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Research and Development

The Vertical Planar Motion Mechanism; A Dynamic Test Apparatus for Evaluating Current Meters and Other Marine Instrumentation

Interagency Energy/Environment R&D Program Report

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THE VERTICAL PLANAR MOTION MECHANISM

A Dynamic Test Apparatus for Evaluating Current Meters and Other Marine Instrumentation

by

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FOREWORD

Oceanic, estuarine, and limnologic circulation studies are conducted for many diverse purposes for which high data quality is important: energy exploration and extraction, development and validation of models, climate research, and pollution and sediment transport, to name but a few. Specifically, measurement of water flow is basic to the development of circulation models which are used to predict transport of energy-related pollutants (oil spills, offshore drilling wastes, etc.). On a smaller scale, current meters are utilized to obtain water particle velocity measurements used in petroleum production platform design.

Most flow measurements are made with current meters, which are instruments that sense and record flow speed and direction as a function of time. If properly calibrated and functional, nearly all current meters will provide high quality data in a steady environment. In the real world, however, the flow sensors are typically exposed to a wide range of time and length scale dynamics which may cause large measurement uncertainties, with errors higher than 100 percent not unusual. These uncertainties may be quantified using several different techniques: (1) mathematical modeling, (2) field intercomparison, and (3) laboratory testing. Mathematical modeling and field intercomparisons must be validated in the laboratory to quantify the uncertainties inherent to these methodologies. The capability to perform dynamic testing in a laboratory will greatly assist in defining performance of currently used sensors and accelerate development of improved current measurement systems and field standards.

ABSTRACT

The overall objective was to provide a dynamic test apparatus that can produce known, controlled high frequency dynamics for the evaluation of current meters and other marine instrumentation. Of primary interest is the establishment of flow sensor measurement capabilities to assure data quality in an unsteady flow environment.

The culmination of this development is a Vertical Planar Motion Mechanism (VPMM) that generates three major modes of dynamics--vertical-circular, vertical, and horizontal--at length scales from 0.15 to 1.22 m and time scales from 5 to 12 s. The VPMM mounts on a tow carriage which provides the steady velocity while the VPMM superimposes oscillatory motions on full-size current meters.

The VPMM is instrumented such that the instantaneous velocities of the test sensors and their outputs may be measured at a 20-Hz sampling rate; an on-board computer allows for near-real time data analysis. This report describes the development and wet acceptance testing of the VPMM using several types of current sensors, including the electromagnetic and the acoustic variety. Current sensor dynamic response is also documented. No deleterious interactions were noted between the VPMM and the test instruments; the VPMM performance was within specifications for all conditions investigated.

This report was submitted to the National Oceanic and Atmospheric Administration (NOAA) in partial fulfillment of Interagency Agreement number EPA-IAG-D5-E693-EA (Energy Pass-Through Funds) and under partial sponsorship of the U.S. Environmental Protection Agency. A substantial amount of the hardware design and fabrication were conducted by the U.S. Naval Ship Research and Development Center, Carderock, Maryland. The electronic interfacing, instrumentation, software, and requirements were generated by the Test and Evaluation Laboratory, Office of Marine Technology, National Ocean Survey, NOAA. This report covers the period March 1975 to July 1977.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

BCD	-- binary coded decimal
cm	-- centimeter
DTNSRDC	-- David Taylor Naval Ship Research and Development Center
g	-- acceleration of gravity
hp	-- horsepower
Hz	-- Hertz; cycles per second
in	-- inch
kg	-- kilograms
m	-- meter
NOAA	-- National Oceanic and Atmospheric Administration
s	-- second
VPMM	-- Vertical Planar Motion Mechanism

SYMBOLS

l	-- Distance between drive system and pinion cluster.
r	-- One-half test instrument displacement; crank arm length.
t	-- Time
u	-- Fluctuating velocity component, vertically orthogonal to $\overline{V}$.
$\underline{v}$	-- Fluctuating velocity component, collinear with $\overline{V}$ and x axis.
$\overline{V}$	-- Mean value of current vector; the measurand; also the tow vehicle velocity.
v_c	-- Oscillatory velocity: vertical circular mode.
v_h	-- Oscillatory velocity: horizontal mode.
v_v	-- Oscillatory velocity: vertical mode.
w	-- Fluctuating velocity component, horizontally orthogonal to $\overline{V}$.
X, Y, Z	-- Mutually orthogonal axes; Z is oriented vertically.
ω	-- Angular velocity of the drive system.

SECTION 1

INTRODUCTION

The Vertical Planar Motion Mechanism (VPMM) was developed primarily for producing known, controlled motions to evaluate flow sensor performance. The VPMM attaches to a tow vehicle mounted over a water filled channel (Figure 1); the tow vehicle provides steady velocities while the VPMM superimposes high frequency dynamics. The tow facility is located at the David Taylor Naval Ship Research and Development Center (DTNSRDC), Carderock, Maryland. Three distinct modes of dynamics can be generated--circular, vertical, and horizontal (Figure 2). The test instrument is attached to the base of the drive beam and submerged below the water line. Although not verified empirically, other devices can be tested. Objects up to 2.0 m long and weighing 80 kg have been tested at instantaneous velocities up to 1.5 m/s. The overall dimensions of the VPMM are 3.4 m high, 1.8 m long, and 0.5 m wide. Constructed primarily from aluminum, the apparatus weighs less than 680 kg and is easily handled with a hoist. The VPMM is designed to also interface with another tow facility at DTNSRDC which develops various combinations of wave conditions.

The VPMM can generate peak amplitudes over a range of 0.15 to 1.22 m in 0.15-m increments. A 3-horsepower variable speed electric motor and a 40-to-1 gearbox allow periods of motion ranging from 5 to 12 s. To maintain a constant speed, the drive system is controlled by a bidirectional servo control unit. Oscillatory motions generated by the VPMM are monitored with a digital timer and an angular position monitor which is attached to the drive shaft of the motor; these time displacement values are then converted into velocity units by a computer. (An error analysis is conducted in a later section of this report.) The VPMM can also rotate the plane of motion from parallel to the direction of tow (0-degree angle of attack), to normal to the tow (90 degrees) in 15-degree increments. In summation, the VPMM is capable of simulating various unsteady flow and dynamics conditions, such as wave particle fields and instrument motions, within a steady water velocity environment.

