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U.S. DEPARTMENT OF COMMERCE
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Coast & Geodetic Survey

Performance Tests of Richardson-Type Current Meters

I. TESTS 1 THROUGH 7

LT. CDR. R. L. SWANSON AND
LT. R. H. KERLEY

ROCKVILLE,
MARYLAND
January 1970

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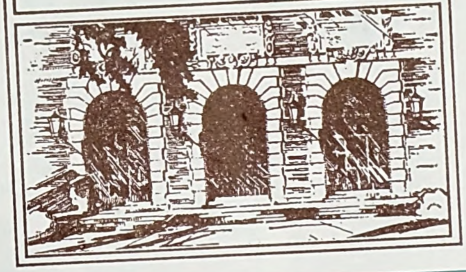

U.S. DEPARTMENT OF COMMERCE
Environmental Science Services Administration
Coast and Geodetic Survey

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PERFORMANCE TESTS OF RICHARDSON-TYPE CURRENT METERS
I. TESTS 1 THROUGH 7

Lt. Cdr. R. L. Swanson and Lt. R. H. Kerley

ROCKVILLE, MD.
January 1970

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ABSTRACT

The Coast and Geodetic Survey has tested the effects of different types of suspension systems on the Tidal Current Survey System (TICUS) and Geodyne Model A-102 ocean current meters and their data outputs. The best suspension system for field use was sought. A bridle-type suspension using flat-bar tension members was found to give the greatest stability for both meters. A bridle-type suspension using chain tension members was the best alternative. For current speeds in excess of 2 kt, a split stabilizer fin is needed to reduce transverse tilt. Theoretical work leading to a better solution is indicated. Further tests are planned.

INTRODUCTION

The Coast and Geodetic Survey is responsible for the prediction of tidal currents in estuaries and other waterways in and around the coastal areas of the United States and its possessions. These predictions are based primarily on a harmonic analysis of time series of observations of currents at numerous geographic locations. The initial C&GS surveys utilized current poles and loglines. These measurements gave way to current meters and systems that provided remote sensing and telemetering of the data. To satisfy the increasing demand for more detailed current information, the C&GS abandoned its traditional hand-processing of current data in favor of much faster computer-oriented methods. However, the design and development of adequate current meters to meet required accuracies of measurement have not kept pace with the improved systems to handle the data. This difficulty is keenly felt in the C&GS where limited in-house design and development capability make it necessary to purchase "off-the-shelf" equipment whenever possible.

In 1965, the Coast and Geodetic Survey purchased several Richardson-type current meters from the Geodyne Corporation. Since then the C&GS has continued to improve its current measuring systems and meters as new technical developments have been made. The most recent advance is the TICUS System (Tidal Current Survey System), which was designed specifically to meet the needs of the C&GS. Unfortunately, the data recorded by these and other Richardson-type meters have never been as satisfactory as necessary or expected. The configuration of the meter is not what one would expect to be the most advantageous for use in an estuarine environment where the C&GS must measure currents that flow at relatively high speeds over shallow depths.

It has been customary to suspend current sensors from a surface buoy in a vertical array (limited to 7 meters), such that the supporting cable is attached to a U-bolt at the top and bottom of each sensor. The surface buoy also houses the telemetering equipment. In the case of the TICUS meters, the data collected in this manner are somewhat suspect when compared with current observations made by drogue, logline, and Roberts Radio Current Meter. These comparisons indicate that at current speeds of 1.25 to 2.00 knots (kt) and greater the Richardson-type meter begins to significantly underestimate the actual current.

The first reaction is to assume that the tilt of the current meter prevents the Savonius rotor from being fully exposed to the flow of the current. Taut wire moorings conceivably could be the solution to this and other problems, but current observations usually are made near the surface and in navigational channels; hence, this type of mooring is not practical. In addition to errors in current speeds, current directions also fluctuate much more than would be expected from turbulence. Direction readings have varied as much as 120° in a 45-second period.

A substantial amount of work has been done in various hydraulics laboratories on the calibration of the Savonius rotor. Most of this work has been under controlled condtions that are dissimilar to the estuarine conditions encountered in Coast and Geodetic Survey studies. For example, meter tilt has been shown to have an effect on recorded current speed (Gaul, 1963). Tilt, however, is caused by the force of the current and the type of suspension system used. Observing the flow with respect to a rotor set at a fixed tilt angle does not represent the problem encountered in the field.

The tests described in this paper were conducted to observe the performance of the Richardson-type meter under conditions simulating the range of current speeds encountered in an estuarine environment; to identify problems in the recording of suspected erroneous data; and to find solutions to these problems so that current data of better quality might be obtained. All tests were performed in the circulating water channel at the Naval Ship Research and Development Center, Carderock, Md., in July 1969. The meters undergoing testing were suspended from a fixed position above the tank. The water in the tank was circulated at regulated speeds. The current speed in the tank can be varied from 0.6 kt to 10 kt and controlled to within 0.1 kt. The optimum range is between 1 kt and 6 kt. The available tank space is 60 feet long, 22 feet wide, and 9 feet deep.

The tests were performed using TICUS meter number TM 127, and Geodyne photographic recording Model A-102, number J-101. It was possible to observe the suspended meter in the tank from each side, from the bottom, and from the top. This provided an excellent opportunity to actually observe the meter in the water and to see the effects of several suspension systems. A camera was mounted facing normal to the flow. A plumbline was kept in the field of view at all times so that tilt of the meter could be determined under various current speeds and various suspension systems.

In addition to the two meters, and necessary electronic support equipment, testing materials included: nylon rope, steel cable, and steel shackles for suspending the meters into the tank; two hanger support devices (consisting of a yoke at the top, tension members, and a meter collar) which allowed the meter to pivot relative to its suspension--one having tension members made of chain, the other having tension members made of flat-bar stainless steel stock; two rudder-action fins; and one 25-pound fish weight. Both meters were modified from the standard configuration as had meters used in previous field operations by having a 30-pound hemispherical lead weight mounted on the base of the meter. The meters are illustrated in figures 1 and 2 with components labeled.

Seven tests were conducted in the circulating water tank. Several additional tests were performed in air at the Coast and Geodetic Survey's Engineering Development Laboratory. A discussion of each follows.

TICUS METER TESTS

Test 1

Layout.--A top-mounted nylon-cable suspension (fig. 3) was used for the first test. The meter was suspended by a cable, consisting of 5 ft of 3/8-in. nylon rope, attached to the U-bolt of the pad lifting assembly. Sufficient cable was payed out to keep the top of the meter submerged approximately 1 ft at all speeds to avoid noticeable surface disturbances. Tank speeds varied from 0.6 to 4.0 kt.

Results.--The tilt of the meter was drastically affected by the speed of the current. Figures 4 and 5 show the tilt of the meter in the direction of flow at speeds of 2 and 4 kt, respectively. The meter behavior was unpredictable throughout the first test. At 0.8 kt the base of the instrument (where the rotor and vane are located) had an apparent circular motion caused by its swinging in a conical trajectory with the apex being the junction of the supporting cable with the meter. The vane pivoted on its axis about $\pm 2^{\circ}$ at this speed. At 1.25 kt it was noticed that the meter was tilting in a plane perpendicular to the direction of the current, in addition to the tilt in the direction of flow. Looking in the direction of flow, the base of the meter was displaced to the right at an angle of 2.5°. This transverse tilt was thought to be negligible, and was ignored for the remainder of the test. The motion of the meter became more pronounced as the speed of the current increased. At 1.75 kt a whiplike motion in the meter and cable, perpendicular to the flow, commenced and was superimposed on the existing circular motion. Vane flutter increased to $\pm 5^{\circ}$.

Test 2

Layout.--In test 2 a side-mounted chain suspension was used (fig. 6). A brass collar encircled the TICUS meter at its center of drag and two brass suspension chains ran from pivots on the collar up to a yoke which was fastened to the main 1/4-in. stainless steel cable.

Prior to running through the complete range of speeds, several trials were performed to determine the best location for the suspension collar. The current speed was set at 2.0 kt and the center of the collar was located alternately at 18, 20, 22, and 24 in. from the top of the pressure end cap. Figure 7 shows that the 24-in. collar setting gave the best results. This collar setting was adopted for use in the more extreme test from 0.6 to 4.0 kt.

Results.--Use of the chain suspension improved the overall operation of the meter. Tilt in the direction of flow was small compared to use of the top suspension. Vane flutter was almost indistinguishable. The meter appeared to be remarkedly stable even at a current speed of 4 kt. At 2.22 kt the flutter might have been 1° or 2°. The meter case oscillated through an arc of ±7°. Transverse tilt, however, became extreme after 2.0 kt, at which point it was 5°. At 4 kt the transverse tilt was estimated to be on the order of 25°.

Test 3

Layout.--Test 2 showed that transverse tilt could be a significant factor in the data output at velocities much greater than 2.0 kt when using a suspension located near the meter's center of drag. The cause of the tilt was suspected to be the reaction of forces on the Savonius rotor. Confirmation was achieved by streaming the meter without the rotor through the range of current speeds from 0 to 4 kt. No transverse tilt was observed throughout this test.

To compensate for transverse tilt and still use the chain suspension, a fin measuring 13 in. in the vertical by 20 in. in the horizontal was mounted so that its top edge butted up against the top pressure end cap. At 4 kt the tilt was still on the order of 15°. Increased compensation was achieved by modifying the fin into a split stabilizer with uppermost section placed at an angle of 40° to the left of the main fin relative to the current direction. Figure 8 is a photograph of the fin assembly. The collar was set 23 in. below the pressure end cap to compensate for the addition of the split stabilizer.

Results.--Streaming the meter at speeds between 1 and 5 kt yielded a maximum transverse tilt of 9°. The split stabilizer concept proved to be effective, although the net result of it and the Savonius rotor was to displace the entire meter to the right of the center of the stream by a few inches.

Test 4

Layout.--In this test a side-mounted flat-bar suspension was used (fig. 9). This suspension is similar to the chain suspension previously described, but the two chains from the yoke to the meter collar were replaced by 1-in. stainless steel flat bars. This bridle-type suspension was supported from above the tank by the main 1/4-in. stainless steel cable. The meter collar was placed 24 in. below the top of the pressure end cap. A stabilizer fin was not used.

Results.--The meter was surprisingly steady. Visually, the vane fluctuations were considered insignificant. The photograph of the meter (fig. 10) shows that meter tilt in the direction of flow was kept to a minimum. Transverse tilt was on the order of 17° at 4 kt. Apparently, the flat-bar suspension added sufficient rigidity to the system to reduce the transverse tilt from that observed when the chain suspension was used. Note in the photograph how the electrical cable was fastened to the frame of the suspension--it is completely out of the way, and there is little chance of fouling in the meter.

Test 5

Layout.--The flat-bar suspension of test 4, was used in test 5, but with a split stabilizer fin to correct the transverse tilt of the meter. The meter collar was 23 in. below the pressure end cap. The fin was butted up against the pressure end cap (fig. 11). Initially, the split in the stabilizer was 35° to the left of the main fin, looking in the direction of flow. With angles of 35° and 30° the fin overcorrected the transverse tilt of the meter, causing the bottom of the meter to be displaced to the left when looking downstream.

Two additional ideas for eliminating transverse tilt were tested. In the first procedure, the vane was replaced by a Savonius rotor spinning clockwise as viewed from the top. Thus the meter consisted of two rotors moving in opposite senses. In the second procedure, a small stabilizer fin was fitted around the hemispherical weight on the base of the meter.

Results.--The most advantageous angle for the split stabilizer appeared to be 25°, which maintained transverse tilt between 3° and 5° although this was also an overcompensation. Again, the meter appeared to be stable with very little fluctuation of the vane. The double set of Savonius rotors reduced the transverse tilt considerably but not completely, owing to the difference in the lengths of the moment arms over which the forces created by the rotors act. The small bottom-mounted fin failed at 2 kt because of a lack of strength; however, the concept appeared to work.

Test 6

Layout.--In this particular test, the flat-bar suspension was used with the Geodyne A-102 meter. The meter collar was placed 33 in. from the top of the end cap. The split stabilizer with an angle of 25° was butted as close to the end cap as possible (fig. 12). This arrangement was considered best after having the fin located at 4, 2.5, and 1.5 in. from the top of the end cap, while the collar was at 32 in. from the top of the end cap.

Results.--The meter appeared to be quite stable. Transverse tilt became obvious at 1.5 kt, reached nearly 10° at 2.0 kt, and remained nearly constant up through 4.0 kt. It is evident from the photographs that the meter collar should have been lower than 33 in., but the hanger bars were not long enough to permit additional lowering.

Test 7

Layout.--Test 7 was run using the flat-bar suspension and a straight fin--13 in. in the horizontal and 20 in. in the vertical. This particular fin was tested because it has been used extensively in the field. The top of the fin was placed 4 1/2 in. below the top of the end cap (fig. 13).

Results.--At low current velocities the meter oscillated considerably. The data indicate that at speeds of 0.6 and 0.75 kt the meter was swinging through an arc of approximately 40°. The period of the meter oscillation was 7 sec at 0.6 kt and 5 sec at 0.75 kt. At speeds of 1.0 kt and greater, the meter oscillations became considerably less. The test was stopped at 2.0 kt. A transverse tilt of 7° was recorded at this speed.

A fish weight was added to this suspension (fig. 14) but did not result in any noticeable advantage. The meter continued to oscillate at low speeds and transverse tilt was not reduced.

DISCUSSION AND CONCLUSIONS

TICUS and A-102 meters are very sensitive to tilting in the direction of flow, unless both ends of the instrument are constrained. Figure 15 indicates that the relationship between current speed and tilt is nearly linear for a single TICUS meter when suspended by cable attached to the U-bolt in the pad lifting assembly. In figure 16 current speed is plotted against meter indicated speed. This shows the difficulty of using a calibration curve to adjust meter speed. When the current exceeds a speed of about 3.0 kt, the curve appears to approach a value of meter speed asymptotically. Consequently, a small error in meter speed could lead to a poor approximation of the current.

If a surface mooring is used and the current to be measured is anticipated to exceed 1 kt, the meter should not be suspended by the top U-bolt.

We believe that a taut wire mooring is probably the best type of mooring, but it is not always feasible, particularly in shallow depths where there is a large tidal range. Because a taut wire mooring is not always practical, a suspension which balances the forces over the length of the meter appears to be the best solution. The side-mounted chain (tests 2 and 3) and side-mounted flat-bar (tests 4 to 7) suspensions appear to work satisfactorily. In all tests where the side-mounted collar-type suspension was used the current speed was overestimated. This result conforms to previous tests reported by Gaul (1962) which indicated that the Savonius rotor overestimates the mean flow when in a turbulent field.

Figure 17 is a plot of actual current speed versus angle of meter tilt in the direction of flow, using the data from test 4. Angles were measured from the photographs taken during the test. The figure shows that the meter was very nearly stable as it oscillated about 0° of tilt with a maximum of only 3°.

In solving one problem, another was created. The rotation of the Savonius rotor in the current meters causes a situation similar to the flow around a rotating cylinder. Rotation of the rotor creates an unsymmetrical velocity distribution as indicated by the streamlines in figure 18. As a result of the velocity distribution, a pressure gradient is established in which the low pressure is associated with the concentration of streamlines. The net force is normal to the undisturbed uniform flow. This condition is known as the "Magnus effect" (Streeter, 1966). Transverse tilt caused by the "Magnus effect" became extreme with the side-mounted collar-type suspension. With the chain suspension the transverse tilt reached 25° at 4 kts. The flat-bar suspension appeared to give a little more rigidity, and the maximum transverse tilt was reduced to 17° at 4 kts. The split stabilizer was used to overcome this new problem. Addition of a split stabilizer to the meter further reduced the tilting; figure 19 shows that the maximum transverse tilt was kept as small as 4° with the flat-bar suspension. A force diagram (fig. 20) illustrates the principle.

