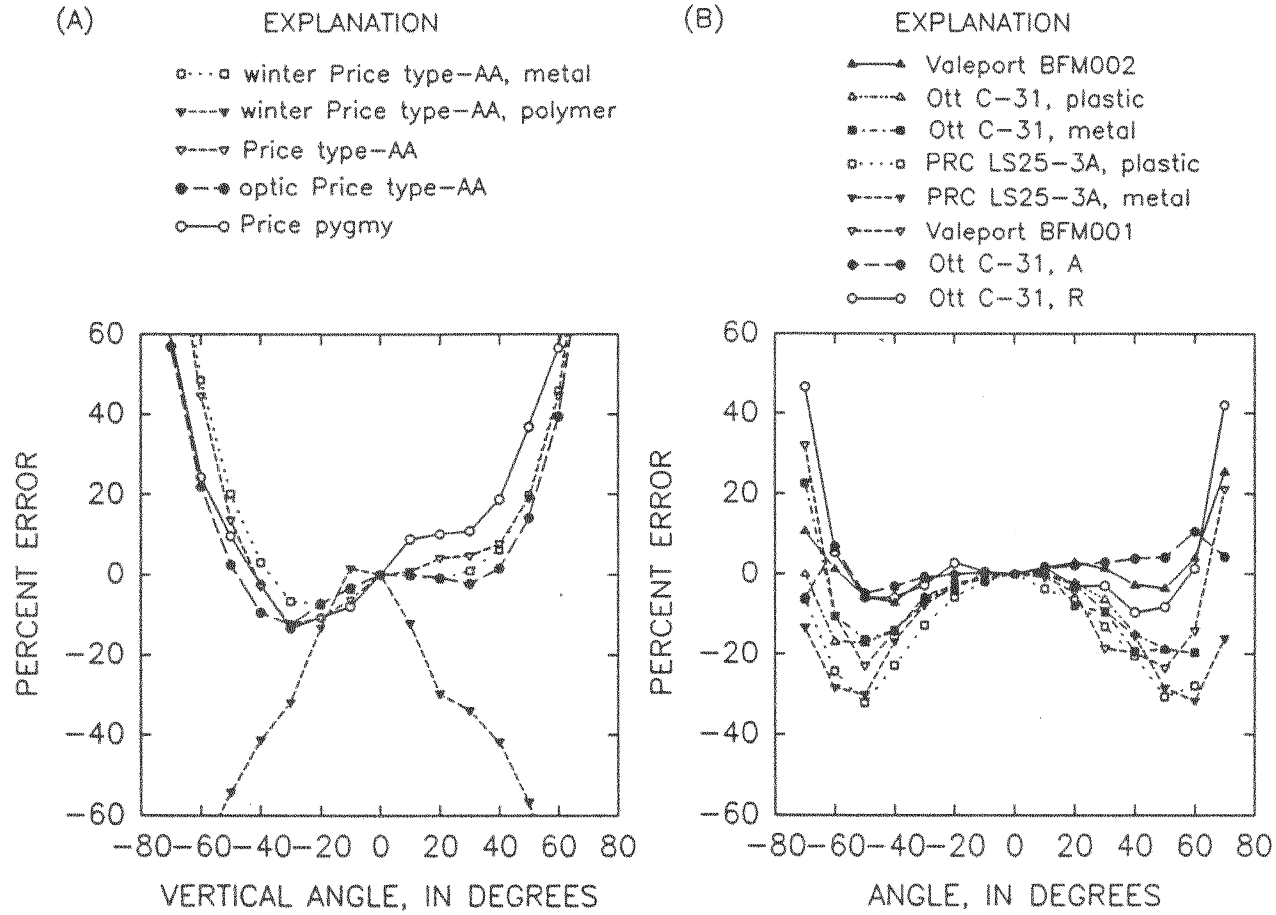


Figure 3. Average response for oblique flows for (A) vertical-axis meters and for (B) horizontal-axis meters (PRC, People's Republic of China).

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 figure 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 0.25 ft/s are omitted from the plot. Both groups of meters have larger errors at larger angles of flow. The Ott meters equipped with component impellers, A and R, have the smallest errors and the Price pygmy and the winter Price with polymer cup have the largest errors in oblique flow. Unlike the horizontal-axis meters, the vertical-axis meters have an obvious asymmetrical response to vertical angles of flow that is probably caused by the contact chamber at the top of the meter.