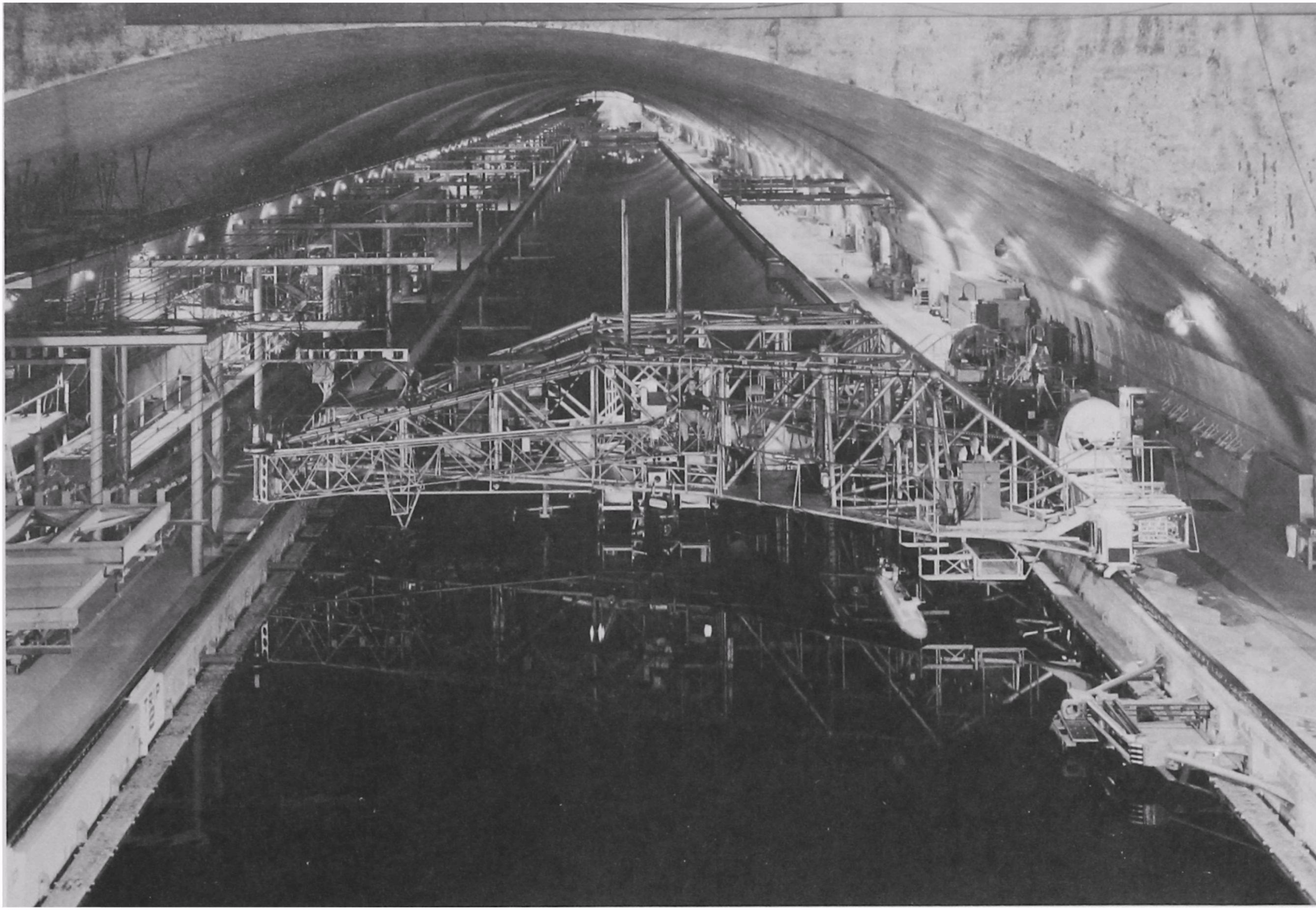


Figure 1. DTNSRDC #1 Tow Carriage

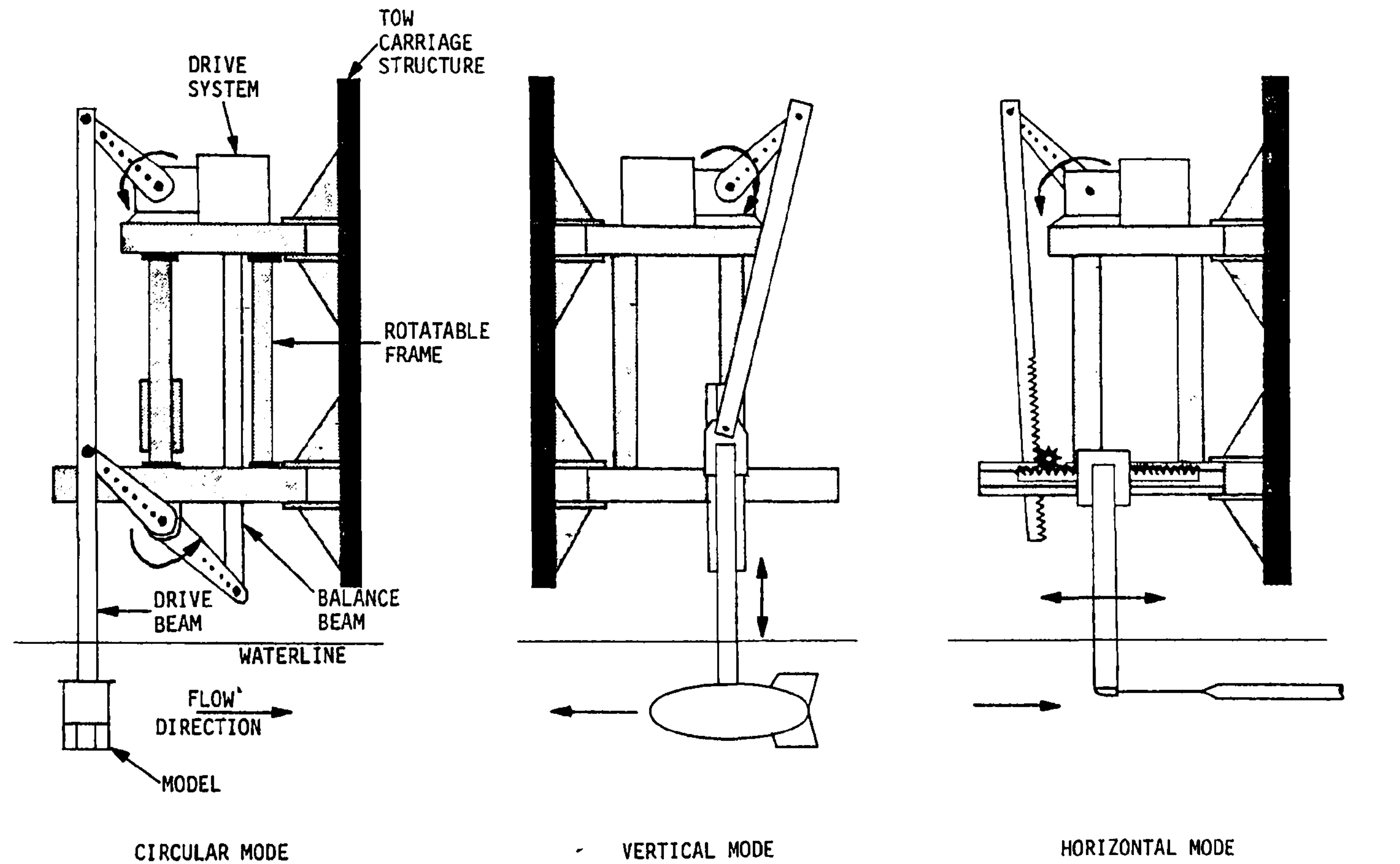


Figure 2. Vertical Planar Motion Mechanism.

SECTION 2

CONCLUSIONS

Based on observations and measurements derived during the acceptance testing phase, the VPMM system operated successfully in all three modes of dynamics. Both the uniformity and repeatibility of the VPMM generated velocities were excellent. An analysis of the data from the tow facility, VPMM, and current sensors indicated no major deleterious interactions. No apparent electromagnetic or acoustic interference was noted. Stray dynamics, such as vortex shedding induced motions, were not detected even during steady state tows. A toggling effect--a high frequency, small displacement phenomenon--was apparent during the vertical-circular mode of operation, but did not affect the test sensor's signals. Rigging and installation of the VPMM to the tow carriage was readily accomplished, although the availability of a suitable staging platform would have simplified the operation. Changes in oscillatory modes and angles of attack were conducted efficiently.

The VPMM provides a unique capability for testing and evaluating sensors at various combinations of length and time scale dynamics. A typical mission scenario would be establishing current meter data quality under dynamic conditions as follows: (1) define measurement system physical characteristics, i.e., platform, mooring, etc.; (2) using appropriate models, quantify the predicted motions of the current meter as a function of anticipated environmental forcing levels; (3) using the VPMM, duplicate the predicted dynamics in the laboratory to error bound the current meters' performance. Other anticipated uses for the VPMM include testing wave measurement systems, validating dynamic response models, and conducting stability tests on towed vehicles.

SECTION 3

THEORY AND DESCRIPTION OF OPERATION

The VPMM (Figure 2) and the tow carriage (Figure 1) may be thought of as a system for superimposing high frequency oscillatory velocities on a known mean velocity. This is illustrated vectorially in Figure 3, where the tow vehicle is represented by $\overline{V}$, and the v, w, and u components are generated by the VPMM. The VPMM can operate in three different modes--vertical-circular, pure vertical, and pure horizontal, all at various angles of attack. The oscillatory motion may be described as follows:

Vertical-Circular Mode $$v_c = r\omega \sin\omega t \quad (1)$$

Pure Horizontal Mode $$v_h = \frac{rl\omega \sin\omega t}{(r^2+l^2-2rl\cos\omega t)^{.5}} \quad (2)$$

Pure Vertical Mode $$v_v = \omega r \sin\omega t - \frac{\omega r^2 \sin\omega t \cos\omega t}{(l^2-r^2\sin^2\omega t)^{.5}} \quad (3)$$

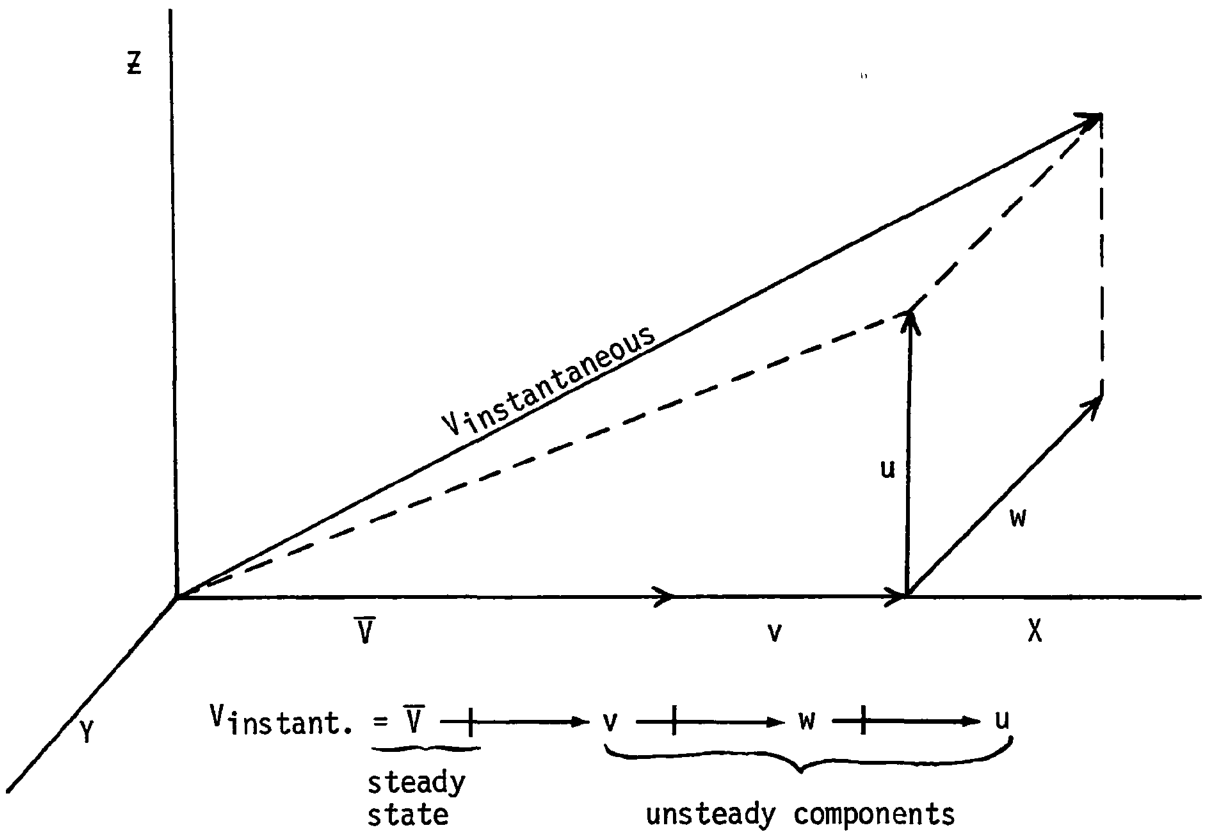
r = one-half test instrument displacement; crank arm length

l = distance between drive system shaft and pinion cluster

ω = angular velocity of drive

t = time

Derivations of equations (1) through (3) are in Appendix A. Note that each mode of dynamics will generate a unique set of instantaneous velocities which result from mechanical arrangements inherent to that mode (Figure 2). The circular motion mode forms a rotating parallelogram such that the test instrument undergoes circular velocity, uniform in nature; thus the velocity projection in the x, y, and z planes is sinusoidal. In the vertical mode, the test instrument motions are limited to the vertical plane by vertically oriented guide shafts and bearings. Higher harmonics are superimposed on the planar sinusoidal velocity because of the ratio of the power transmission beam (i.e., the connecting rod) to the crank. In the horizontal mode, a pair of pinion gears and a pair of racks transmit oscillatory motions to the test instrument. The horizontal rack is attached to a slider-bearing combination which rides a horizontal guide shaft. The resulting oscillatory velocity is nearly sinusoidal. Normalized comparisons of the three types of oscillatory



where

$\overline{V}$ = mean value of current vector, the measurand; also tow vehicle velocity.

v = fluctuating velocity component, collinear with $\overline{V}$.

u = fluctuating velocity component, vertically orthogonal to $\overline{V}$.

w = fluctuating velocity component, horizontally orthogonal to $\overline{V}$.