The meter with a split stabilizer is awkward to handle. An equally effective device which would make the meter easier to manipulate is desirable. A possible solution is to place on the bottom of the meter a fin which would not extend beyond the meter case. The area of the fin should be designed so that the force created by the Savonius rotor would be balanced by an equal and opposite force from the fin. The general principle is illustrated in figure 21.

Direction as indicated by the meters is the sum of the compass card and vane follower card readings. The first four tests indicated a general trend for the direction readings of the meter to lose accuracy with a decrease in current speed. The circulating water channel is far from ideal for calibrating a compass, and the relationship of direction and speed caused concern. To establish the effect of the 3 phase, 60 cycle, 2300 volt impeller motors on the magnetic field at the tank, hand compass observations were made over the meter for currents between 0.6 and 2.50 kts. The mean magnetic direction was 285°

and the maximum deviation was ±3°. The actual direction of flow was 293° magnetic. This has lead us to believe that the magnetic field in the tank does not change with the motor speed, and consequently with increase in water speed.

Meter position within the tank was critical. As current speed increased, the meter moved in relation to its starting position both in the direction of and perpendicular to the flow. This occurred as a result of maintaining the vertical position of the meter at constant depth. Figure 22 shows a sketch of the tank with the relative position of the meter indicated for several different water speeds. Positions one, two, and three were the positions at which the meter was most commonly observed. The TICUS meter was positioned at each of the indicated locations in a current flow of 0.6 kt. Variation of the compass, vane, and direction are tabulated in the appendix. While position within the tank did affect the compass, the magnitude of the change for the three positions occurring most often was only about half the change observed in the other tests. Position four should have caused the direction output to read higher in the other tests. This was not observed, the indication being that factors other than position of the meter in the tank were affecting the direction readings.

Consideration also was given to the possibility that the magnets on the Savonius rotor (used to indicate rotation) might set up their own variable magnetic field as the rate of rotation changed. Comparison of rotation rate and direction in air disproved this hypothesis.

A series of plots were made showing how the direction, compass, and vane readings varied with speed. The relationship between actual current speed and indicated current direction from the TICUS meter is shown in figure 23. The change in direction output was considerably less in test 5, when the split stabilizer was used to reduce the amount of transverse tilt. Our only explanation for the displacement of the curves is that the meters were in slightly different positions within the tank. It should be noted, however, that the curves do tend to converge at low current speeds.

If the meter case changes its position relative to the current, both the compass card and vane follower card will change even though the direction of the current remains constant. The principle of the direction readout is described in the appendix. In order to eliminate the change in position of the meter case with respect to the current, we made the assumption that the mean position of the vane at each speed remained constant relative to the current. We took the vane readout at 4.0 kt as a reference in each test. The difference, or variation, between the meter vane readout at 4.0 kt, and the vane readout at the other speeds was an indication of the rotation of the meter case. Figure 24 is a plot of this data. The graph indicates a general trend for the readout of the vane follower to change with current speed, test 5 excepted. In test 5 the variation in the vane follower changed very little.

A similar procedure was used for the compass card readings. In addition, the differences between the vane follower at 4 kt and the vane follower readings at the other speeds were subtracted from the compass card differences referenced to 4 kt. These give an estimation of the compass readings with the meter rotation removed. A plot is shown in figure 25. The indication is that the compass readings varied with current speed. Test 5, which used the split stabilizer, had less variation than the other tests.

Several readings were taken of vane follower direction and compass direction for each speed for all the test configurations, and a range of direction readings were obtained for both at each individual speed. These data are plotted in figures 26 and 27. We found it interesting that in test 1, when the meter was suspended from its top, a wide fluctuation of both compass and vane follower occurred, particularly in the 1.50 to 2.50 kt range.

The last five graphs suggest an apparent relationship between vane follower and compass direction and the current speed. Our tests with the hand compass and rotation of the Savonius rotor in air indicate that this relationship should not exist.

An alternative to the implication that rotor speed affects the compass is that the compass and vane readings are actually related to the tilt of the meter, either in the direction of, or perpendicular to the flow. To test this hypothesis, the meter was tilted at fixed angles of 0°, 7°, 12°, 17°, and 22° from the vertical, rotated clockwise from 0° to 360° magnetic and returned counterclockwise to 0°. These data are presented in figure 28. There is a definite trend for the deviation of the meter compass and the magnetic heading to increase with tilt of the meter.

Hysteresis is also present in this relationship, since the graph relating meter compass and magnetic directions for clockwise rotation of the meter differs from the graph for counterclockwise rotation.

These results show that this particular meter did not meet Geodyne's specification, which implies that tilt in the meter as much as 35° will have no effect on its direction indications (EG&G International, 1969). The behavior of this one meter may not be a general characteristic of all meters of this type. However, the importance of the results is that if tilt is kept to a minimum, the output of the meter will probably be more reliable, especially if the compass is faulty in any way.

An estimate of the line tension on the cable for test 5 has been made by applying the formula:

$$\text{Tension} = \frac{W}{\cos\theta}$$

Where, W is the weight of the meter in water, and θ the angle the suspension makes with the vertical. The angles were measured from the pictures obtained at the various speeds. The results are shown in figure 29.

In our opinion the tests accomplished the goals which were originally established.

RECOMMENDATIONS

The tests and evaluation of the data from the tests have yielded pertinent information regarding utilization and areas for future study of the TICUS and A-102 current meters. The following recommendations are made:

(1) If currents are expected to be between 1.0 and 4.0 kt, all TICUS and Geodyne A-102 type meters should be suspended with a bridle of the flat-bar or chain type when a surface buoy is used. The flat-bar suspension is preferred because it appears to add rigidity to the system. The meter collar should be placed 24 and 34 in. below the top of the pressure end cap for the TICUS and the A-102 meters, respectively.

(2) If currents are expected to exceed 2 kt, a split stabilizer fin should be used to reduce transverse tilt. When a split stabilizer is used the meter collar should be about an inch higher than the values given in (1) above, to compensate for the additional drag. At speeds below 2 kt the fin is not considered necessary and, in order to keep the suspension as simple as possible, should not be used.

(3) The standard straight fin, which has dimensions of 13 in. by 20 in., should not be used on the A-102 meter because it induces oscillations. Although these oscillations were not observed on the TICUS meter, use of the fin is not recommended. If a fin is needed, use the split stabilizer.

(4) Neither the design of the split stabilizer nor the bottom-mounted fin is considered complete. The results of these tests will aid in designing a stabilizing fin that will satisfy the hydrodynamic equations. A reverse Savonius rotor, if it provides the desired stability, and a bottom-mounted fin are of particular interest because they permit easy handling of the meter.

(5) Calibration of the Savonius rotor under conditions which simulate actual use is necessary. It should be tested in a towing tank using the side-mounted or bridle-type suspensions recommended in this report.

(6) Extensive tests should be made on the new TICUS meter which will be delivered in early 1970. This meter differs in size and almost certainly in behavior, from those we have described in this report.

(7) We suggest further investigations of compass and vane response. The compass appears to be the least reliable part of the meter.

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APPENDIX 1

A. Test 1 current speed and meter tilt data

Actual current speed (knots)	Average speed recorded by meter (knots)	Amount of error (percent)	Tilt of meter (degrees)
.60	.61	1.71	0.9
.74	.79	6.81	2.2
.82	.85	3.7	2.6
.90	.99	10.0	3.8
1.00	1.07	7.0	5.3
1.25	1.16	7.2	5.8
1.50	1.37	8.7	8.0
1.75	1.62	8.6	12.6
2.00	1.81	9.5	16.0
2.25	1.97	12.4	19.5
2.50	2.08	16.8	23.0
2.75	2.29	16.7	26.4
3.00	2.37	21.0	27.5
3.50	2.38	32.0	35.0
4.00	2.48	38.0	40.7

B. Test 1 current speed and meter direction data

Actual current speed (knots)	Average meter direction of current (degrees)	Range of meter direction of current (degrees)
.60	317	6
.74	317	3
.82	316	6
.90	310	5
1.00	311	5
1.25	311	5
1.50	311	34
1.75	305	27
2.00	307	23
2.25	306	33
2.50	294	22
2.75	301	11
3.00	302	12
3.50	293	12
4.00	317	28

C. Test 1 current speed and meter compass direction data

Actual current speed (knots)	Average meter compass direction (degrees)	Range of meter compass direction (degrees)
.60	37	0
.74	29	3
.82	21	2
.90	6	0
1.00	7	8
1.25	332	3
1.50	330	6
1.75	210	26
2.00	202	17
2.25	207	14
2.50	207	11
2.75	230	3
3.00	241	3
3.50	226	9
4.00	237	6

D. Test 1 current speed and meter vane direction data

Actual current speed (knots)	Average meter vane direction (degrees)	Range of meter vane direction (degrees)
.60	280	6
.74	288	3
.82	295	6
.90	304	5
1.00	304	5
1.25	340	8
1.50	342	37
1.75	96	45
2.00	106	31
2.25	99	36
2.50	84	19
2.75	70	14
3.00	62	9
3.50	67	8
4.00	80	8

E. Test 2 current speed and meter speed data

Actual current speed (knots)	Average speed recorded by meter (knots)	Amount of error (percent)
.60	.53	11.6
.75	.76	1.3
1.00	1.03	3.0
1.30	1.30	0.0
1.60	1.58	1.2
1.75	1.71	2.3
2.00	1.94	3.0
2.22	2.29	2.7
2.50	2.71	8.4
2.75	2.87	4.4
3.05	3.14	2.9
3.50	3.63	3.7
4.00	4.12	3.0

F. Test 2 current speed and meter direction data

Actual current speed (knots)	Average meter direction of current (degrees)	Range of meter direction of current (degrees)
.60	323	5
.75	323	0
1.00	319	3
1.30	316	5
1.60	316	3
1.75	312	3
2.00	312	0
2.22	307	5
2.50	304	3
2.75	298	6
3.05	295	3
3.50	290	0
4.00	283	3

G. Test 2 current speed, compass direction, and vane direction data

Actual current speed (knots)	Average meter compass direction (degrees)	Range of meter compass direction (degrees)	Average meter vane direction (degrees)	Range of meter vane direction (degrees)
.60	197	0	126	5
.75	191	0	132	0
1.00	180	0	139	3
1.30	174	2	142	5
1.60	185	3	132	6
1.75	182	3	130	3
2.00	180	3	132	3
2.22	174	2	132	7
2.50	168	3	135	0
2.75	162	3	136	3
3.05	159	2	136	3
3.50	155	0	135	0
4.00	148	6	134	3

H. Test 3 current speed and meter speed data

Actual current speed (knots)	Average speed recorded by meter (knots)	Amount of error (percent)
1.00	.97	3.0
2.00	2.04	2.0
3.00	3.05	1.7
4.00	4.11	2.8
4.50	4.73	5.1
5.00	5.12	2.4

I. Test 3 current speed and meter direction data

Actual current speed (knots)	Average meter direction of current (degrees)	Range of meter direction of current (degrees)
1.00	309	8
2.00	302	11
3.00	295	5
4.00	285	3
4.50	289	12
5.00	279	9

J. Test 3 current speed and meter compass data

Actual current speed	Average meter compass direction	Range of meter compass direction
(knots)	(degrees)	(degrees)
1.00	16	6
2.00	1	11
3.00	354	5
4.00	342	3
4.50	344	12
5.00	332	6

K. Test 3 current speed and meter vane data

Actual current speed (knots)	Average meter vane direction (degrees)	Range of meter vane direction (degrees)
1.00	294	2
2.00	301	6
3.00	302	3
4.00	304	0
4.50	304	2
5.00	308	3

L. Test 4 current speed and meter speed data

Actual current speed	Average speed recorded by meter	Amount of error
(knots)	(knots)	(percent)
.60	.58	3.4
.75	.83	10.6
1.00	1.09	9.0
1.25	1.35	8.0
1.50	1.60	6.7
1.75	1.85	5.7
2.00	2.10	5.0
2.26	2.40	6.2
2.50	2.59	3.6
2.75	2.95	7.3
3.00	3.22	7.3
3.60	3.87	7.5
4.00	4.26	6.5

M. Test 4 current speed and meter direction data

Actual current speed (knots)	Average meter direction of current (degrees)	Range of meter direction of current (degrees)
.60	330	3
.75	329	0
1.00	325	3
1.25	324	3
1.50	321	0
1.75	316	3
2.00	313	3
2.26	318	0
2.50	316	2
2.75	310	5
3.00	301	4
3.60	299	6
4.00	298	8

N. Test 4 current speed and meter compass data

Actual current speed (knots)	Average meter compass direction (degrees)	Range of meter compass direction (degrees)
.60	227	3
.75	219	0
1.00	211	0
1.25	205	0
1.50	198	3
1.75	192	3
2.00	189	3
2.26	192	3
2.50	189	3
2.75	182	3
3.00	176	6
3.60	170	6
4.00	170	8

O. Test 4 current speed and meter vane data

Actual current speed (knots)	Average meter vane direction (degrees)	Range of meter vane direction (degrees)
.60	103	6
.75	110	0
1.00	114	3
1.25	119	3
1.50	122	3
1.75	124	0
2.00	124	0
2.26	126	3
2.50	127	5
2.75	128	2
3.00	128	2
3.60	129	0
4.00	128	2

P. Test 5 current speed and meter speed data

Actual current speed (knots)	Average speed recorded by meter (knots)	Amount of error (percent)
1.00	.86	14.0
2.00	2.09	4.5
3.00	3.19	6.3
4.00	4.23	5.7

Q. Test 5 current speed and meter direction data

Actual current speed	Average meter direction of current	Range of meter direction of current
(knots)	(degrees)	(degrees)
1.00	342	3
2.00	334	3
3.00	332	0
4.00	333	14

R. Test 5 current speed and meter compass data

Actual current speed (knots)	Average meter compass direction (degrees)	Range of meter compass direction (degrees)
1.00	225	0
2.00	214	0
3.00	216	3
4.00	218	14

S. Test 5 current speed and meter vane data

Actual current speed (knots)	Average meter vane direction (degrees)	Range of meter vane direction (degrees)
1.00	117	3
2.00	120	3
3.00	116	3
4.00	115	0

T. Test 6 current speed and meter speed data

Actual current speed (knots)	Average speed recorded by meter (knots)	Amount of error (percent)
.60	.58	3.4
.75	.74	1.34
1.00	.98	2.0
1.50	1.56	4.0
1.75	1.85	5.7
2.00	2.04	2.0
2.50	2.63	5.2
3.00	3.12	4.0
3.50	3.70	5.7
4.00	4.19	4.7

U. Test 6 current speed and meter direction data

Actual current speed (knots)	Average meter direction of current (degrees)	Range of meter direction of current (degrees)
.60	322	6
.75	324	3
1.00	324	0
1.50	324	3
1.75	325	3
2.00	325	6
2.50	330	3
3.00	327	2
3.50	334	5
4.00	335	5

V. Test 6 current speed and meter compass data

Actual current speed (knots)	Average meter compass direction (degrees)	Range of meter compass direction (degrees)
.60	153	3
.75	155	0
1.00	155	0
1.50	154	3
1.75	153	3
2.00	150	3
2.50	154	3
3.00	150	3
3.50	157	5
4.00	158	5

W. Test 6 current speed and meter vane data

Actual current speed (knots)	Average meter vane direction (degrees)	Range of meter vane direction (degrees)
.60	168	3
.75	168	3
1.00	169	0
1.50	170	3
1.75	172	2
2.00	174	0
2.50	175	3
3.00	177	0
3.50	177	0
4.00	177	0