FIELD TESTS

Laboratory testing approximates and does not duplicate the field conditions in which current meters are used. In field flows 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

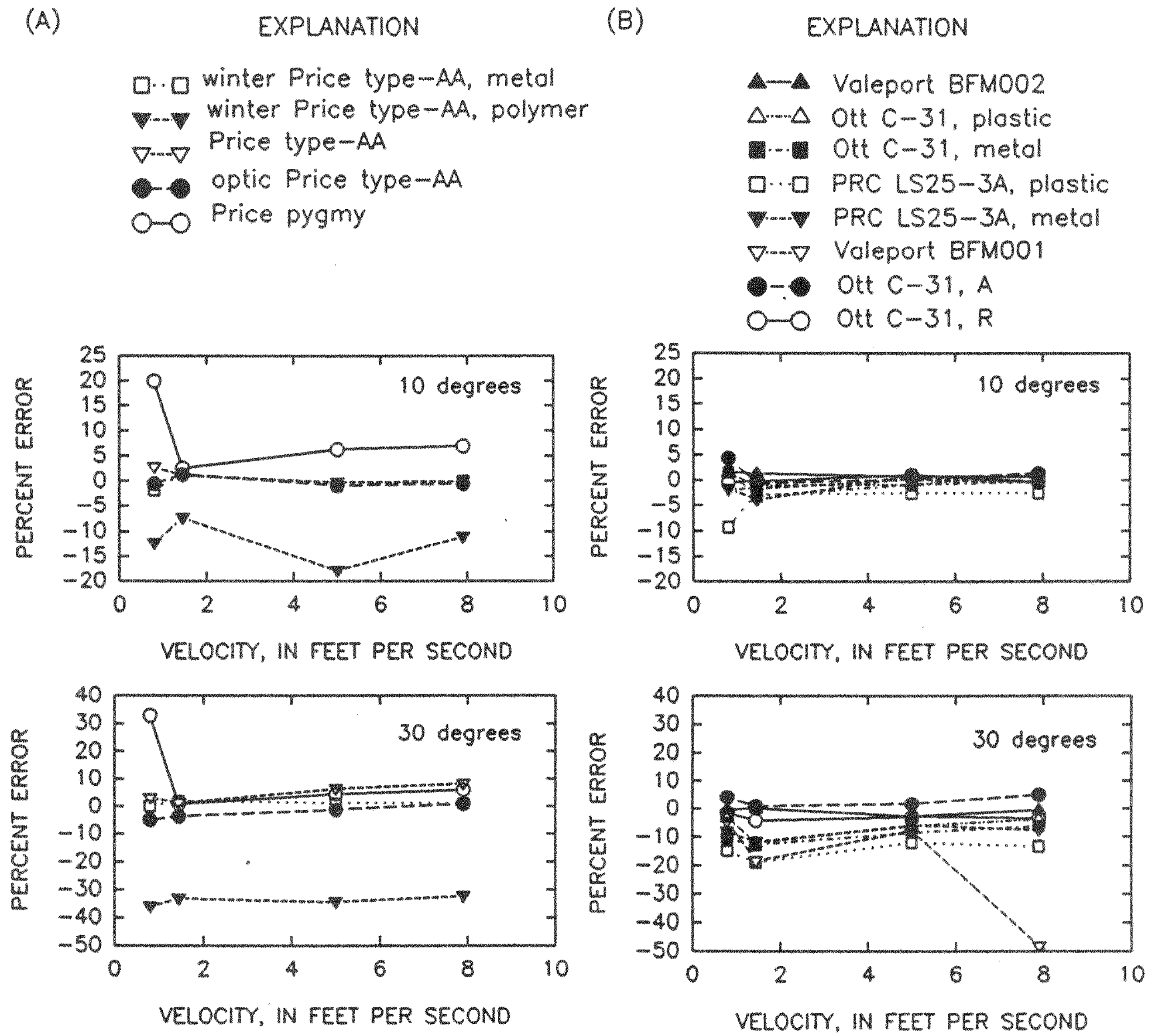


Figure 4. Velocity response for 10° and 30° oblique flows for (A) vertical-axis meters and for (B) horizontal-axis meters (PRC, People's Republic of China).

testing was done in four sections at the floodplain facility at the Stennis Space Center 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 cobbled bottoms. Discharge measurements were made using U.S. Geological Survey 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, Price-AA, Price pygmy 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