Figure 3. Velocity Diagram of Tow Vehicle and VPMM.

dynamics are illustrated in Appendix B. As expected, the three curves converge as the crank arm radius (r) is decreased from 0.61 m (24 in) to 0.15 m (6 in).

SECTION 4

GENERAL ACCEPTANCE METHODOLOGY

The VPMM development was based on the set of requirements shown in Table 1. Prior to operation of the dynamic test apparatus in water with actual current meters, it was demonstrated in-air under simulated weights and hydrodynamic loads to induce and correct any design deficiencies.

TABLE 1. VPMM OPERATING REQUIREMENTS

Maximum steady state velocity without dynamics	200 cm/s
Maximum steady state velocity with dynamics	70 cm/s
Maximum oscillatory velocity	85 cm/s
Period of dynamics	5 to 12 s
Amplitude, peak-to-peak increment	15 to 122 cm 15 cm
Angle of attack increment	0° to 90° 15°
Test instrument loading (worst case)	weight in air 80 kg length 180 cm diameter 25 cm

IN-AIR DEMONSTRATION

After the major components of the system were fabricated, the VPMM was assembled in a laboratory at DTNSRDC for an in-air or "dry" demonstration. The vertical-circular mode of operation was validated first. For these experiments, weights up to 45 kg were clamped to the drive and balance arms, and the system was operated at various speeds. Problems with the mechanical fit of moving parts, structural stiffness, and inadequate speed control were noted and subsequently corrected. For the final in-air demonstration, weights and an elastomeric cord were attached to the drive arm to simultaneously simulate current meter mass and hydrodynamic loading, respectively.

The load conditions that were simulated were derived from mathematical predictions and were based on the "worst case" current meter for the severest combination of circular velocities, superimposed on steady state values. During this experiment, tachometer output from the drive system was measured to evaluate the speed control; concurrently, the vertical acceleration of the drive arm was measured. The initial speed control variations were found to be satisfactory within 5 percent of the mean value. Acceleration spikes induced by toggling of the drive crank at top and bottom dead center, representing small changes in displacement, were noted. All in all, the fixture performance was deemed acceptable. Since both abnormalities were minor from the standpoint of current meter evaluations, the wet demonstrations were begun.

The other two modes of dynamics, vertical and horizontal, were checked in a similar manner, using weights and elastomeric cords. As in the previous tests, the fixture was subjected to maximum predicted stresses, with no major deficiencies uncovered.

IN-WATER DEMONSTRATION

The purpose of the in-water, or "wet," demonstration, with the VPMM mounted on an DTNSRDC towing carriage, was to evaluate the performance of the total system over a wide range of conditions which could be expected for standard current meter evaluations. In other words, anomalous interactions between the test sensor (current meter), the tow carriage/basin, and the ancillary equipment would hopefully surface during these in-water demonstrations.

FACILITIES AND EQUIPMENT

The tow vehicle (Figure 1) on which the VPMM (Figure 2) is mounted is an electrohydraulically powered wheeled platform, weighing 40,000 kg, that rides on rails mounted atop the channel walls; the vehicle has a velocity range of 2.5 to 600 cm/s. The tow channel itself is 335 m long, 13.5 m wide, with depths of 3.3 and 6.7 m. The facility is located at the David Taylor Ship Research and Development Center, Carderock, Maryland. Tow vehicle displacements are monitored with an electronic counter and magnetic pickup which senses magnetic pulses generated by a steel gear coupled to a precision wheel. A computer converts the pulses into velocity units, normally centimeters/second.

Wet acceptance testing of the VPMM involved a complex, interrelated suite of equipment and instrumentation (Figure 4). For simplicity, this configuration may be divided into several major sectors--steady state

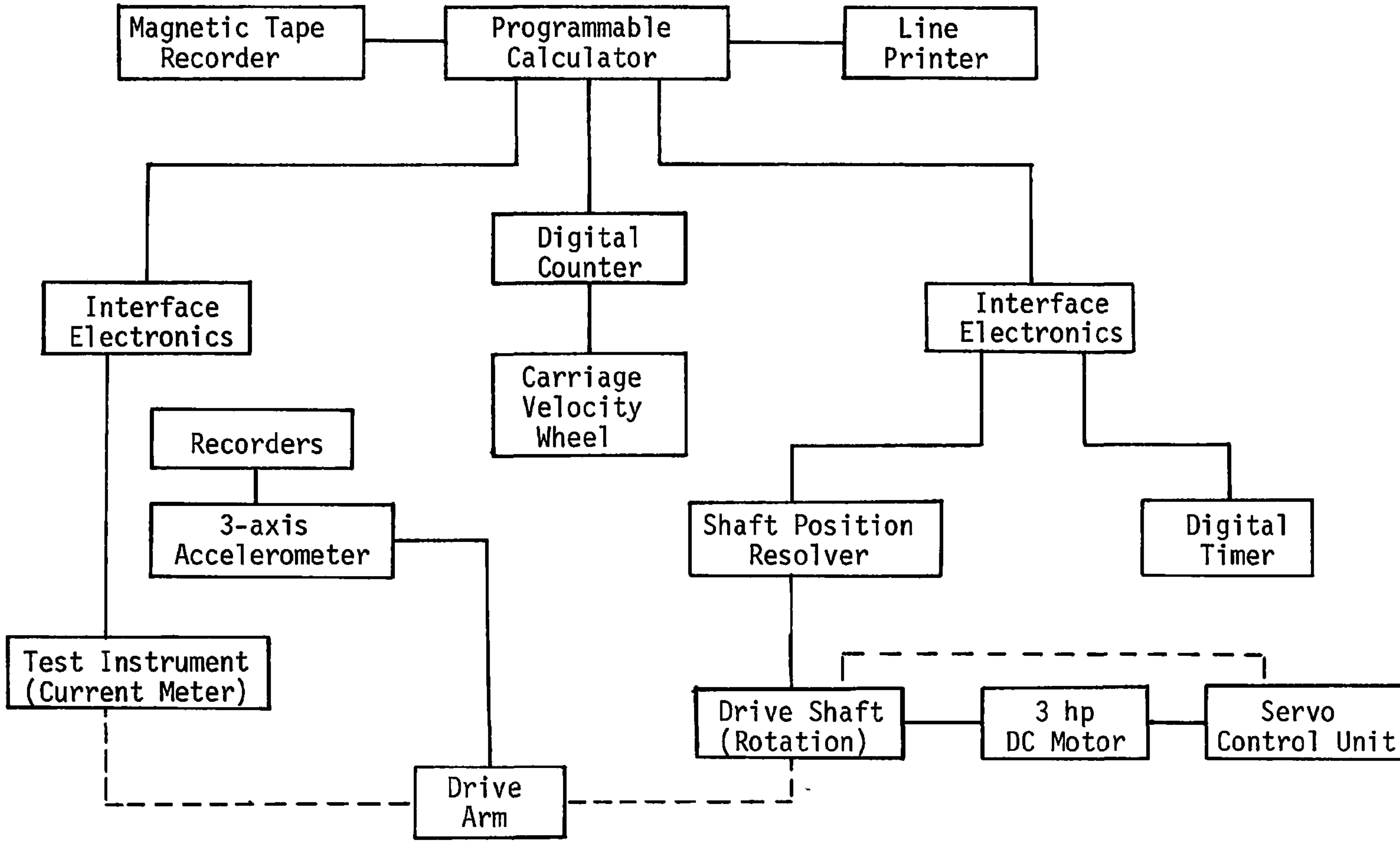


Figure 4. VPMM Acceptance Test Instrumentation System.

measurements (carriage velocity), nonsteady state measurements (VPMM generated dynamics), current meter outputs, and a data collection/analysis system (programmable calculator) which serves as the measurement control tool. The following is a descriptive listing of the ancillary equipment:

Absolute Encoder

Converts shaft input to BCD or binary information corresponding directly to shaft angle while simultaneously displaying a four-digit display of the shaft angle. The basic unit consists of an electromagnetic transducer (resolver) and an electronic converter package. The overall accuracy is 0.1 degree of arc. Sampling intervals of 400 conversions/second are attainable.

Time Interval Meter

Measures time intervals between absolute encoder conversions. The output data are in BCD format, and the meter also features a six-digit display of the time. The accuracy of the interval time base models is typically 1 part in 10^6 at 25°C and is insured by the use of a crystal controlled oscillator circuit.

Bidirectional Servo Control Unit

Acts as an electronic flywheel to maintain a constant motor rotation rate by means of a feedback loop from a tachometer mounted on the motor shaft.

Servo Accelerometer/Amplifier System

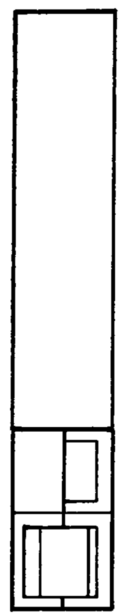
Triaxial accelerometers are mounted above the current meters to monitor the dynamics generated by the VPMM and the current meters themselves. The accelerometers have an uncertainty of 1 percent of full scale and operate on the principle of a seismic mass suspended in a magnetic field.

Programmable Calculator

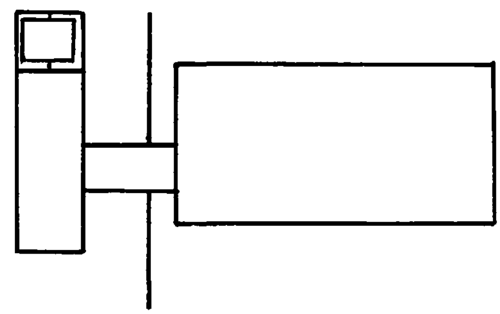
Acts as the data collection and reduction system for the VPMM, tow carriage, and test sensors. A portable calculator monitors and computes carriage velocity, instantaneous velocity of the apparatus, and sensor outputs, along with the associated statistical manipulations such as mean, standard deviation, etc. Data are recorded on magnetic tape cartridges.