X. Test 7 current speed and meter speed data

Actual current speed (knots)	Average speed recorded by meter (knots)	Amount of error (percent)
.60	.69	15.0
.75	.79	5.3
1.00	.99	1.0
1.50	1.41	6.0
2.00	2.00	0.0

Y. Test 7 current speed and meter direction data

Actual current speed	Average meter direction of current	Range of meter direction of current
(knots)	(degrees)	(degrees)
.60	318	40
.75	323	45
1.00	319	8
1.50	320	5
2.00	323	3

Z. Test 7 current speed and meter compass data

Actual current speed (knots)	Average meter compass direction (degrees)	Range of meter compass direction (degrees)
.60	315	34
.75	321	20
1.00	313	3
1.50	314	3
2.00	315	0

AA. Test 7 current speed and meter vane data

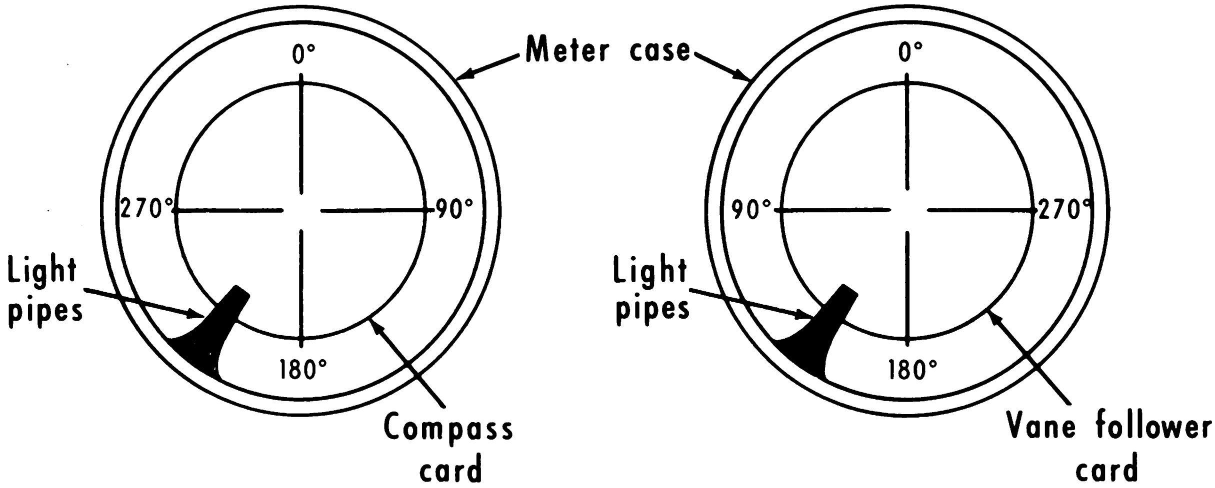
Actual current speed (knots)	Average meter vane direction (degrees)	Range of meter vane direction (degrees)
.60	003	34
.75	001	31
1.00	005	5
1.50	006	5
2.00	008	3

APPENDIX II

PRINCIPLE OF DIRECTION READOUT

The Meter Compass Card is fixed with respect to the compass and is labeled clockwise.

The Meter Vane Follower Card is fixed with respect to the vane follower magnet and is labeled counterclockwise.



The fiber optics which take the readings from both cards are fixed with respect to the case.

The direction reading is therefore the sum of the Meter Compass Card reading and the Meter Vane Follower Card reading or this sum minus 360° if the sum is greater than 360°. Therefore, it can be seen that if the meter case rotates clockwise, the Meter Compass Card reading increases while the Meter Vane Follower Card reading decreases by the same amount thereby yielding the same direction value.

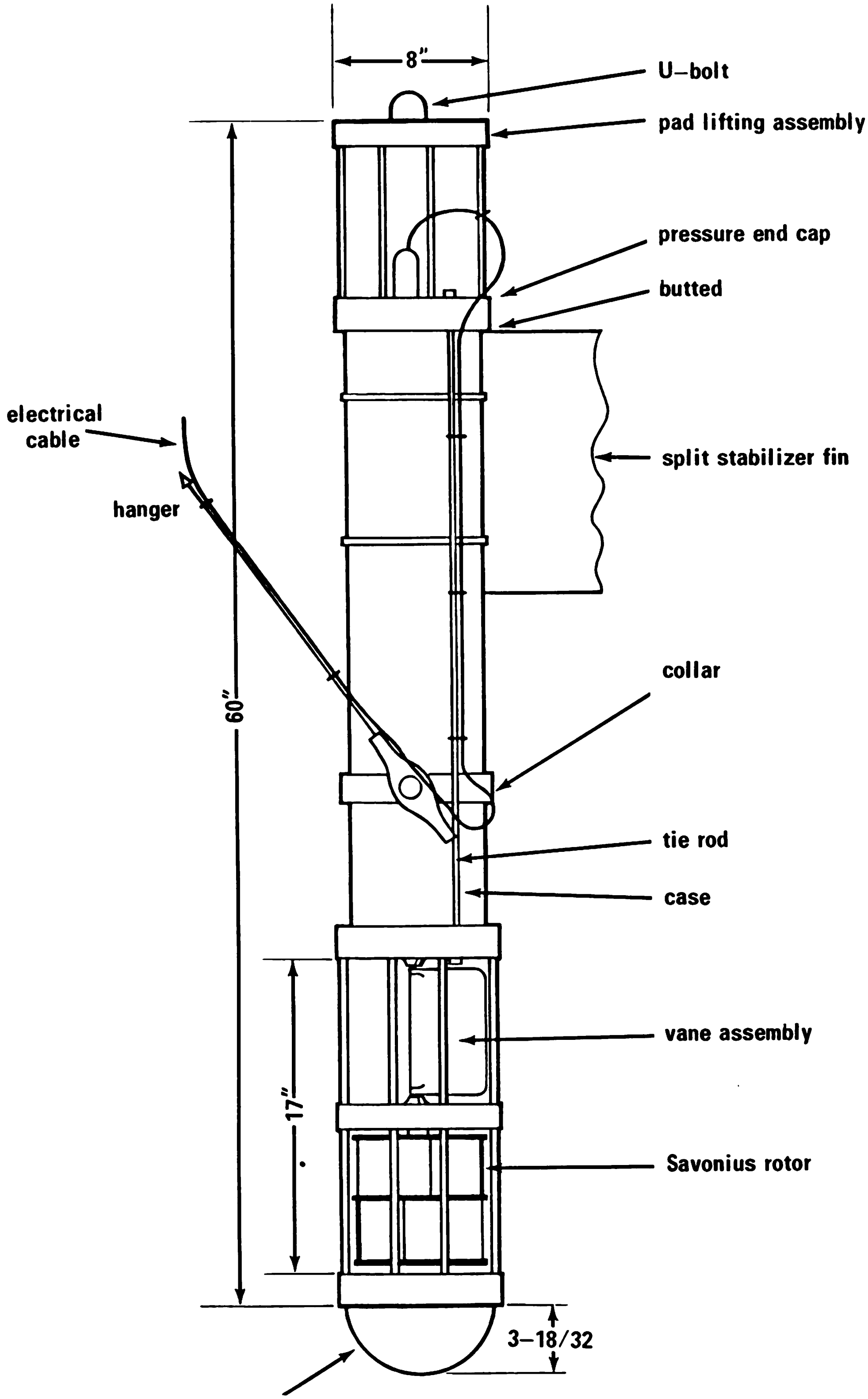


Figure 1. -- TICUS current meter.