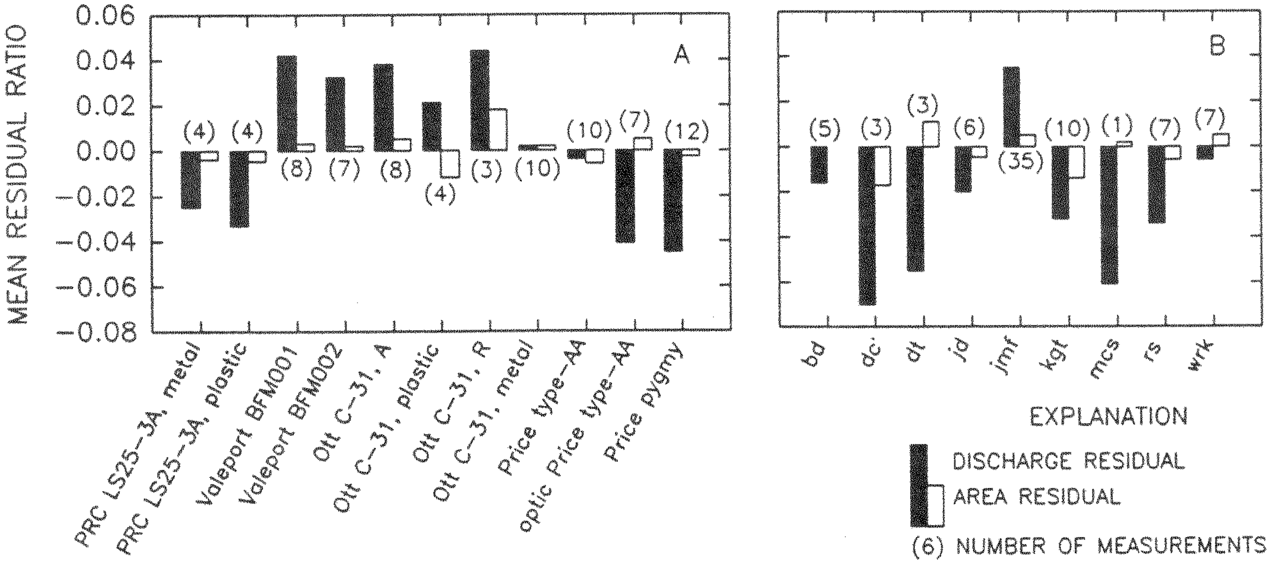


Figure 5. Mean percent residual ratio grouped by (A) meter and by (B) stream gager (PRC, People's Republic of China).

possible. Multiple stream gagers used various meters to measure the discharge, however only three stream gagers made discharge measurements at each of the sites. Usually only one discharge measurement was made at a site with a meter. 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 the current meter measurements. As a result, meters performance can only be compared relative to the other meters. Of the total seventy-seven discharge measurements, 37 were made in the floodplain and 40 were made in Colorado and Wyoming. Mean flow depths ranged from approximately 1 to 2 feet. Discharges ranged from 27 to 212 cubic feet per second (cfs) for the sites in Colorado and Wyoming and from 65 to 75 cfs for the floodplain sites.

Most meters operated satisfactorily during the field tests. All meters functioned in the 110°F water of the Hot River in Wyoming. However, the Valeport BFM001 nose cone loosen 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 did the vertical-axis meters.

Residual ratios were computed for discharge and area for each measurement location as residual ratio = (measured $value_i$ - mean $value_i$) $\div$ 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 are 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 (figure 5A) and for the stream gagers (figure 5B). Mean area residual ratios range from -0.012 to 0.018 grouped by meter and from -0.014 to 0.011 grouped by gager. The mean discharge residual ratios for most meters and stream gagers average 4 times larger than the mean area residual ratios. Mean discharge residual ratios range from -0.045 to 0.044 for the meters and from -0.070 to 0.035 for the gagers. Except for the PRC meters, horizontal-axis meters have positive mean discharge residual ratios. The vertical-axis meters have negative residual ratios. The Ott C-31 and Price type-AA had the smallest discharge residual ratios with the Ott having a slight positive bias and the Price a slight negative bias. Because each gager did not use every meter at each measurement location, the mean residual ratios represent not only stream gager bias in discharge measurements but meter bias as well. Conversely, because some meters were used by one gager, gager bias is represented in the chart for the meters.