Four different ocean current meters (Figure 5) were used to certify VPMM compliance with the design specifications. The rationale for each selection is shown in Table 2.

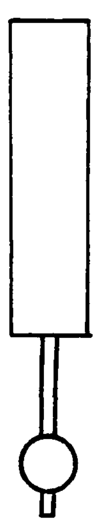
The rotor and small vane type used in these empirical investigations weighed 80 kg in air (35 kg in water) and was approximately 2 m long. By virtue of the size and mass, it imparted the largest loading on the fixture of any of the current meters. The rotor with large vane weighed 28 kg in air and 21 kg in water, with an overall length of 1.4 m including a 1-m long vane with a height of 0.75 m. The electromagnetic current meter weighed 43 kg in air and had an overall length of 1.5 m. The acoustic current meter weighed



Rotor with small vane



Rotor with large vane



2-axis Electromagnetic

2-axis Acoustic

Figure 5. VPMM Acceptance Test Current Meters.

34 kg and was 1.3 m long, with an overall diameter of 22 cm.

TABLE 2. CURRENT METER SELECTION CRITERIA FOR ACCEPTANCE TESTING

Current Meter	Rationale for Selection	VPMM Mode Validated
Rotor with small vane	Largest and heaviest current meter	Horizontal & vertical
Rotor with large vane	Most common current meter	Vertical-circular
2-axis Electromagnetic	Very susceptible to electronic noise	Vertical-circular
2-axis Acoustic	0.2 second time constant	Horizontal & vertical

EMPIRICAL PROCEDURES

The VPMM was mounted on the front of Tow Carriage #1 at DTNSRDC and configured to operate in the vertical-circular mode with a fixed peak amplitude of 1.22 m. After installing the resolver on the drive arm shaft and attaching the 3-axis accelerometers, the current meter was affixed and the data collection system activated. Preliminary calibrations were made on the system dynamics by measuring the drive arm oscillation period versus motor speed setting.

Once the fixture calibrations were completed, the in-water dynamics were initiated with the least severe structural loadings and slowest oscillatory periods. Oscillatory VPMM dynamics of 5-, 8-, and 12-s periods at 1.22-m peak amplitudes were superimposed on steady carriage velocities of 0, 10, 35, and 70 cm/s. Outputs from all instruments and equipment were recorded, most at a nominal rate of 25 times per oscillatory period. Thus, the sampling density was constant for all three dynamic time scales of 5, 8, and 12 s. Each data point consisted of approximately 250 samples, encompassing 10 total periods. Averaging bias errors were minimized by initiating and terminating sampling near the zero-crossing points. Additional real-time data analyses were conducted for each data point; statistical computations were made of the mean, standard deviation, minimum, maximum, range, and 95-percent confidence level in the mean for both the standard (carriage velocity) and the test instrument (current meter). A sample printout of the statistical computations is shown in Appendix C. After completing these investigations using the rotor with large vane-type current meter, the electromagnetic flow sensor was substituted and similar empirical procedures were followed.

Similar techniques were followed in validating the pure vertical and pure horizontal modes except that an acoustic current meter and a rotor with a small vane were used as the test instrument.

SECTION 5

RESULTS

The ultimate purpose of the "wet" acceptance testing was to confirm the operational capabilities of the VPMM and to identify and quantify any interaction between the test instruments (current meters) and the VPMM, and vice versa. Criteria used to describe the overall performance of the VPMM were: uniformity of oscillatory motions; degree of high frequency vibrations; electromagnetic or acoustic interference; ease of handling, installation, and adjustment; changing modes of dynamics; and overall system reliability and accuracy.

Uniformity of oscillatory motions was determined using outputs from the angular position resolver attached to the motor drive shaft which couples to the drive arm holding the test instrument. For all three modes of operation--circular, vertical, and horizontal--the standard deviation of the drive shaft angular velocity averaged less than 4 percent of the mean using the largest and heaviest test instrument and the most severe unsteady conditions. Figure 6 illustrates typical instantaneous oscillatory velocities, and Figure 7 the corresponding drive shaft angular increments as a function of sample number (time). The oscillatory velocities were computed using incremental shaft position (resolver) measurements as a function of time and equations (1), (2), or (3).

Fixture installation and integration efforts were minimal. The VPMM was attached to the front face of the tow carriage with a series of clamps; mounting and adjustment took approximately two hours. Changing the angle of attack, relative to the tow direction, involved removing two pins and manually rotating the superstructure, a several-minute procedure. Changing modes of operation, i.e., from vertical to horizontal, was also easily accomplished, normally requiring one hour.

High frequency vibrations and accelerations were monitored using a triaxial accelerometer system. Various combinations of simultaneous stresses were generated to establish the effects of oscillatory period, tow speed, angle of attack, and various current meters. The most significant acceleration levels (1.6 g in the horizontal plane) were noted in the vertical orbital mode and have been attributed to a mechanical type toggle. A spectrum analysis of the corresponding vertical acceleration records revealed the levels to be less than 0.15 g at between 1 and 10 Hz. Initially, large accelerations of approximately 2 g at approximately 1 Hz were noted in the horizontal mode. These were caused by an erratic feedback signal to the motor speed control which was subsequently repaired. Except for the minor toggling in the vertical circular mode, the high frequency acceleration levels were small and seemed unaffected by angle of attack, test instrument

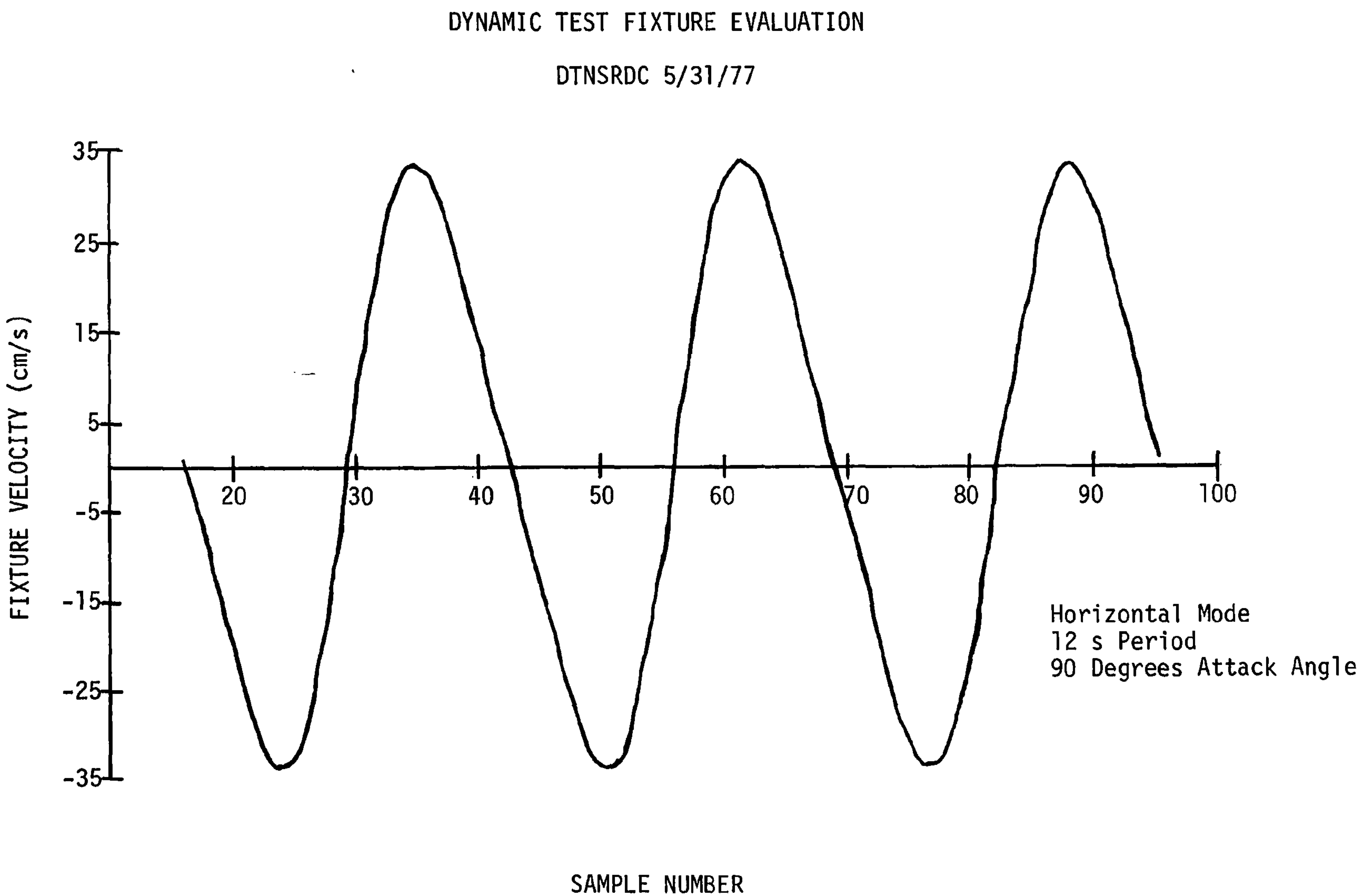


Figure 6. Computed VPMM Oscillatory Velocities.