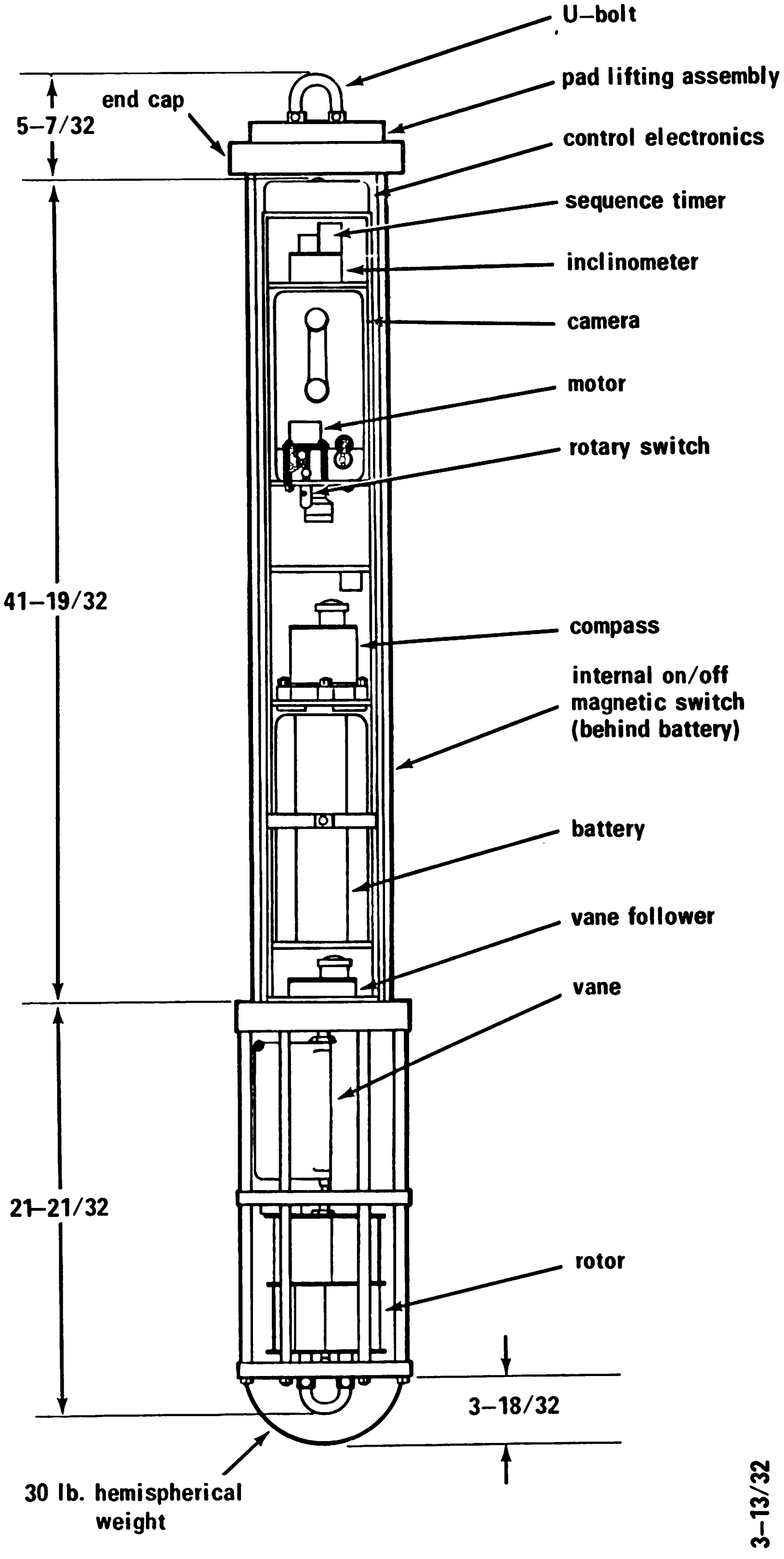


Figure 2.––Model A–102 current meter

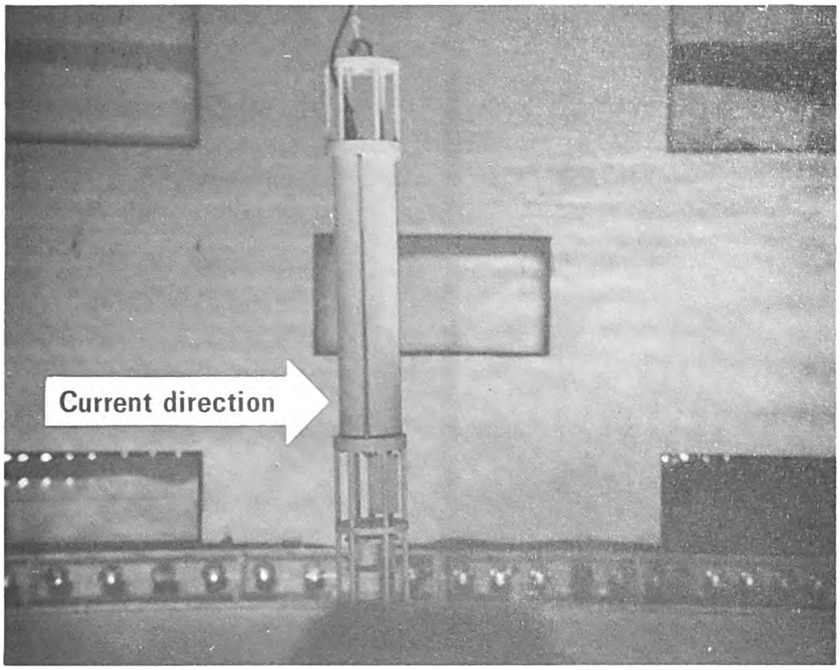


Figure 3.--Test 1, TICUS meter top suspension–0.6 kt; tilt 1.5°

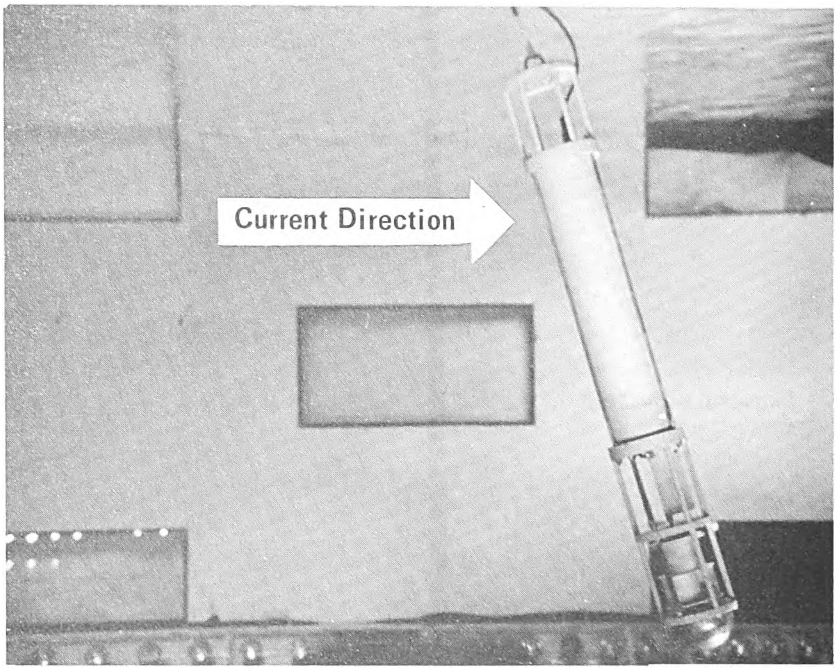


Figure 4.--Test 1, TICUS meter top suspension–2.0 kt; tilt 16°

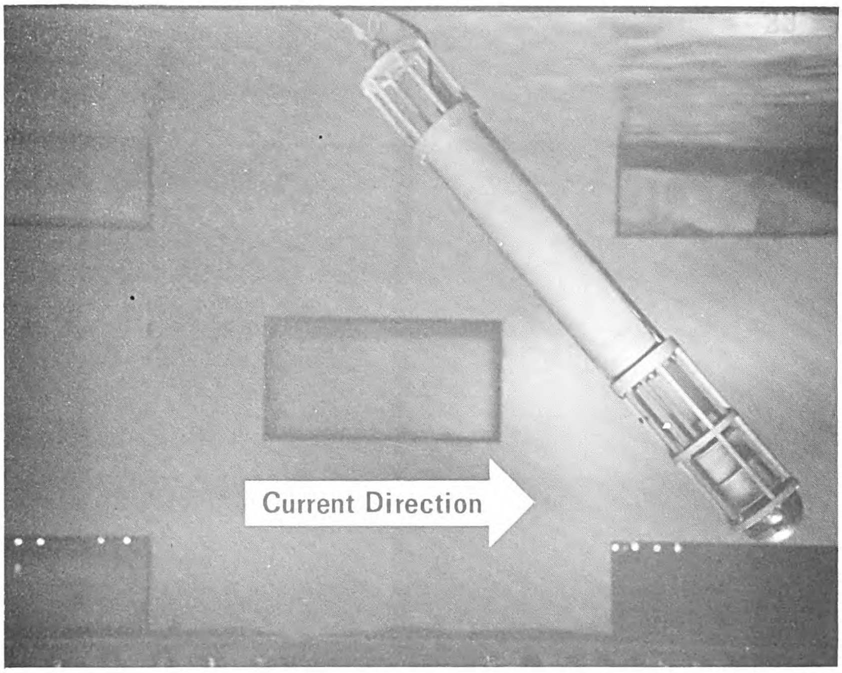


Figure 5.--Test 1, TICUS meter top suspension–4.0 kt; tilt 40.7°

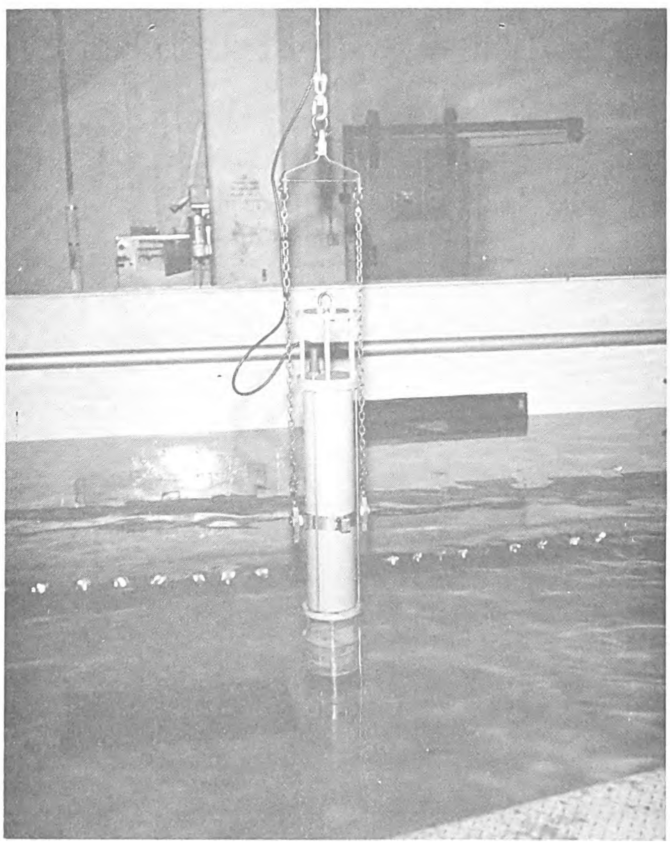


Figure 6.--TICUS meter chain suspension.

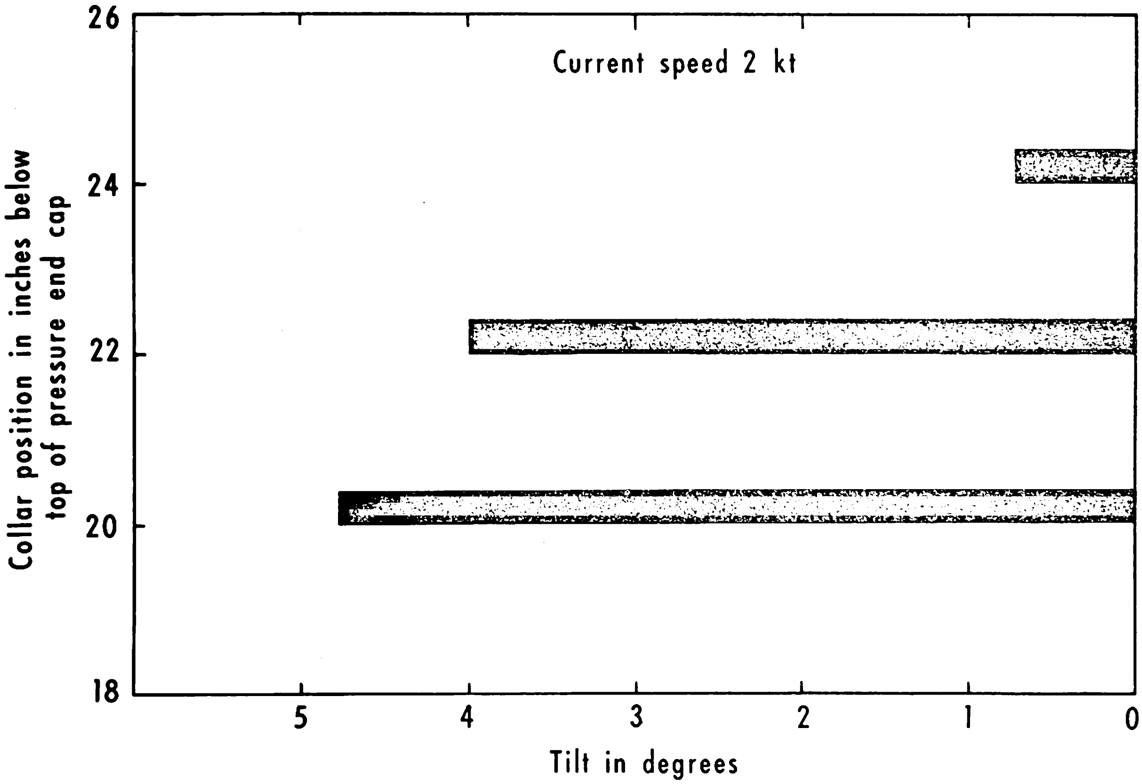


Figure 7.--TICUS meter tilt vs. collar position–2.0 kt.

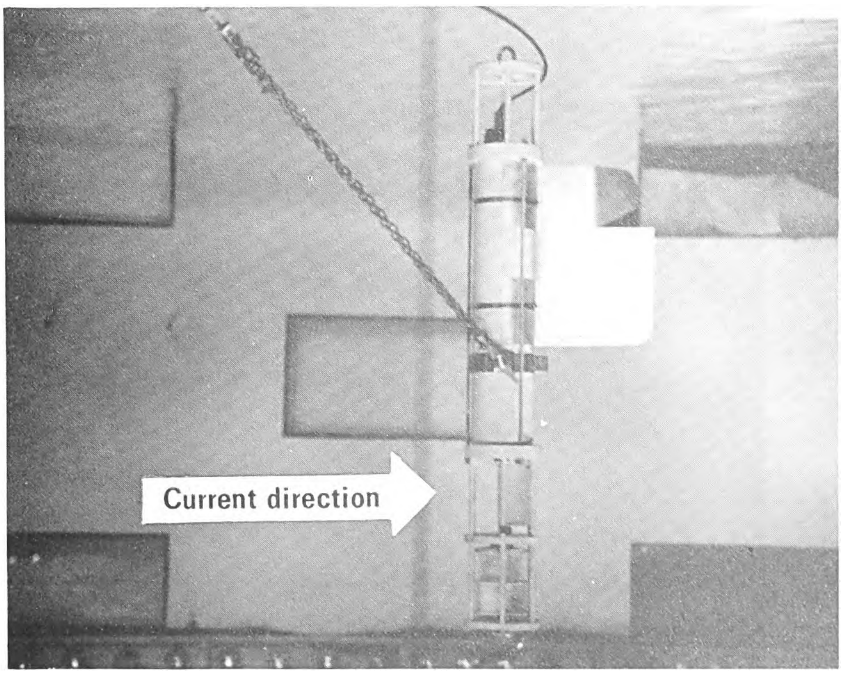


Figure 8.--Test 3, TICUS meter chain suspension and split stabilizer fin–3–0 kt.

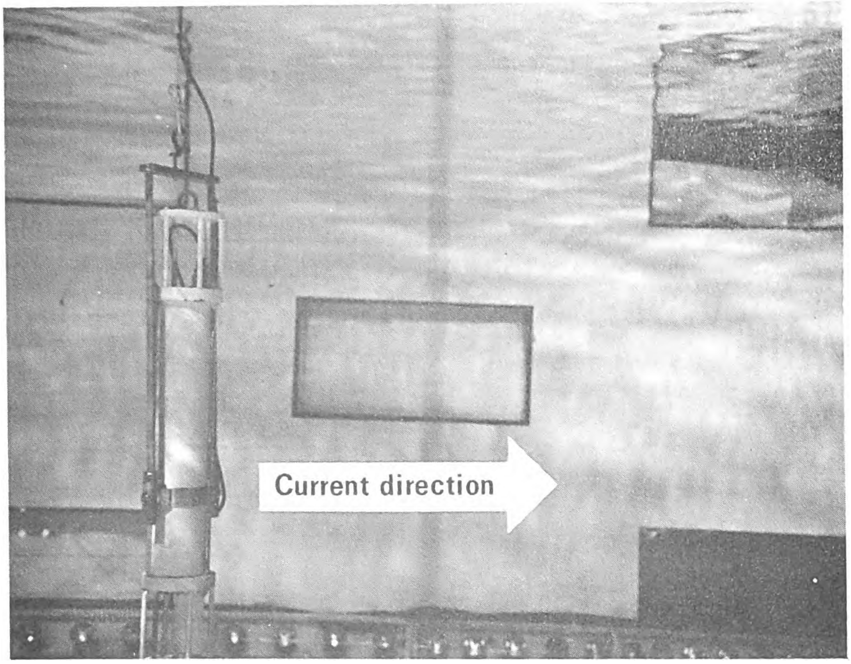


Figure 9.--Test 4, TICUS meter flat-bar suspension-0.6 kt.

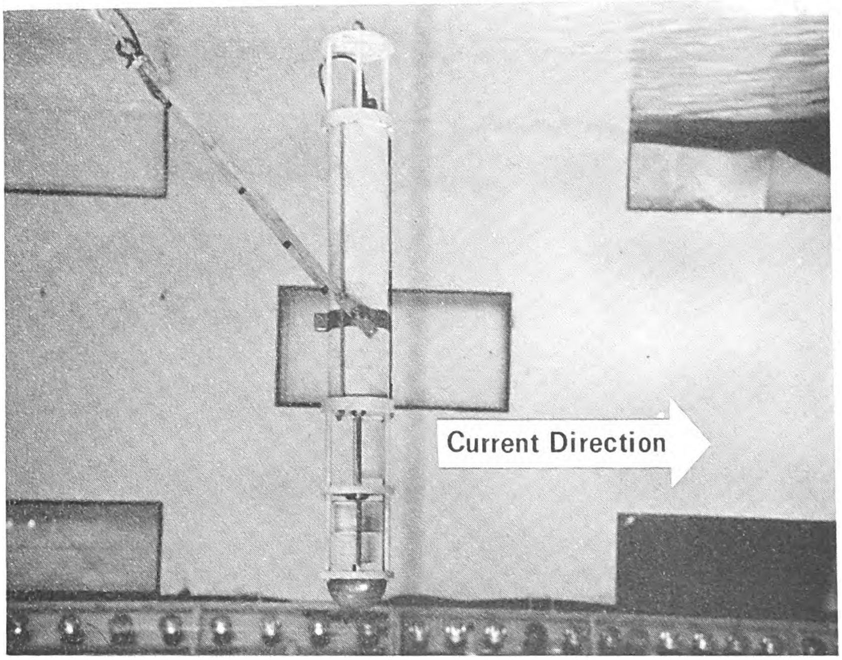


Figure 10.--Test 4, TICUS meter flat-bar suspension—2.75 kt.

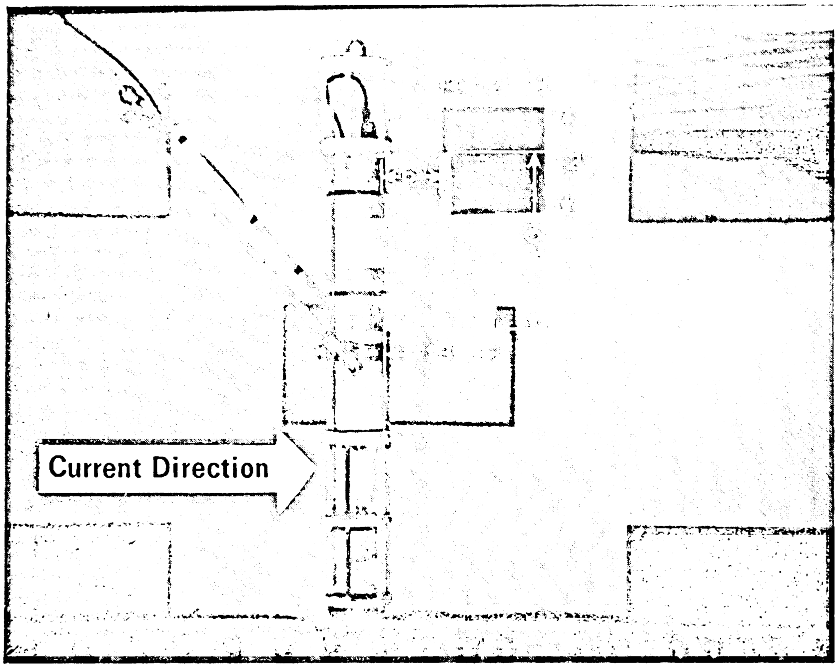


Figure 11.--Test 5, TICUS meter flat-bar suspension and split stabilizer fin–3.0 kt.

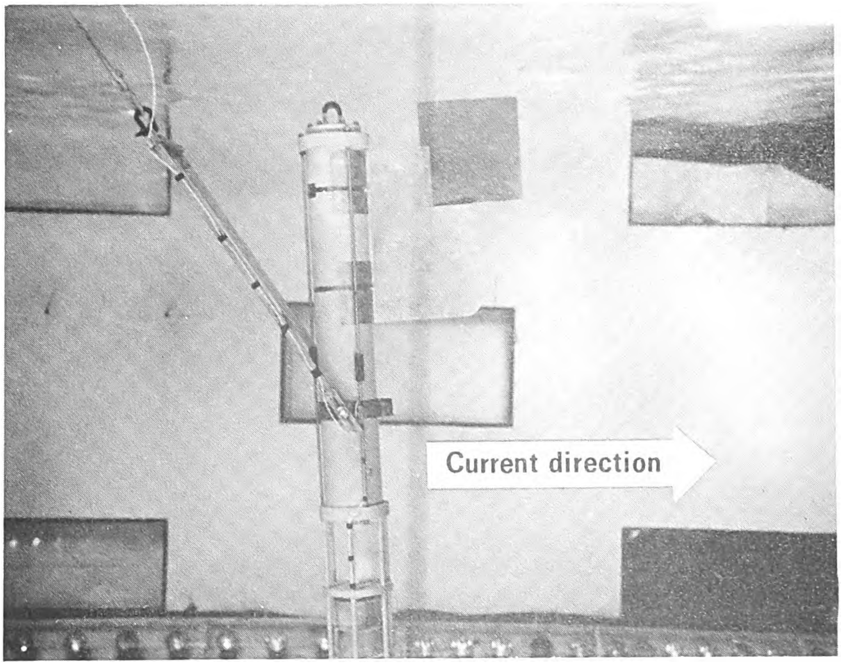


Figure 12.--Test 6, A-102 meter flat-bar suspension and split stabilizer fin-3.0 kt.