Averages of discharge, mean velocity (discharge/area), and area were computed for each measurement location for the measurements made using vertical-axis meters and for the measurements made using horizontal-axis meters. These averages were computed for all the data and for the data not collected by stream gager "jmf" because of the possible bias of this gager (figure 5B) and the large number of measurements made by this gager using horizontal-axis meters. Plots of average 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 measured for either the entire data

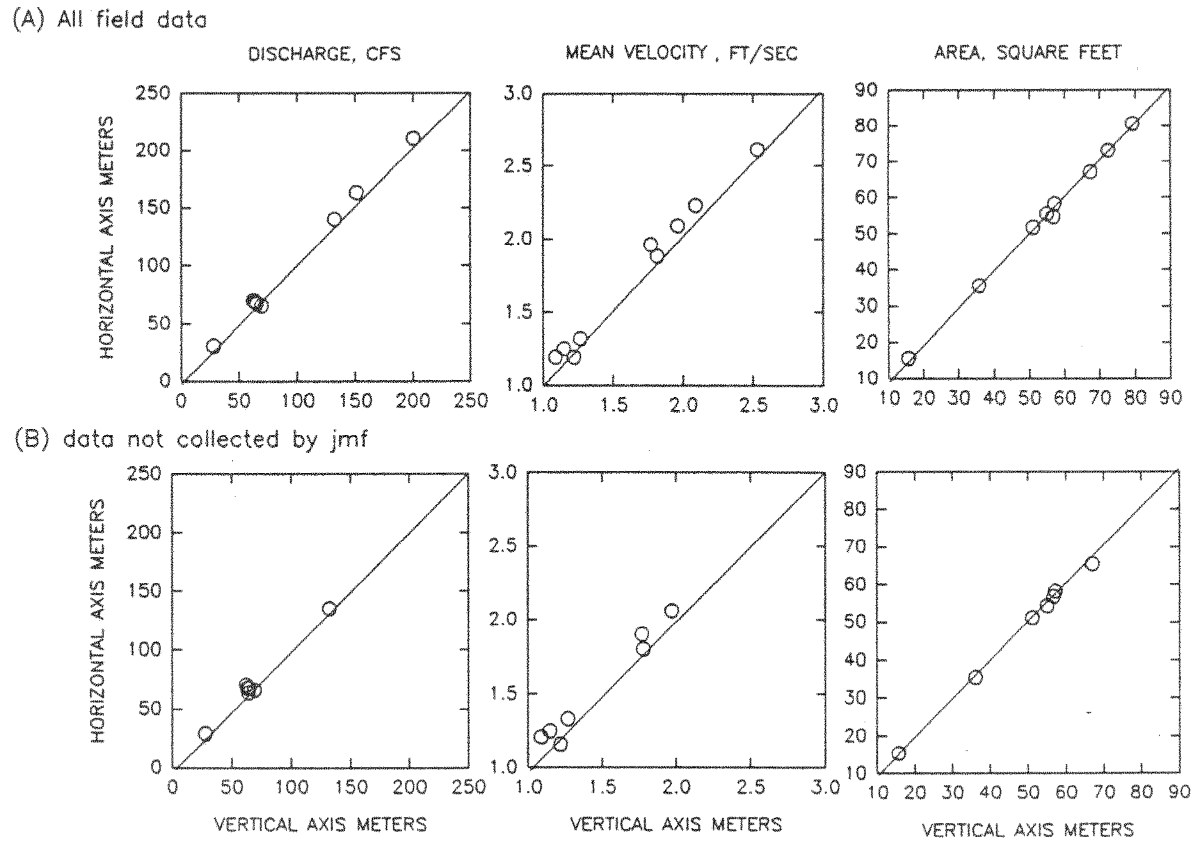


Figure 6. Field test location averages of discharge, mean velocity, and area for horizontal-axis meters plotted versus averages for vertical-axis meters.

set (figure 6A)or the data excluding "jmf" are distributed about the line of perfect agreement between the meters. Because horizontal-axis meters usually measured more velocity than the vertical-axis meters, the discharge and mean velocity are distributed above the line of agreement in figures 6A and 6B. Omitting data collected by gager "jmf" did not significantly alter the distribution of the points about the line of agreement.

SUMMARY

Both horizontal- and vertical-axis meters tested had good precision (percent standard errors < 0.75% for velocities >0.8 ft/s) and a similar linearity of response (RMS <0.066 ft/s). Two horizontal-axis meters, 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 ±40°. Horizontal-axis meters tended to under register oblique flows with angles between ±40°. At angles between ±10°, errors ranged from -7.87% to 8.92% for the vertical-axis meters and from -2.02% to 3.77% for the horizontal-axis meters. The magnitude of error for horizontal-axis meters is usually smaller than those for vertical-axis meters in oblique flows. Laboratory test results were similar to those found for the old models of the meters previously tested by others. In previous literature it had been concluded that vertical-axis meters over register in "turbulent" flows in comparisons to horizontal-axis meters. For the field data collected the vertical-axis meters registered less velocity when compared with most of the horizontal-axis meters. The PRC meters registered less velocity in comparison to the Price type-AA and more velocity in comparison to the optic Price type-AA and the Price pygmy.

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