DYNAMIC TEST FIXTURE EVALUATION

DTNSRDC 5/31/77

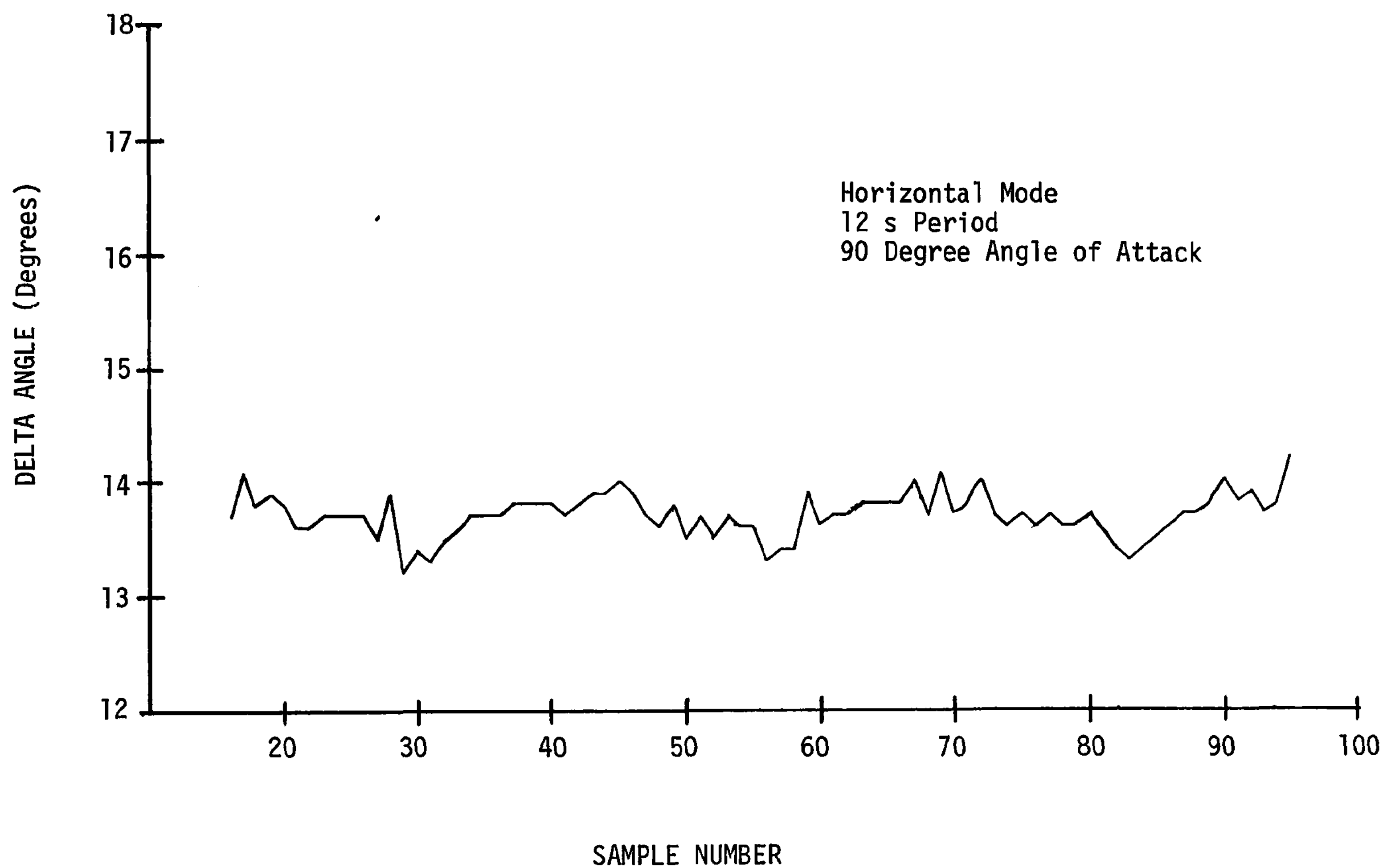


Figure 7. Incremental Angular Displacements of VPMM Drive Shaft.

configuration and mass, oscillatory dynamics, and horizontal velocity.

An examination of analog records from the electromagnetic and acoustic current meter indicated that no apparent stray electromagnetic or acoustic noise was generated by the VPMM system. Although both current meters exhibit fast time constants, 0.2 s for the acoustic, and 1.0 s for the electromagnetic, neither signal was adversely distorted. The uniformity of each record suggests no apparent deleterious interaction between the VPMM, tow basin, and tow carriage.

Numerous tests, both static and dynamic, were made at various positions and depths in the tow channel; no significant difference was noted in the shallow end of the channel. In summation, the empirical results confirmed that the operational capabilities of the VPMM system meet requirements documented in Table 1.

SECTION 6

ERROR ANALYSIS

Since the VPMM will be used to generate controlled, known dynamics for determining current meter performance, it is important to quantify the system uncertainties in the standards, specifically the tow carriage velocity, stray water currents, and the VPMM superimposed velocity. The velocity measurement of the tow vehicle and the VPMM generated dynamics are traceable to the National Bureau of Standards by the time and distance parameters, which are primary units of measurement. Thus, the uncertainties in the absolute instantaneous velocity of the test instrument over the Earth may be readily computed. The total system error is comprised of several individual components which may be grouped into two major categories--systematic errors and random errors. The systematic errors arise from estimated uncertainties of standards used--i.e., instrumentation to measure carriage velocity and dynamic (VPMM) velocity--and estimated magnitudes of residual currents and blockage effects. The random errors are a measure of the scatter of instantaneous velocity values about the computed mean. The error terms for the VPMM and tow facility are listed below; except where noted, computation to support the numerical estimates are shown in Appendix D. It should be noted that error estimates yielding a percent-of-reading result have been converted to absolute velocity by using a maximum velocity value.

SYSTEMATIC ERRORS

- Uncertainties in steady state (tow carriage) velocity measurements. {0.014 cm/s}
- Residual, convection, stray currents in tow basin. (estimate based on prior tests at DTNSRDC) {1 cm/s}
- Uncertainties in nonsteady (VPMM) velocity measurements. {0.68 cm/s}
- Velocity blockage induced by test instruments placed in tow basin. {0.02 cm/s}
- Sampling error--maximum uncertainty in determining peak instantaneous velocity of VPMM. {0.6 cm/s max.}

RANDOM ERRORS

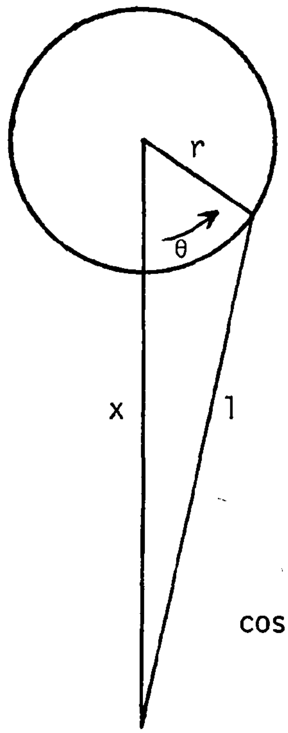
- Steady state (tow carriage) 95-percent confidence level in mean for n = 250. {0.04 cm/s}
- Nonsteady state (VPMM) averaging error. {0.1 cm/s}

Note that the largest component in the error budget, 1 cm/s, is due to residual, convection, and stray currents in the basin. These uncertainties result largely from circulations established from previous tows. Residual current errors may be minimized by allowing time between test points for dissipation.

APPENDIX A

Derivation of oscillatory velocity equations for VPMM.

VERTICAL EQUATION OF MOTION



cos law $a^2 = b^2 + c^2 - 2bc \cos A$

$$a = l;\ b = r;\ c = x$$

$$A = \theta;\ \theta = \omega t$$

$$l^2 = x^2 + r^2 - 2xr \cos \theta$$

$$l^2 = x^2 - 2xr \cos\theta + r^2\cos^2\theta - r^2\cos^2\theta + r^2$$

$$l^2 = r^2 (1-\cos^2\theta) + (x-r \cos\theta)^2$$

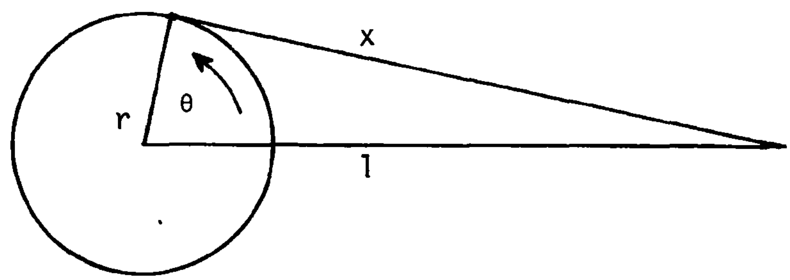
$$l^2 = r^2 \sin^2\theta + (x-r \cos \theta)^2$$

$$x-r \cos \theta = (l^2 - r^2\sin^2\theta)^{1/2} \quad :\theta = \omega t$$

$$x = (l^2 - r^2\sin^2\omega t)^{1/2} + r \cos\omega t$$

$$V = \frac{dx}{dt} = -\omega r \sin\omega t - \frac{\omega r^2 \sin\omega t \cos\omega t}{(l^2 - r^2\sin^2\omega t)^{1/2}}$$

HORIZONTAL EQUATION OF MOTION



cos law $a^2 = b^2 + c^2 - 2bc \cos A$

$a = x;\ b = r;\ c = l$

$A = \theta;\ \theta = \omega t$

$x^2 = r^2 + l^2 - 2rl \cos \theta$

$x = (r^2 + l^2 - 2rl \cos \theta)^{1/2}$

$V = \frac{dx}{dL} = 1/2\ (r^2 + l^2 - 2rl \cos\omega t)^{-1/2}[-2rl\ (-\omega \sin\omega t)]$

$V = \frac{dx}{dt} = \frac{rl\omega \sin\omega t}{(r^2 + l^2 - 2rl \cos\omega t)^{1/2}}$