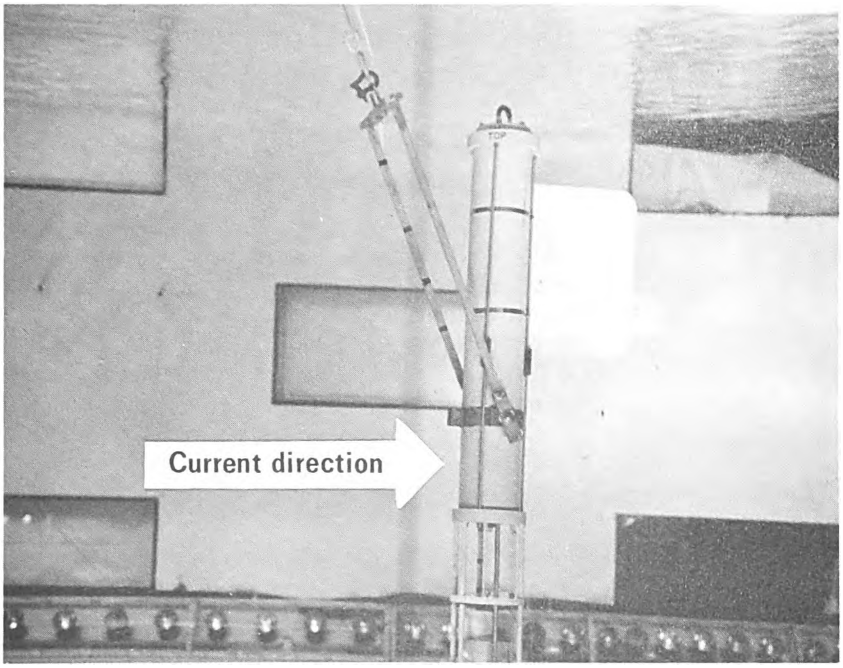


Figure 13.--Test 7, A-102 meter flat-bar suspension and straight stabilizer fin-2.0 kt.

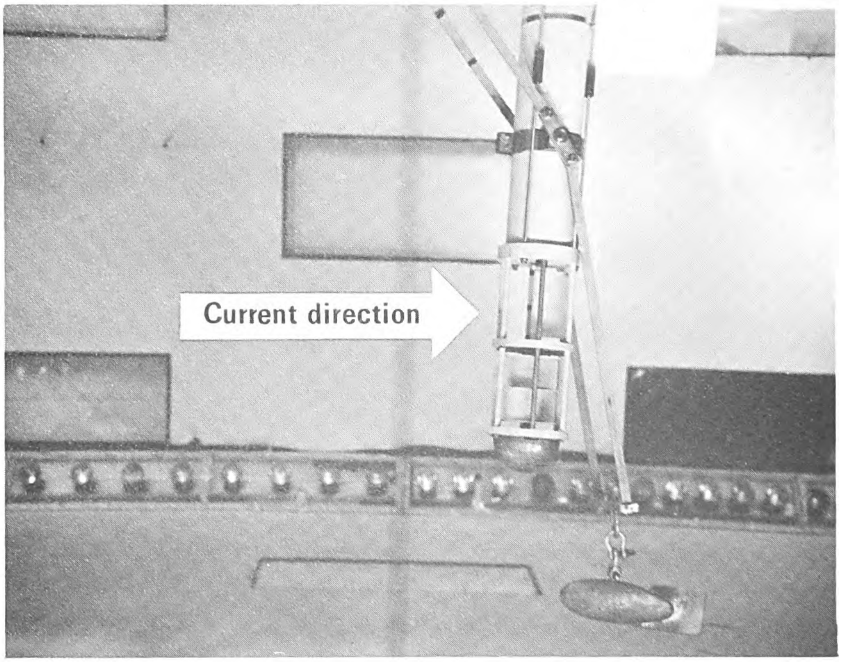


Figure 14.--Test 7, A-102 meter flat-bar suspension, straight stabilizer fin, and fish weight-3.0 kt.

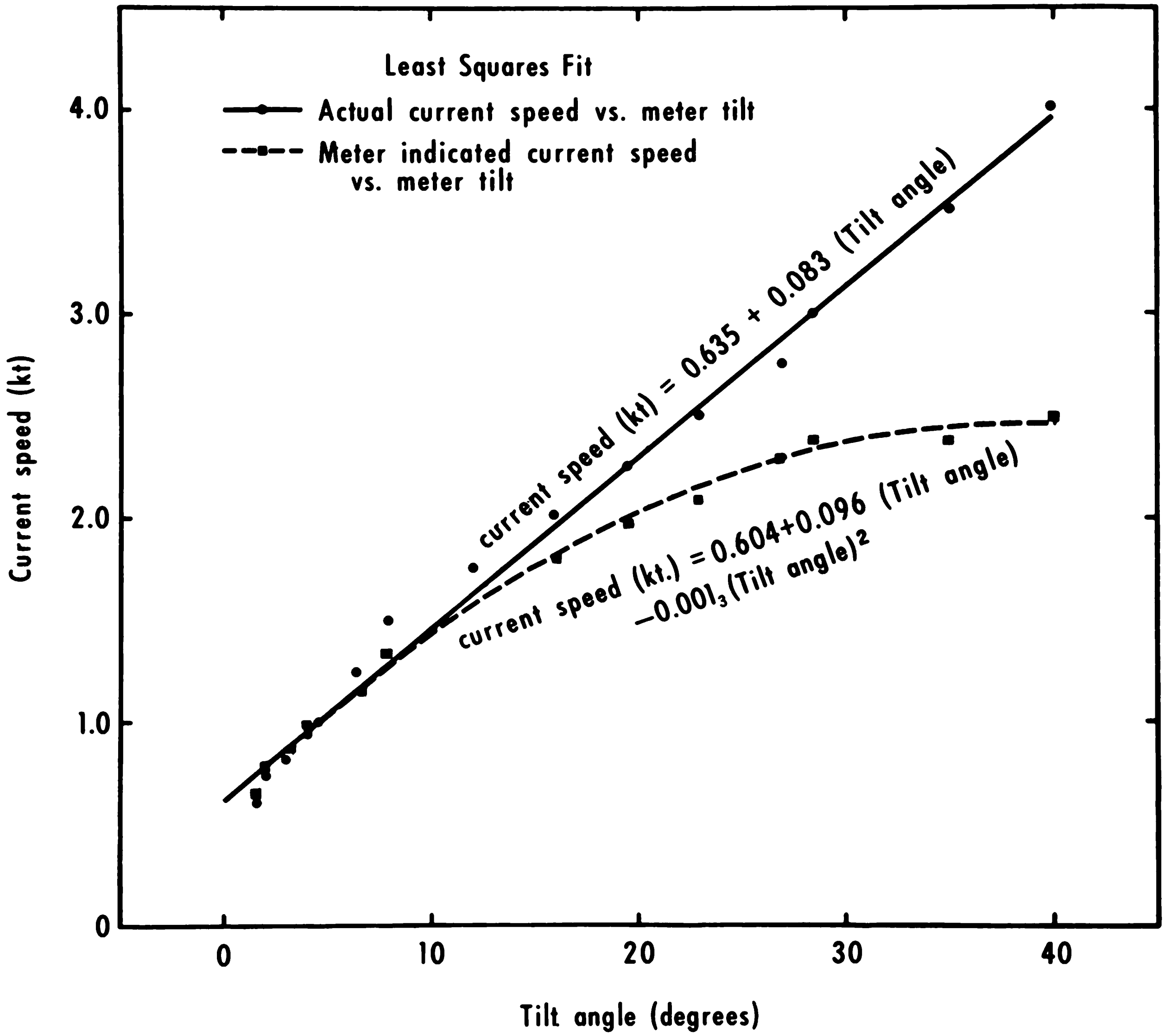


Figure 15.--TICUS meter tilt vs. current speed in Test 1.

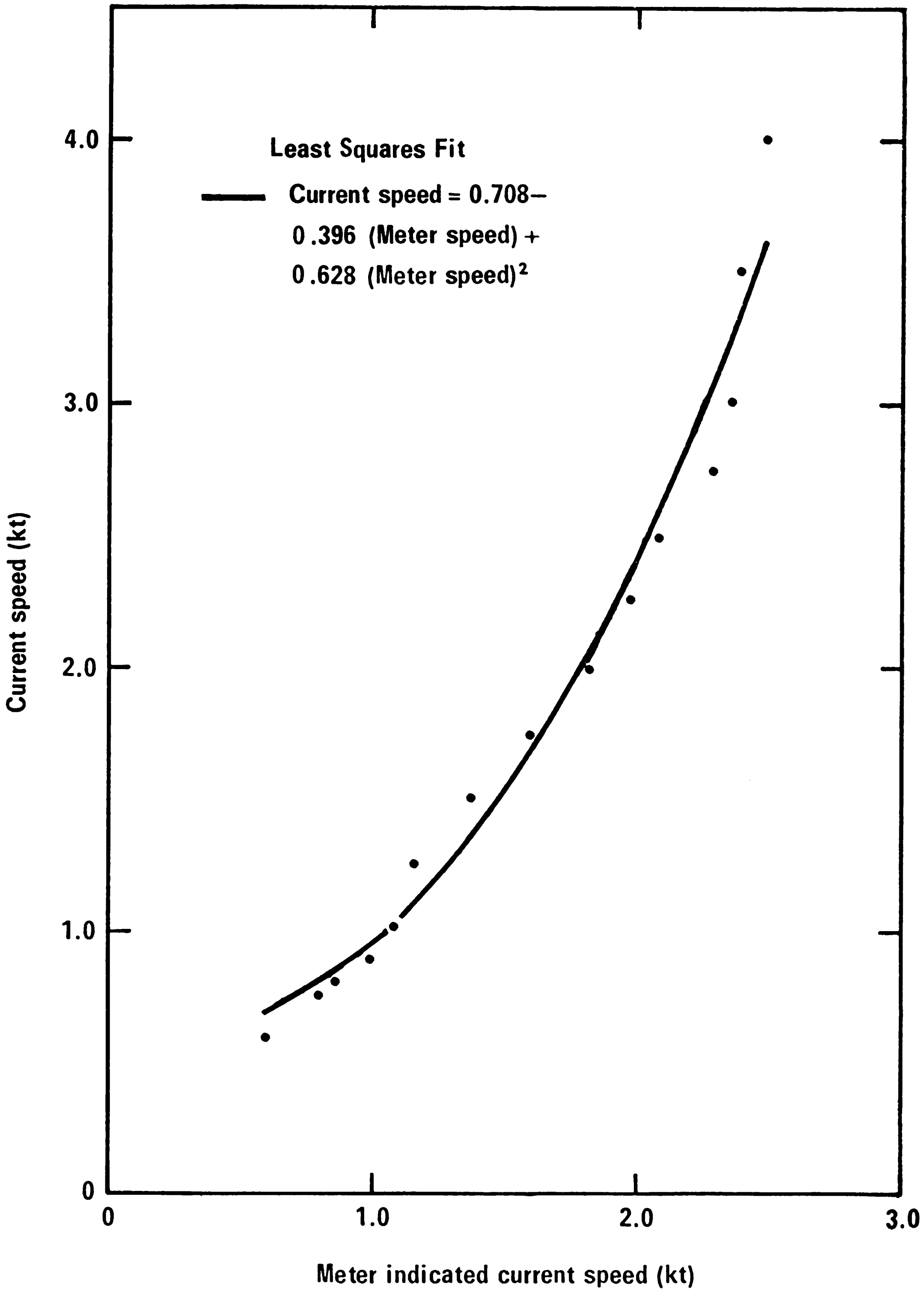


Figure 16.—Meter indicated speed vs. actual current speed in Test 1.

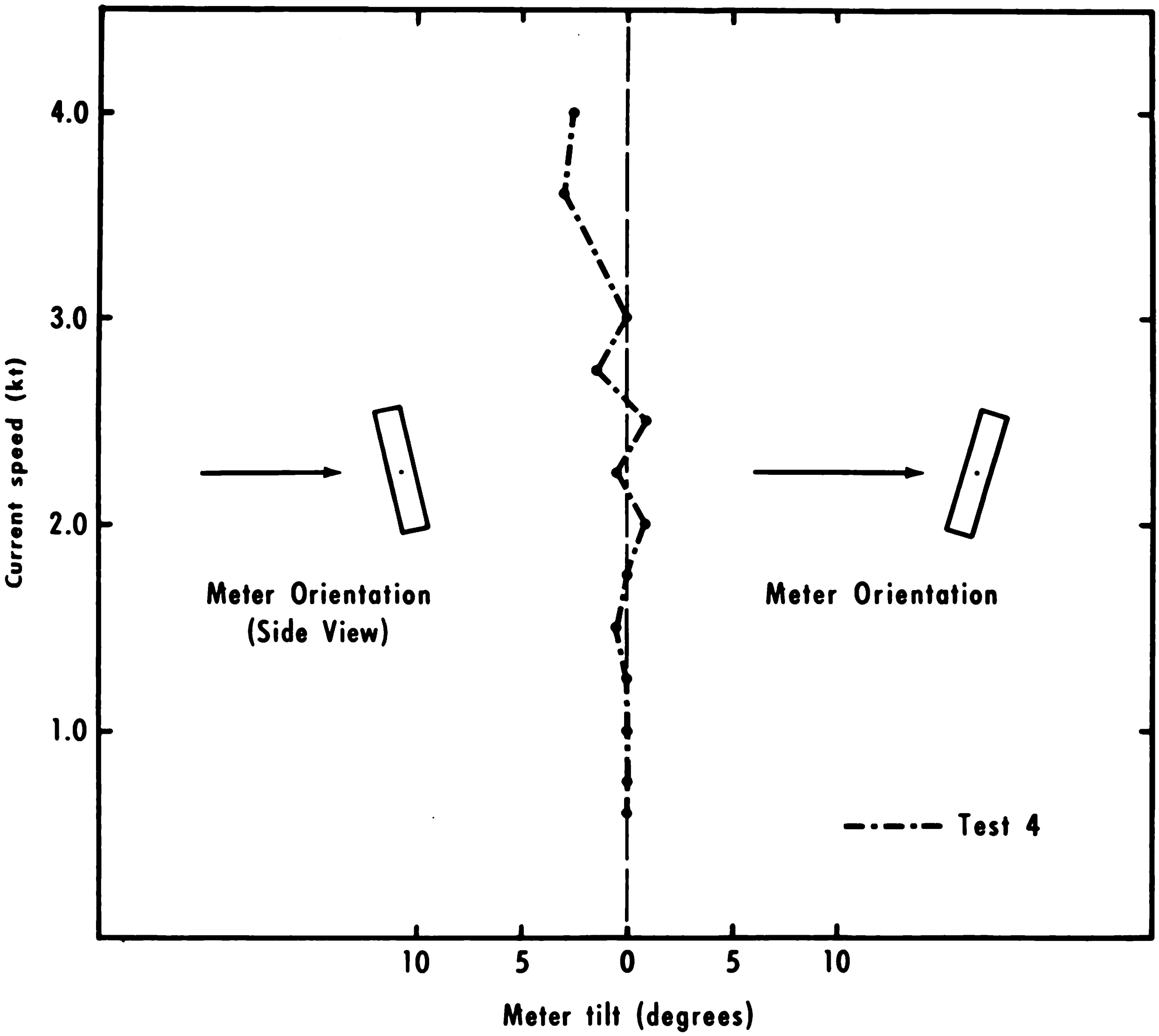


Figure 17.——Meter tilt vs..current speed in Test 4.

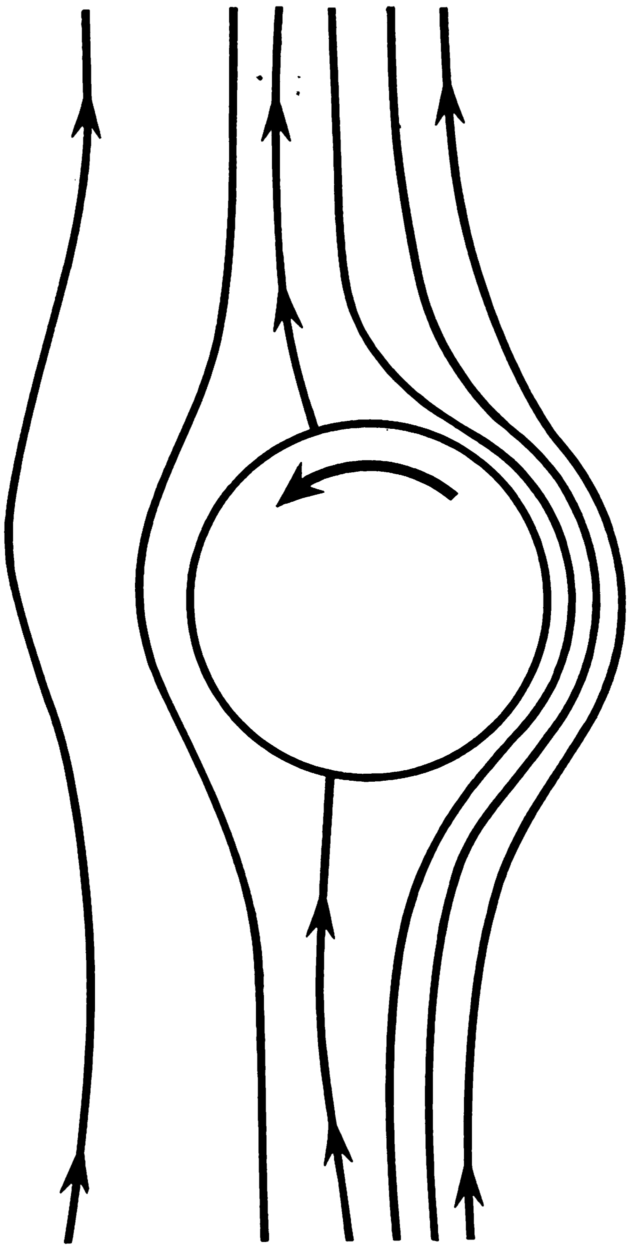


FIGURE 18.--Streamline of flow around a cylinder (after Streeter, 1966)

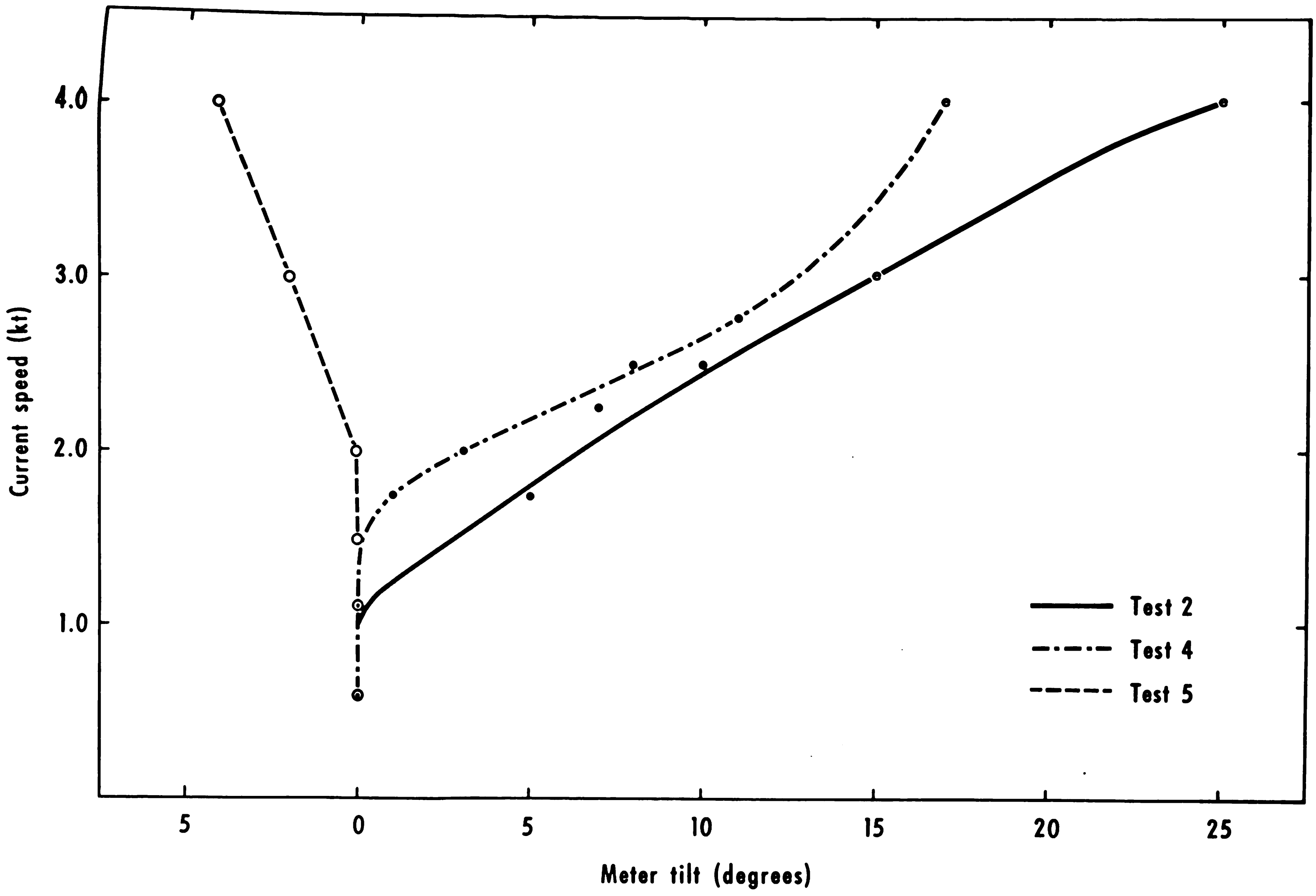
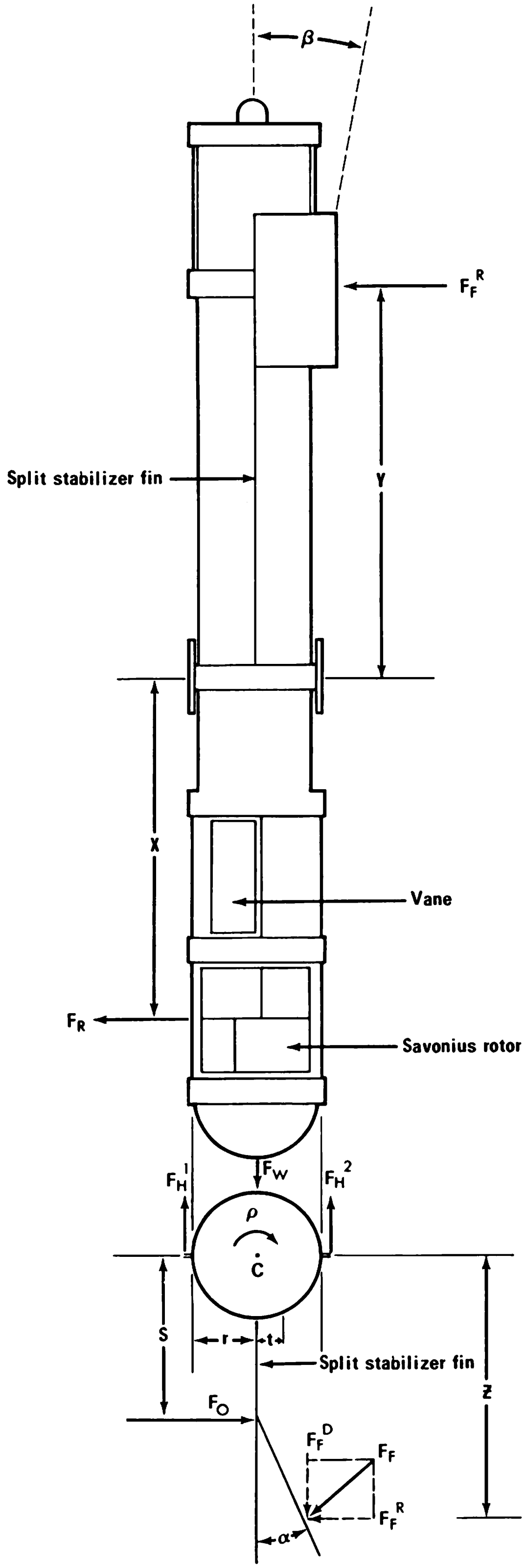


Figure 19.—–Meter transverse tilt vs. current speed in Tests 4 and 5.



F_W = force of water

F_F = force on fin

F_F^R = force on fin, rotational component

F_F^D = force on fin, drag component

F_R = force of rotor

F_H^1 = force on hanger

F_H^2 = force on hanger

F_O = force on backside of fin resulting from clockwise meter rotation

α = angle of split stabilizer

β = angle of transverse meter tilt

ρ = rotation of meter case

$F_F = (f)\ F_W,\ \alpha,$ area of tab, ρ

for $\beta = o$

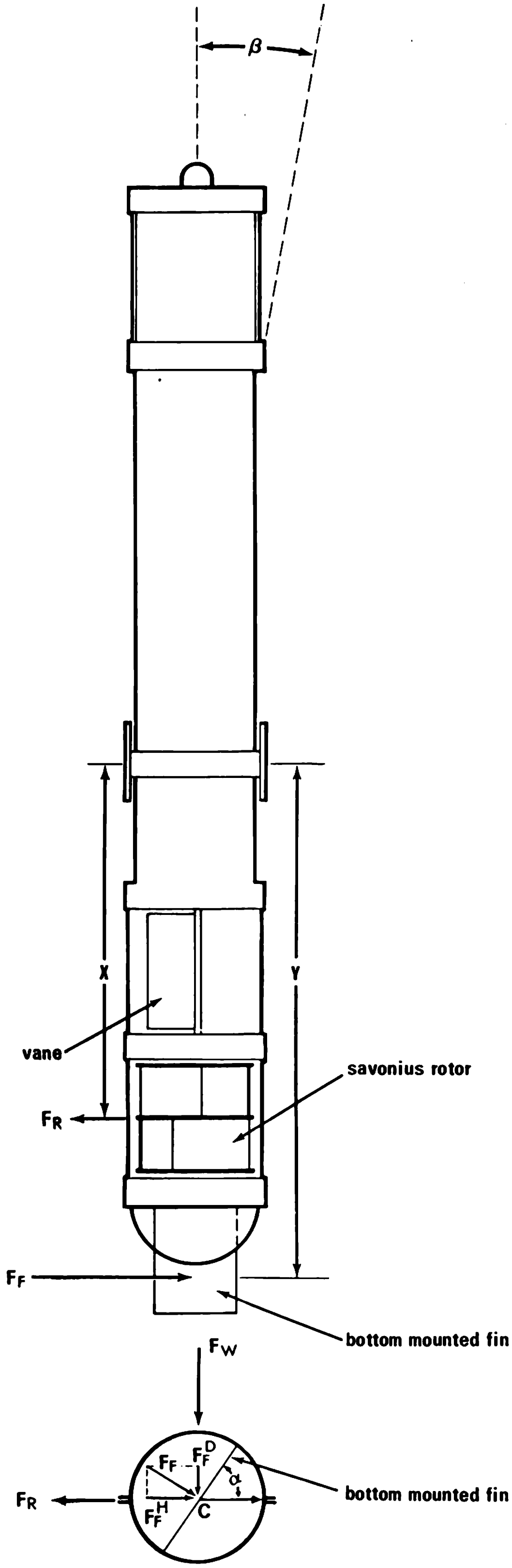
$$F_F^R\ y = F_R\ x$$

for $\rho = o$

$$F_F^R\ z + F_F^D\ t + F_H^1\ r = F_H^2\ r + F_O S$$

$F_O = (f)\ F_W,\ \rho,$ area of fin

Figure 20.—TICUS meter split stabilizer fin stress analysis.



$F_F = (f)\, F_{W}, \alpha$

$\Delta\alpha = 0 = (f) \begin{Bmatrix} F_F \\ F_R \end{Bmatrix}$ acting through C

for $\beta = 0$

$F_R\, X = F_F\, Y$

Assumption; Fin is built with equal areas on either side of c

F_W = force of water

F_F = force on fin

$F_F^{\,D}$ = component of F_F

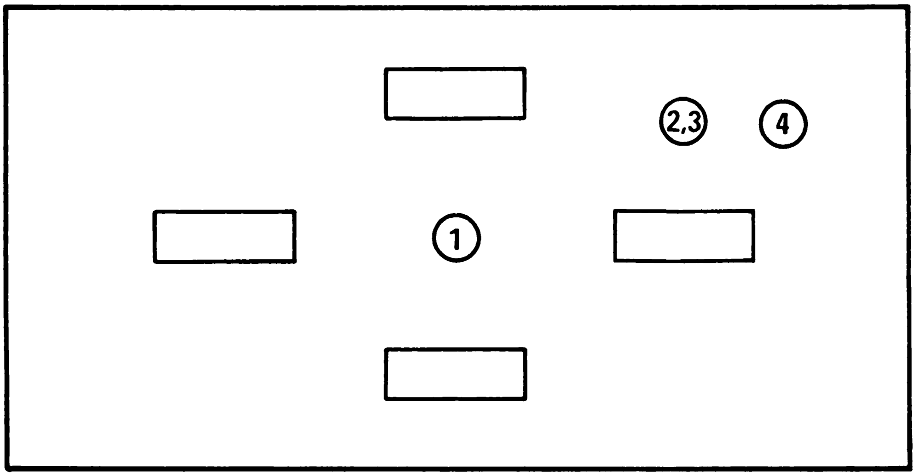
$F_F^{\,H}$ = component of F_F

F_R = force of rotor

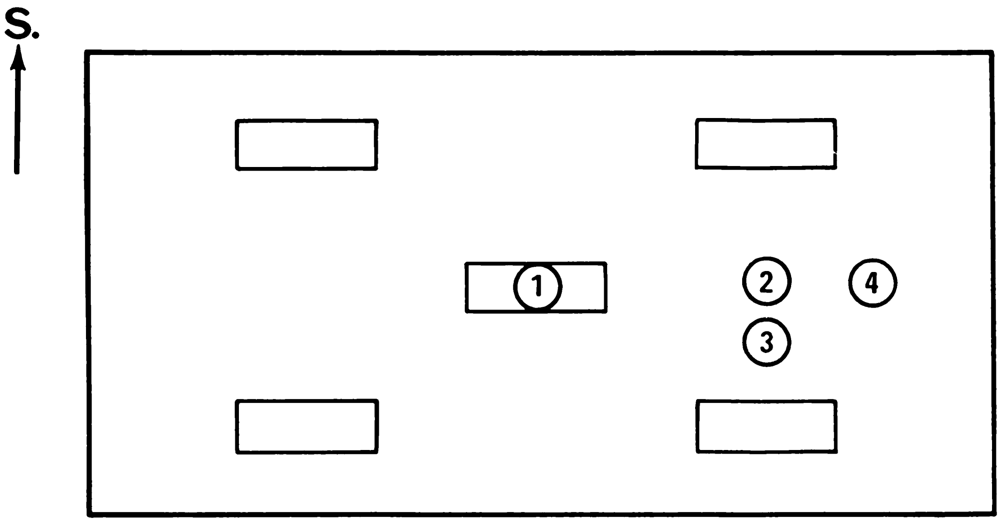
α = angle of fin

β = angle of transverse meter tilt

Figure 21.--TICUS meter bottom-mounted fin stress analysis



Water Channel (Side View)



Water Channel (Top View)

1 pos @ 1kt approx.