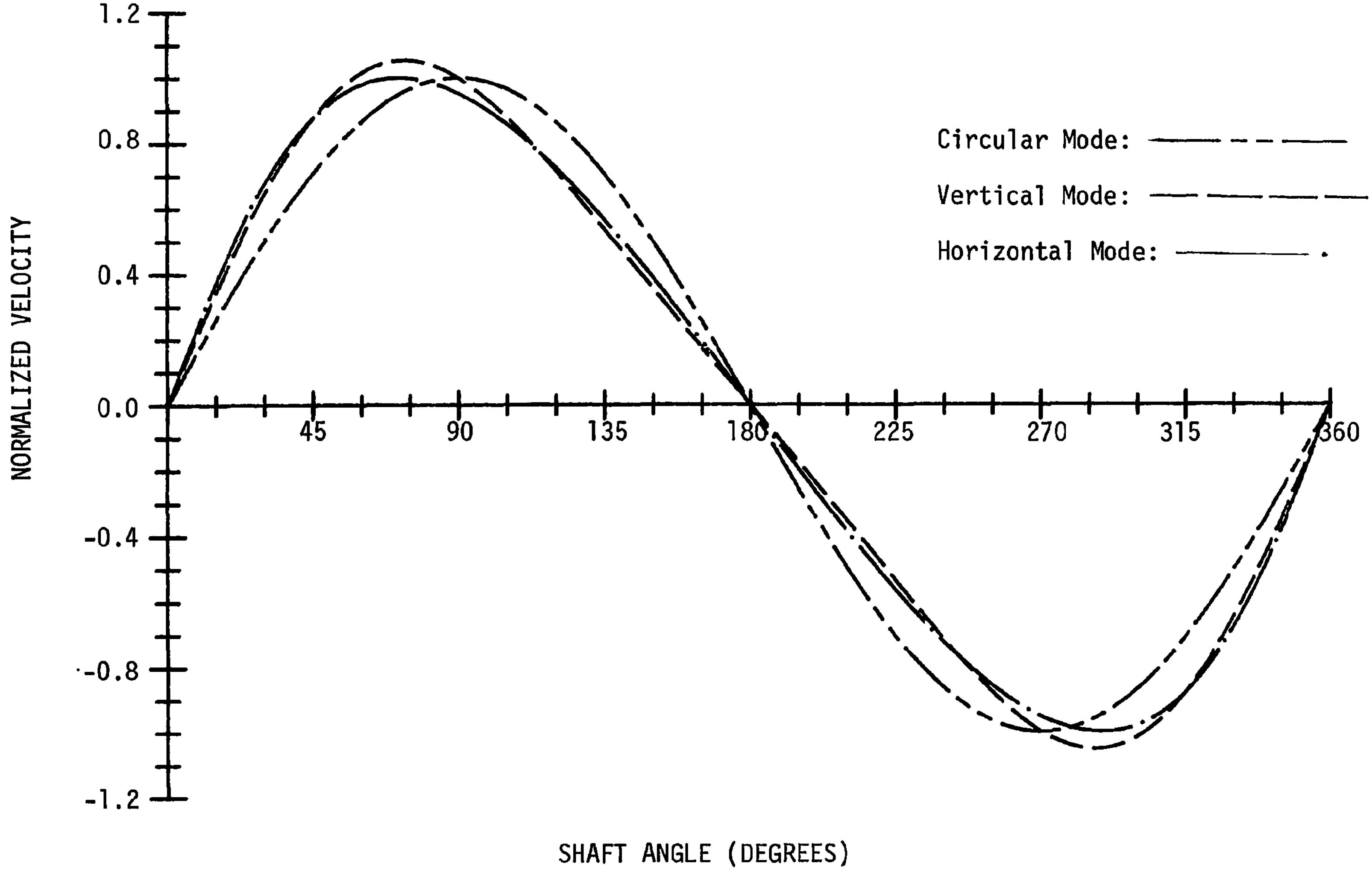
APPENDIX B

VPMM oscillatory velocity (normalized) vs. drive shaft angle, intercomparing the three modes of dynamics.

NORMALIZED INSTANTANEOUS VPMM

OSCILLATORY VELOCITY VS DRIVE SHAFT ANGLE

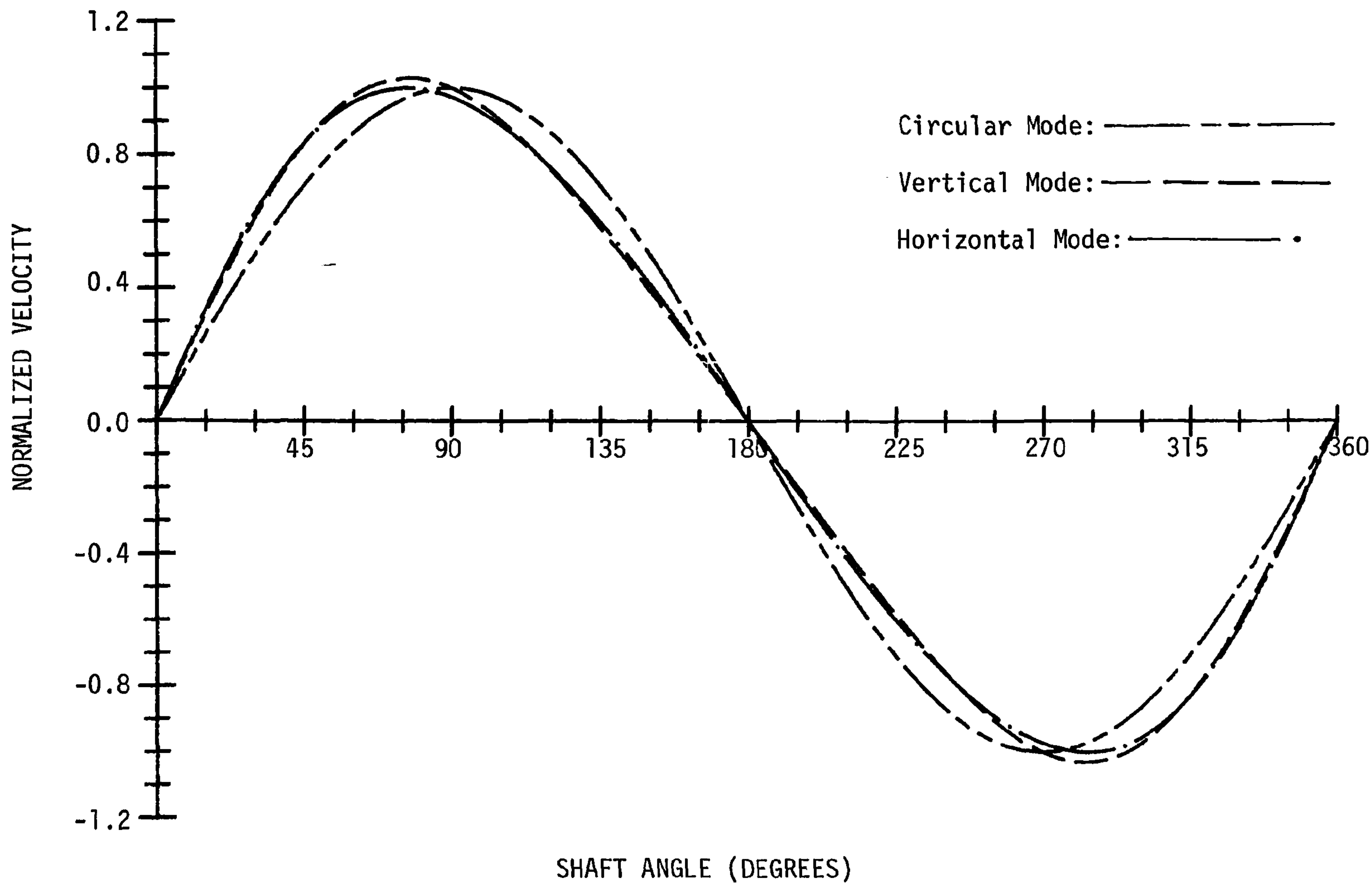
CRANK ARM RADIUS = 24 INCHES



NORMALIZED INSTANTANEOUS VPMM

OSCILLATORY VELOCITY VS DRIVE SHAFT ANGLE

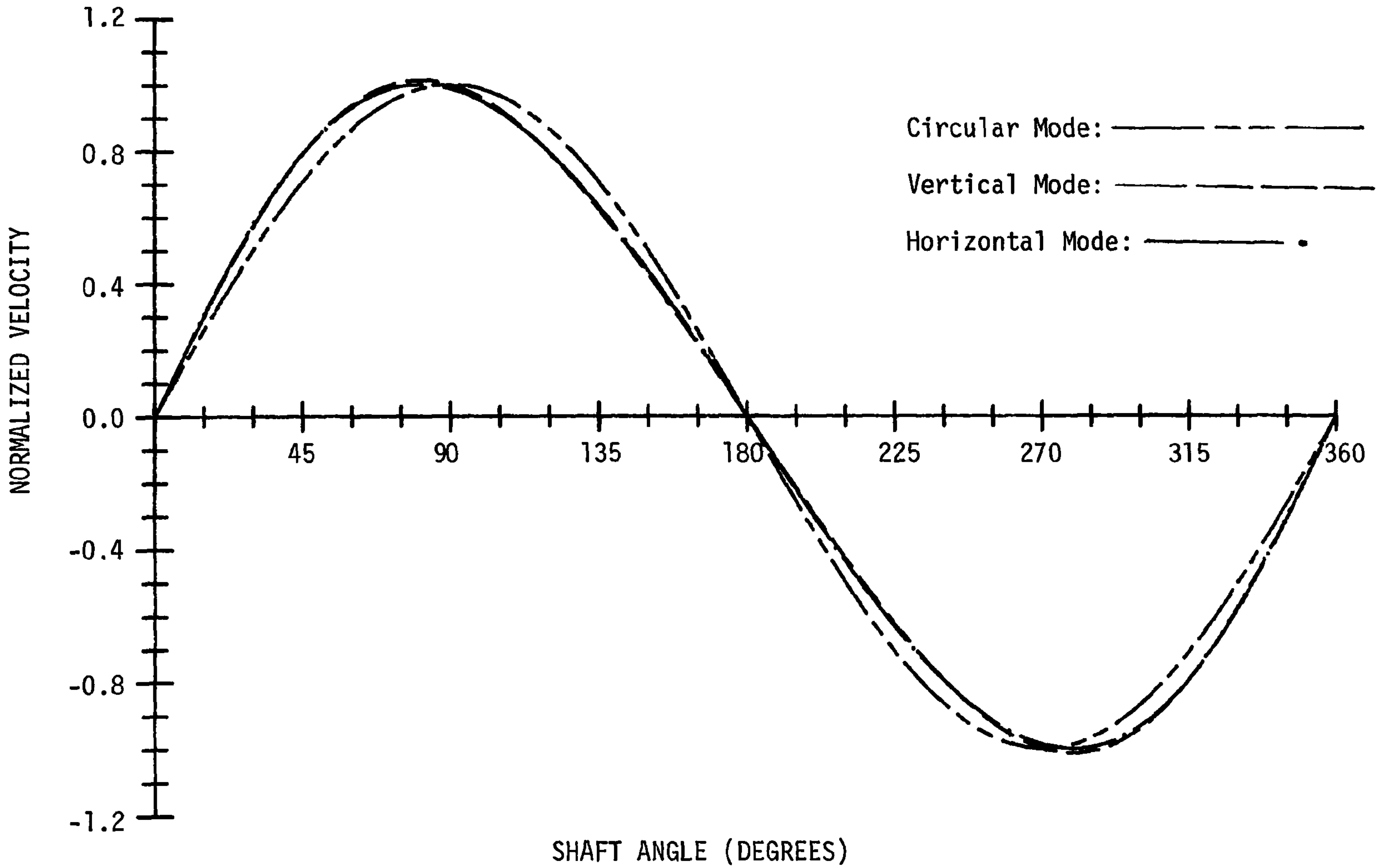
CRANK ARM RADIUS = 18 INCHES



NORMALIZED INSTANTANEOUS VPMM

OSCILLATORY VELOCITY VS DRIVE SHAFT ANGLE

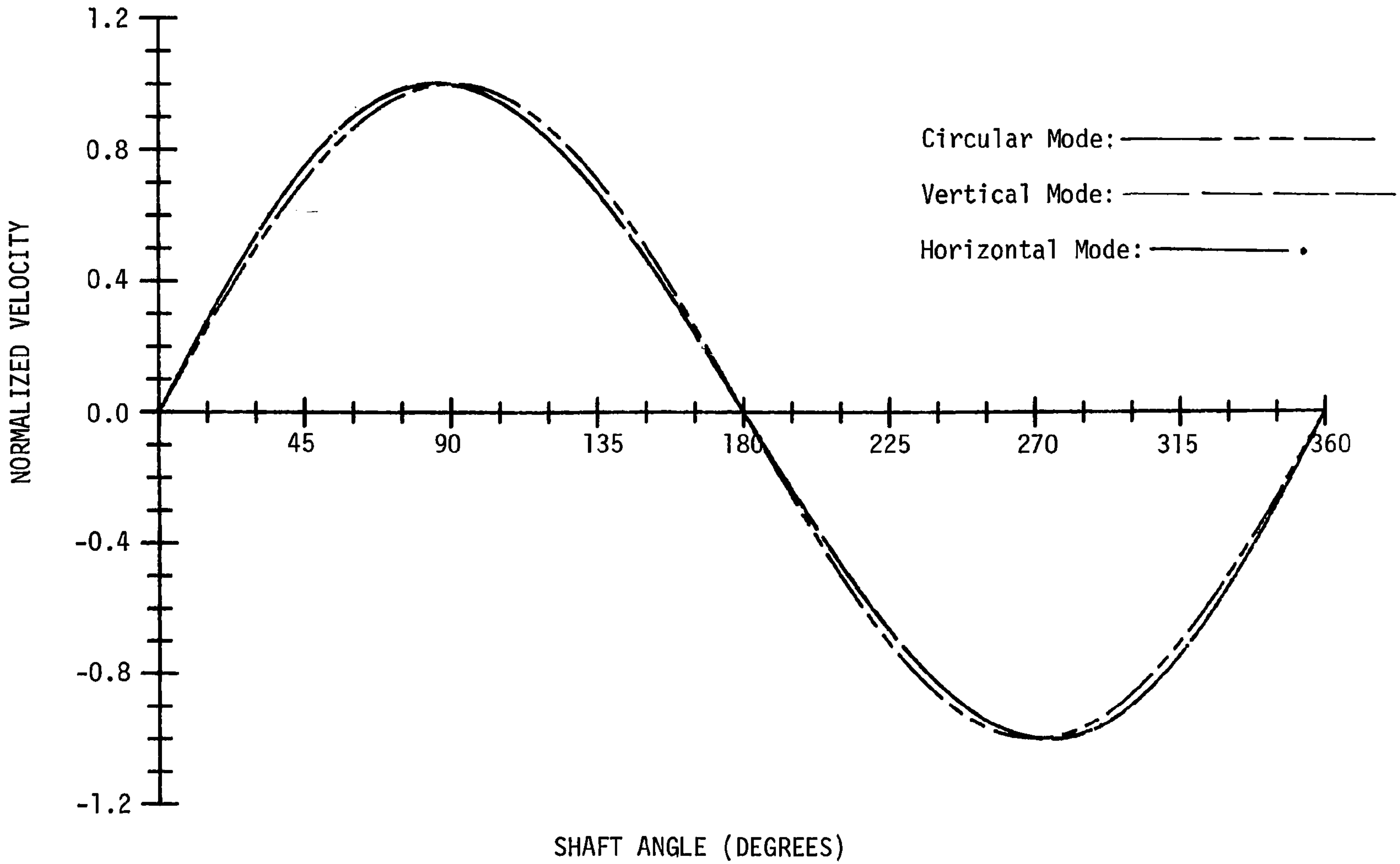
CRANK ARM RADIUS = 12 INCHES



NORMALIZED INSTANTANEOUS VPMM

OSCILLATORY VELOCITY VS DRIVE SHAFT ANGLE

CRANK ARM RADIUS = 6 INCHES



APPENDIX C

Sample printout record of a test point.

Run # 9 Run Id 12.00 Date 527 Time 190639

N = 235 Carriage Speed = 35.8 cm/s

Statistical Analysis

	Fix. Mag cm/s	VACM Mag cm/s	Delt. Ang deg.
Mean	3.588E 01	3.272E 01	4.226E 01
Std. Dev.	2.328E-01	7.045E 00	4.397E-01
Min	3.541E 01	2.593E 01	1.130E 01
Max	3.656E 01	1.354E 02	1.340E 01
Range	1.153E 00	1.095E 02	2.100E 00
S/N	1.541E 02	4.645E 00	2.789E 01
95% conf.	2.976E-02	9.008E-01	5.622E-02

VACM Mag. Error = -3.2 cm/s

Run # 10 Run Id 12.00 Date 527 Time 201503

N = 243 Carriage Speed = 72.6 cm/s

Statistical Analysis

	Fix. Mag cm/s	VACM Mag cm/s	Delt. Ang deg.
Mean	7.199E 01	6.870E 01	1.186E 01
Std. Dev.	4.422E-01	3.939E 00	3.350E-01
Min	7.044E 01	6.014E 01	1.120E 01
Max	7.313E 01	7.934E 01	1.270E 01
Range	2.693E 00	1.920E 01	1.500E 00
S/N	1.628E 02	1.744E 01	3.540E 01
95% conf.	5.560E-02	4.953E-01	4.212E-02

VACM Mag. Error = -3.3 cm/s

APPENDIX D

Examples of computations and assumptions in error analysis for velocity uncertainties.

SYSTEMATIC ERROR ASSOCIATED WITH DYNAMICS GENERATION SYSTEM

$V_{true} = r\omega$

$V_{measured} = (r \pm \varepsilon_r)(\omega \pm \varepsilon_\omega)$

$$\varepsilon_V = \frac{V_{true} - V_{measured}}{V_{true}}$$

where V = circular velocity of VPMM arm.

r = amplitude of dynamics, i.e., radius of crank arm.

ω = angular velocity, radians/second.

$\varepsilon_{V,r,\omega}$ = error terms in fixture velocity, crank arm radius, and angular velocity respectively.

$V_{measured} = r\omega \pm \varepsilon_r\omega \pm \varepsilon_\omega r \pm \varepsilon_r\varepsilon_\omega$

$$\varepsilon_V = \frac{r\omega - (r\omega \pm \varepsilon_r\omega \pm \varepsilon_\omega r)}{r\omega}$$, dropping the second order term $\varepsilon_r\varepsilon_\omega$

$$\varepsilon_V = \frac{\pm \varepsilon_r\omega \pm \varepsilon_\omega r}{r\omega}$$

If the sign of the errors are unknown, we can use the summation of errors rule.

$$\varepsilon_V = \frac{(\varepsilon_r{}^2\omega^2 + \varepsilon_\omega{}^2 r^2)^{1/2}}{r\omega} = \left[\left(\frac{\varepsilon r}{r}\right)^2 + \left(\frac{\varepsilon\omega}{\omega}\right)^2\right]^{1/2}$$

$$\varepsilon_V = \left[\left(\frac{1/64}{24}\right)^2 + \left(\frac{.1}{12}\right)^2\right]^{1/2}$$ substituting worst case values

ε_V = 0.8% of reading

SYSTEMATIC ERROR ASSOCIATED WITH CARRIAGE VELOCITY

$V_{true} = S/t$

$V_{measured} = (S \pm \varepsilon_S) / (t \pm \varepsilon_t)$

$$\varepsilon_V = \frac{V_{true} - V_{measured}}{V_{true}}$$

where V = linear velocity of carriage

S = circumference of carriage measurement wheel

t = time

$\varepsilon_{V,S,t}$ = error terms in carriage velocity, wheel circumference, and time, respectively.