2 pos @ 3–4kt approx.

3 pos @ 3–4kt offset.

4 pos @ 3–4kt, downstream setting.

run at 0.6 to 1.0 kts

Figure 22.––Meter positions in circulating water channel for compass variation studies.

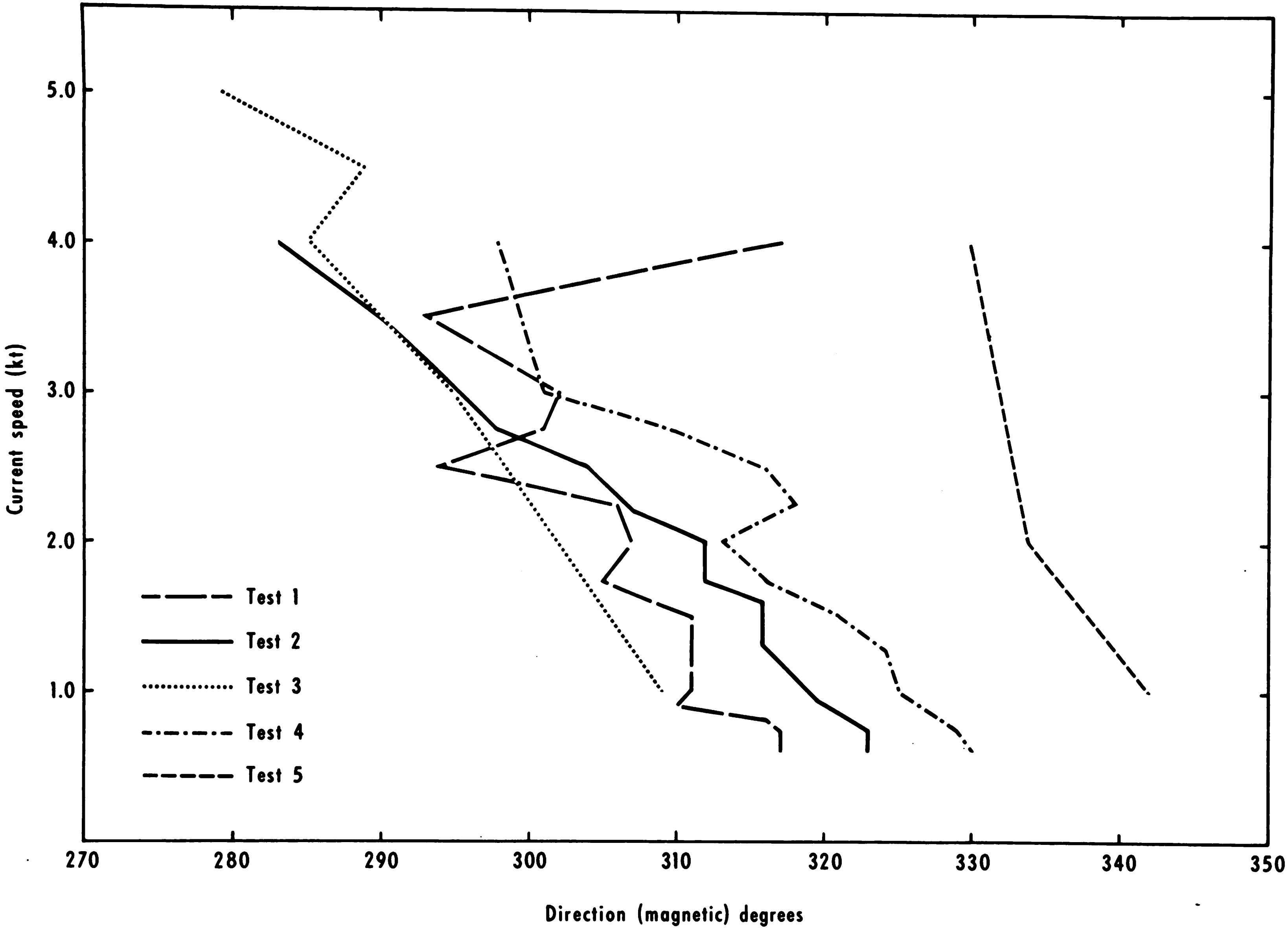


Figure 23.––Meter indicated current direction vs. current speed in Tests 1 – 5

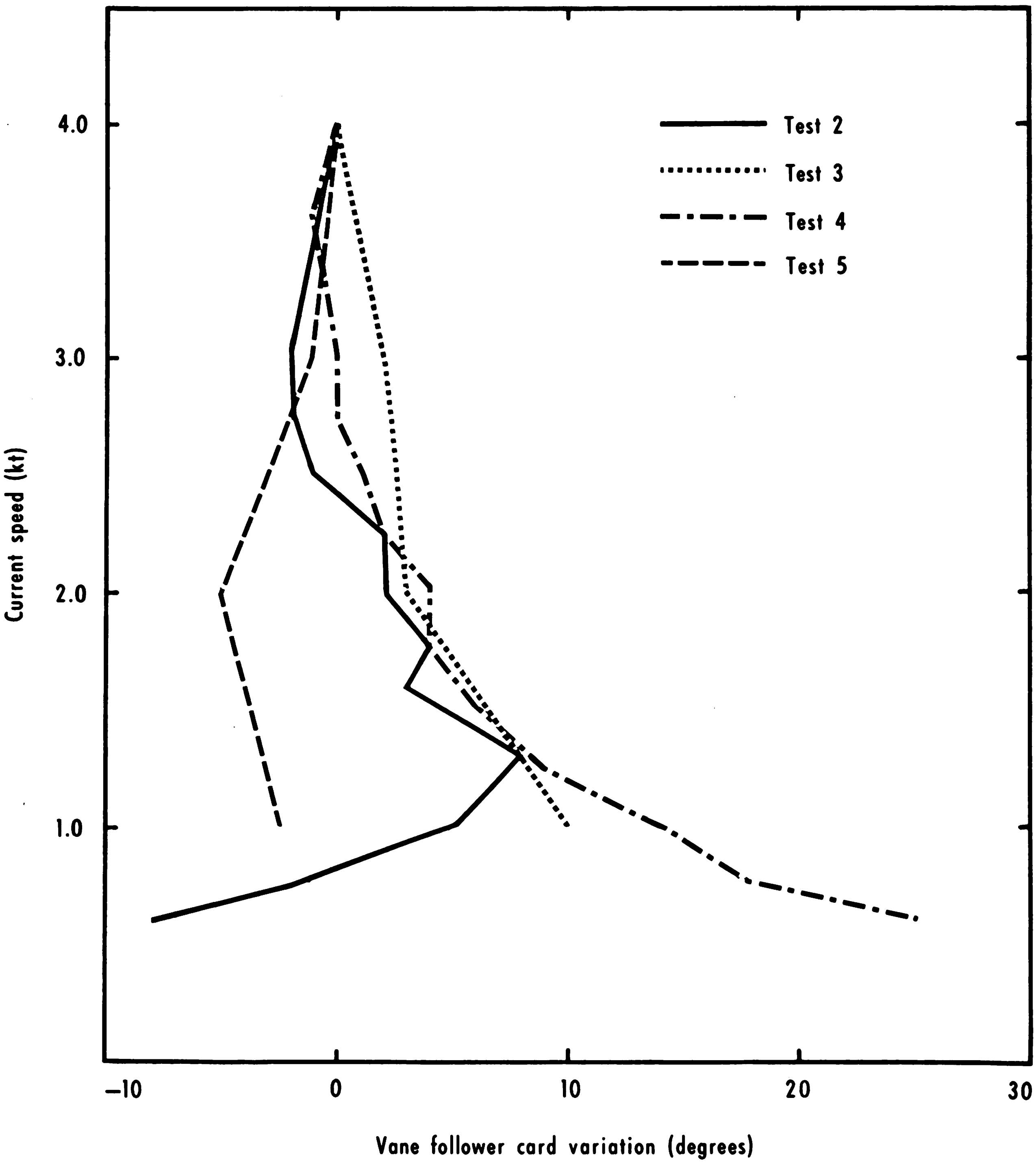


Figure 24.--Variation in vane follower card readings vs. current speed in Tests 2 - 5

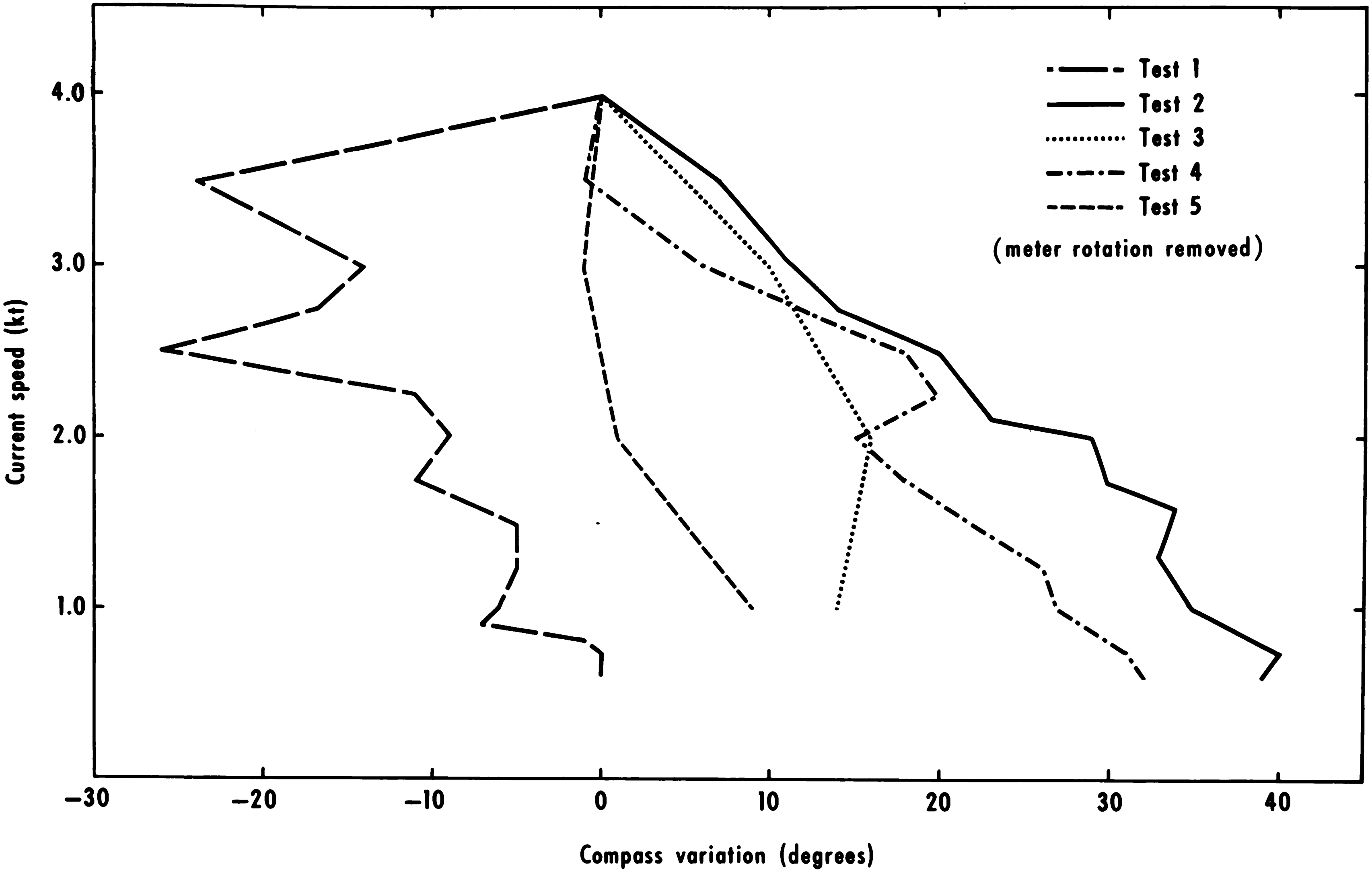


Figure 25.––Variation in compass direction vs. current speed in Tests 1 – 5

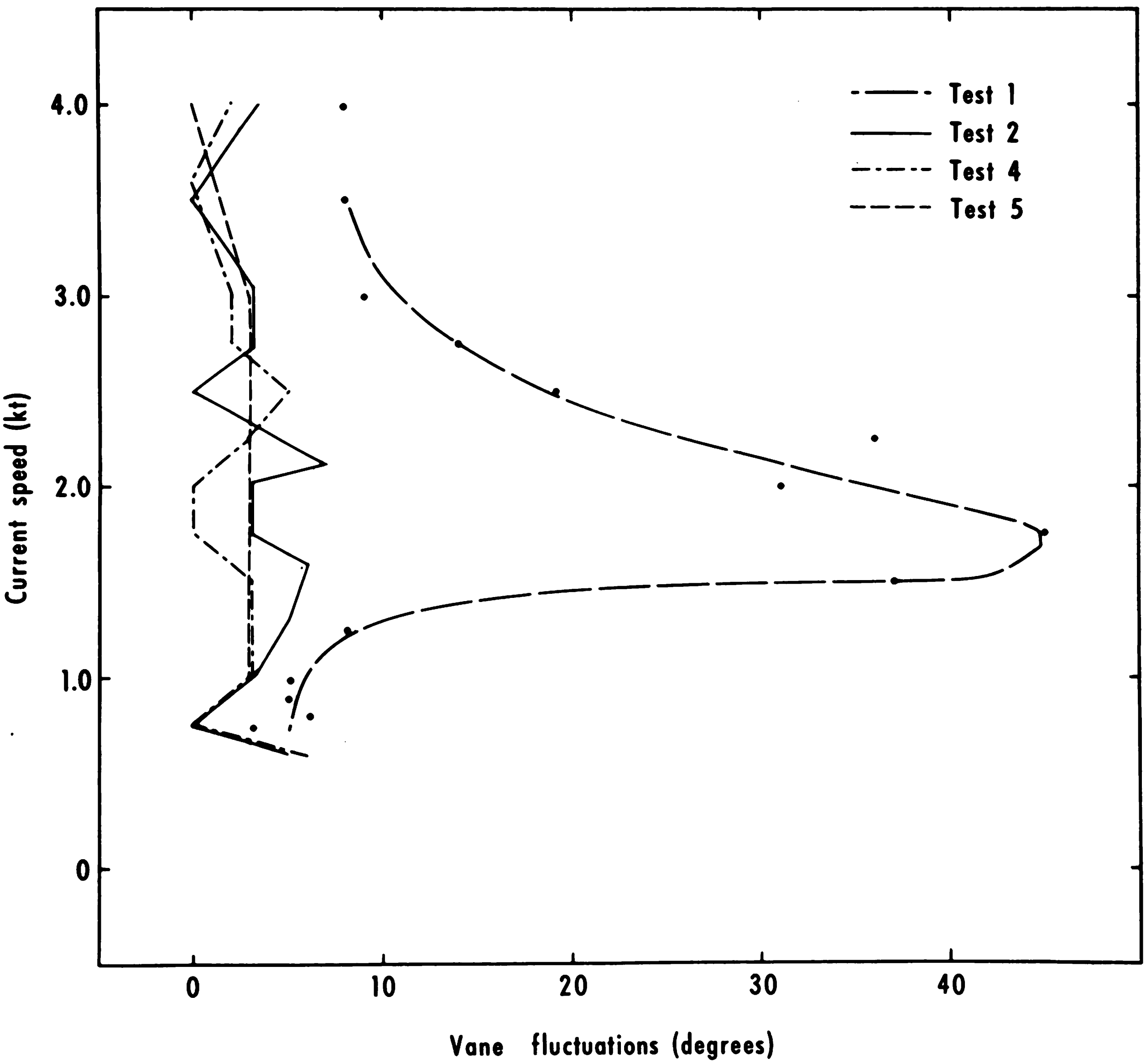


Figure 26.--Fluctuations in vane follower readings vs. current speed in Tests 1, 2, 4, and 5.