If the sign of the errors are unknown, we can use the summation of errors rule.

$$\varepsilon_V = \left[\left(\frac{\varepsilon_S}{S}\right)^2 + \left(\frac{\varepsilon_t}{t}\right)^2 \right]^{1/2}$$

$$\varepsilon_V = \left[\left(\frac{1 \times 10^{-2}}{50.79}\right)^2 + \left(\frac{1 \times 10^{-6}}{1}\right)^2 \right]^{1/2}$$

ε_V = 0.02% of reading

VELOCITY BLOCKAGE

$$V_b = \frac{1}{4}\frac{a}{A}V_a$$

where a = cross sectional area of test instrument

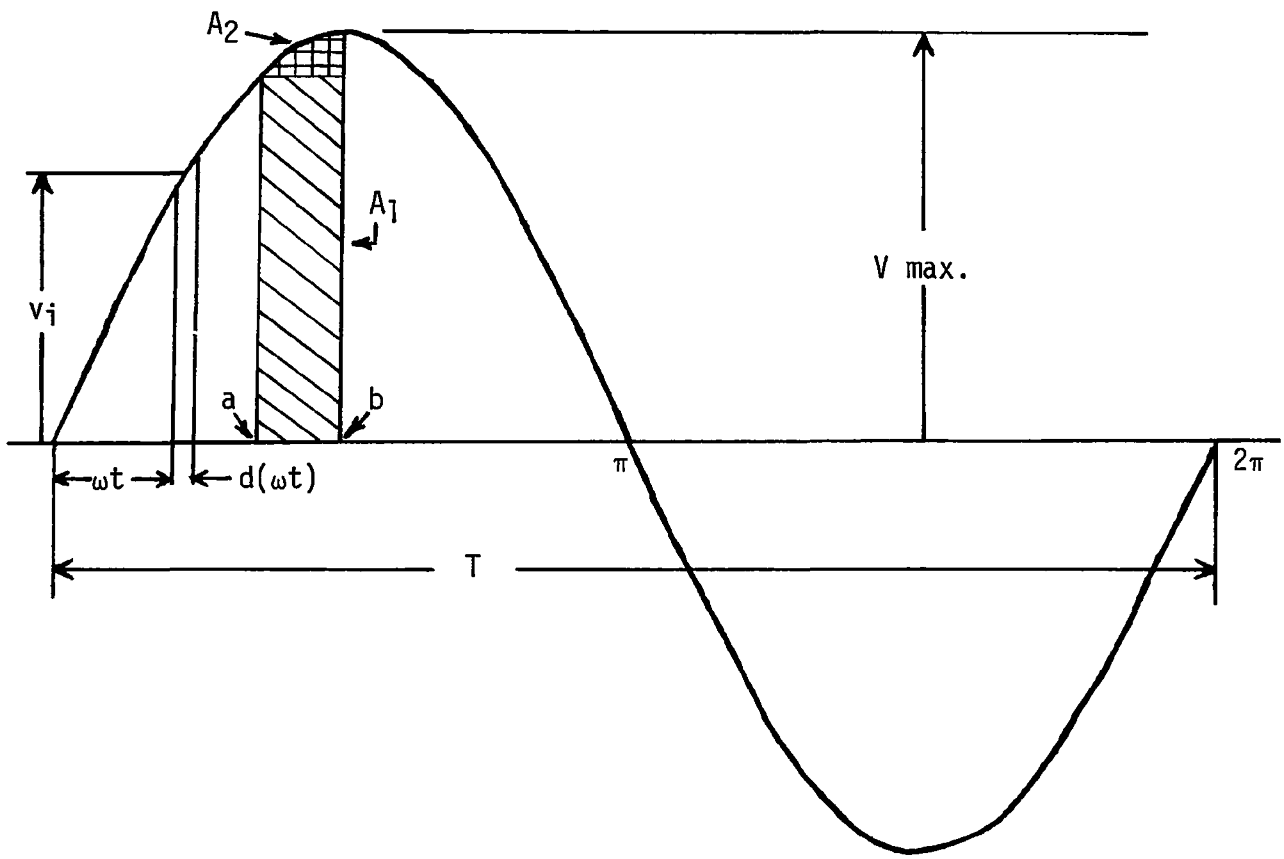
A = cross sectional area of test basin

V_a = velocity, actual

$$V_b = \frac{1}{4}\frac{(.2)\ (.75)}{(6.7)\ (15.5)}V_a$$

$V_b = 0.0004V_a$ or 0.04% of reading

UNCERTAINTIES ASSOCIATED WITH SAMPLING
PEAK INSTANTANEOUS VELOCITY



In the dynamic testing of current sensors, the indicated peak instantaneous velocity is often compared to the known value computed from VPMM and tow carriage velocities to obtain a measure of the sensor's high frequency response. Since the current sensor output is discretely sampled, there is some error introduced by the sample missing the peak. The following analysis evaluates this error with the assumption that the sample occurs between the true peak and the furthest distance possible from the true peak output.

$\theta = \omega t$

where

ω = radians/second

t = time, seconds

$v_i = V_{max} \sin \omega t$

Total area of cross hatched sections = $A_1 + A_2$

$$= \int_a^b v_i d(\omega t) \quad \text{, where } a = (\pi/2 - 2\pi/2n)$$

$$b = \pi/2$$

$$n = \text{number of samples per cycle}$$

since

$$v_i = V_{max} \sin\omega t$$

$$= V_{max} \int_a^b \sin\omega t \; d(\omega t)$$

solving:

$$= V_{max} \left[-\cos\omega t \right]_a^b$$

$$= V_{max} \left[-\cos \pi/2 + \cos(\pi/2 - \tfrac{2\pi}{50}) \right] \text{ for } n = 25$$

$A_1 + A_2 = V_{max}$ (0.12533)

Height of A_1 = sin 82.8° = 0.992115

Base of $A_1 = \frac{\pi}{2} - [\frac{\pi}{2} - \frac{2\pi}{2(25)}] = \frac{\pi}{25} = 0.125664$

Area of rectangle, A_1 = (base)(height)
= 0.992115 (π/25)
= 0.12467

Area of $A_2 = (A_1 + A_2) - A_1$
= 0.12533 - 0.12467
= 0.00066

Average ordinate for $A_2 = \frac{\text{area}}{\text{base}} = \frac{0.00066}{0.125664}$
= 0.005252

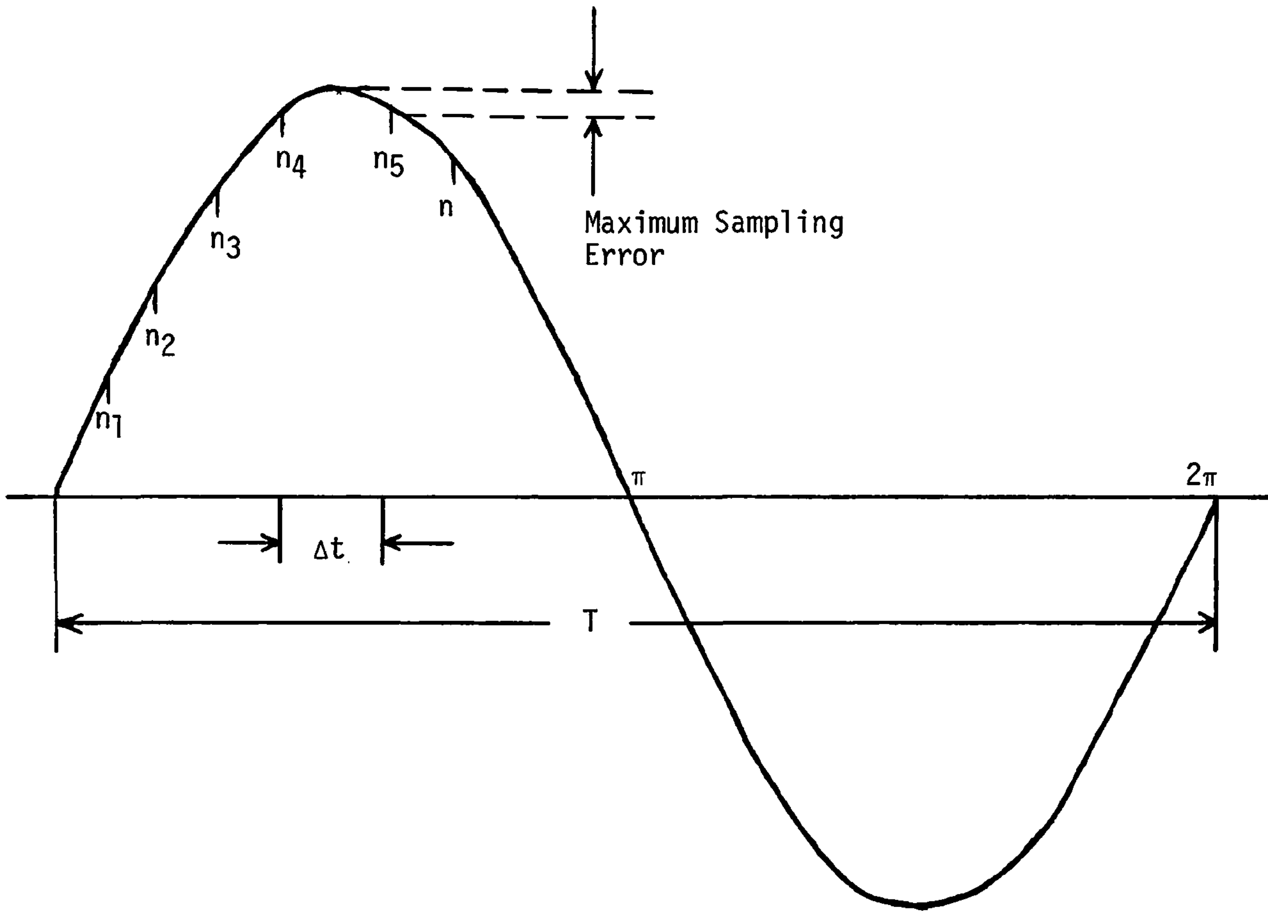
Total ordinate = height of A_1 + A_2 average ordinate

= 0.005252 + 0.992115
= 0.9974

Average error in peak instantaneous velocity

= (1 – 0.9974) V_{max}

Average error = 0.26% of reading



The following analysis evaluates the sampling error under maximum conditions, i.e., the sample occurs as far as possible (for a given sample rate) from the true peak output.

$$\text{Maximum Error} = \left[1-\cos\left(\frac{\pi\ \Delta t}{T}\right)\right]$$

for n = 25; i.e, 5 Hz, for T = 5 s, and at all other periods Δt/T the same value.

$$= \left[1-\cos\left(\frac{.2\pi}{5}\right)\right]$$

$$= [1-\cos(0.125664)]$$

$$= (1-0.992115)$$

Maximum error = 0.79% of reading

RANDOM UNCERTAINTY ASSOCIATED WITH TOW CARRIAGE VELOCITY VARIATIONS

The random error velocity component is determined statistically from 250 carriage velocity measurements per data point and by computing the 95 percent confidence level of the mean. For all data points, including those during the VPMM operation, the random error component seldom exceded 0.04 cm/s. This value is computed as follows:

$$X_{l,u} = \overline{X} \pm Z \frac{\sigma}{\sqrt{n}}$$

where

$\overline{X}$ = mean

Z = number from cumulative normal distribution table

σ = standard deviation

Random error = 0.04 cm/s