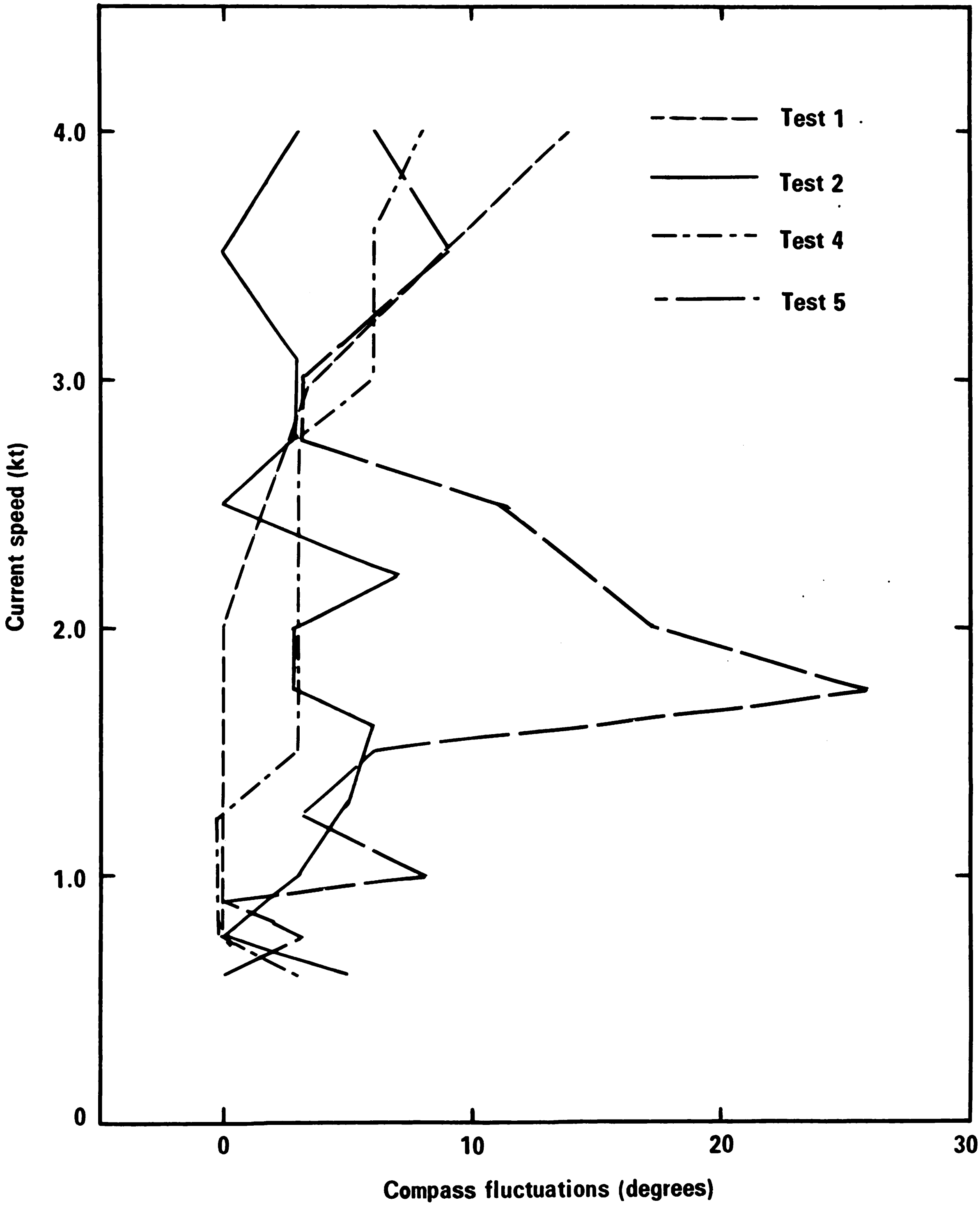


Figure 27.--Fluctuations in meter compass readings vs. current speed in Tests 1, 2, 4, and 5

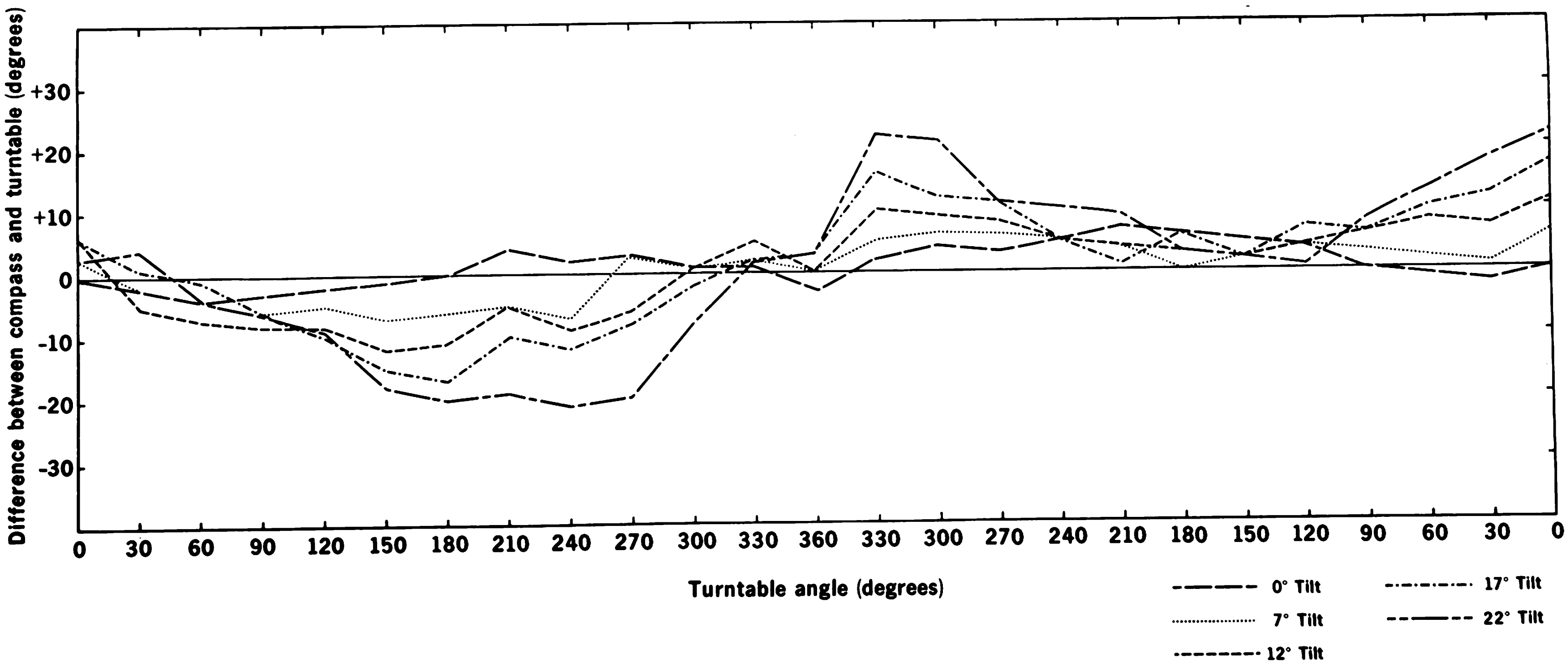


Figure 28.--Deviation of compass readings as a function of meter tilt.

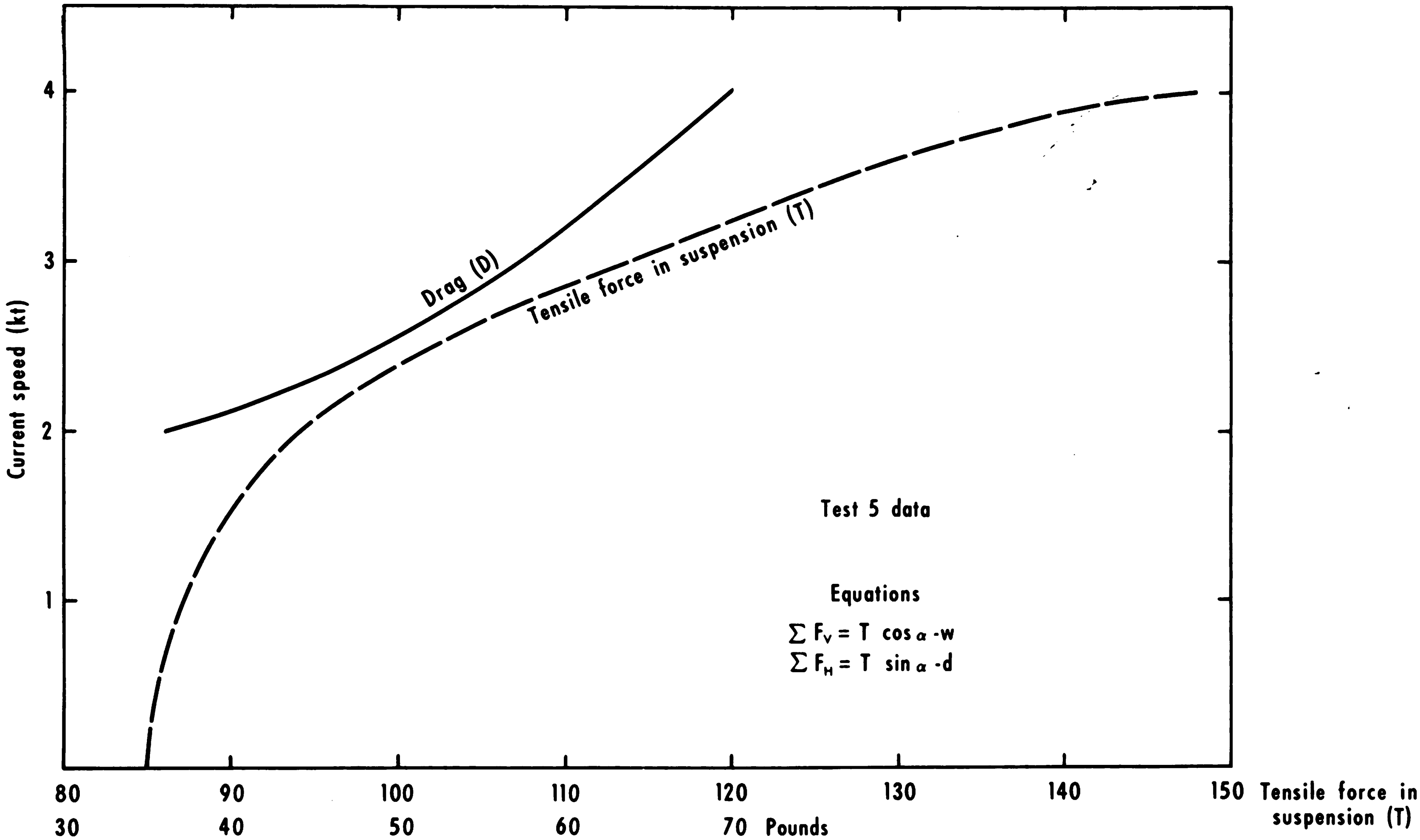


Figure 29.—Tensile force vs. current speed in Test 5.

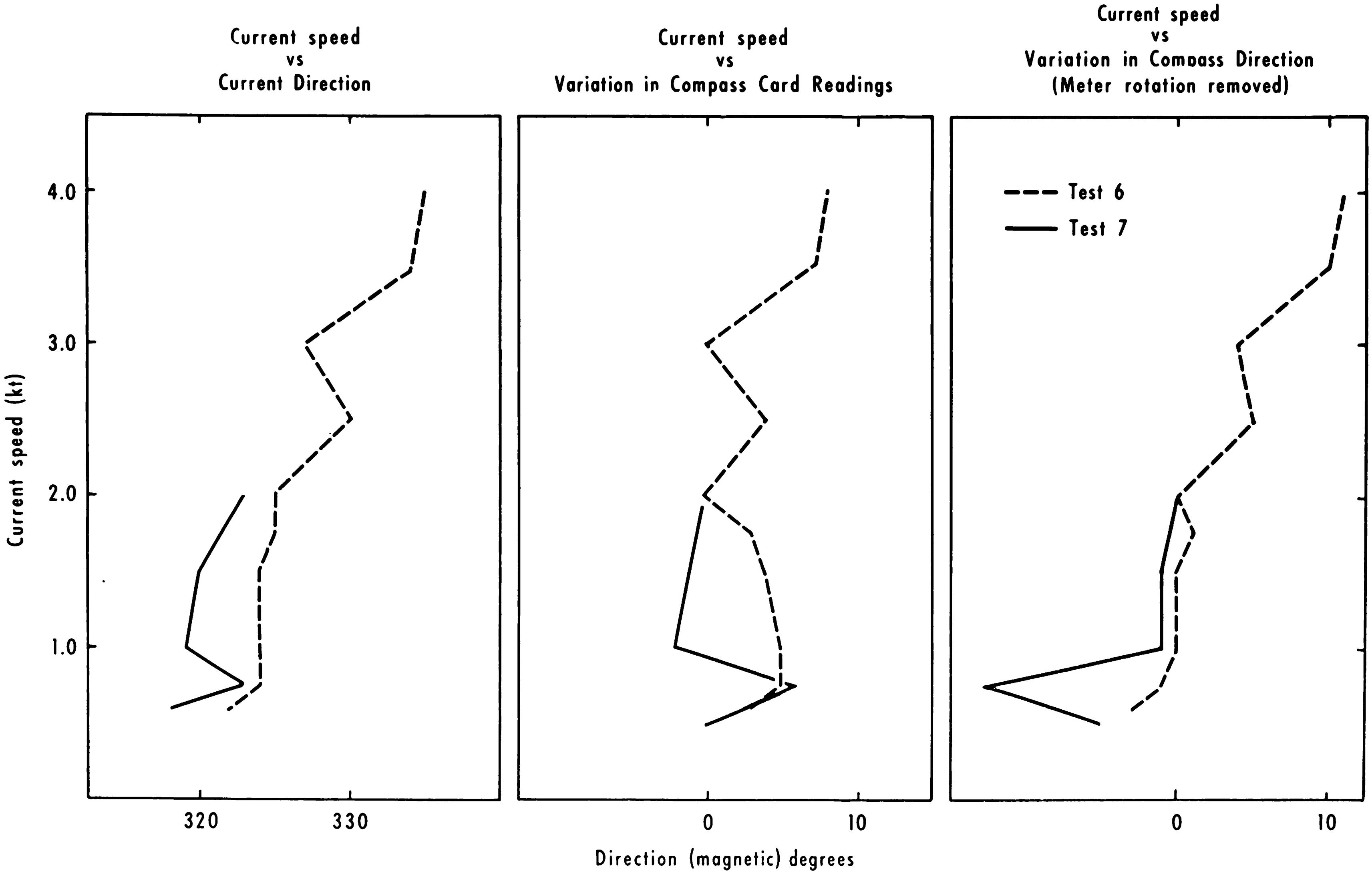


Figure 30.--Directional plots for A-102 meter in Tests 6 and 7.