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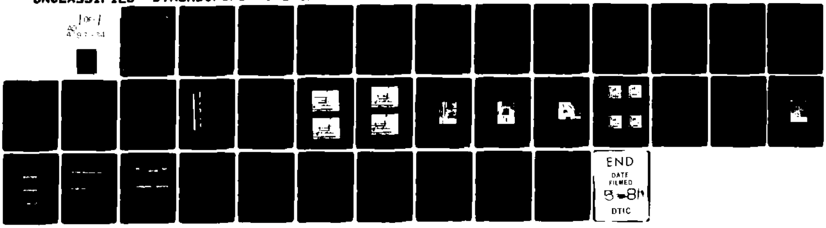

DAV:D W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

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ELECTRO-MECHANICAL OSCILLATOR FOR PRODUCING
VERTICAL, HORIZONTAL OR CIRCULAR
MOTION IN A VERTICAL PLANE

by

J. H. Pattison

G. M. Wilburn

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DEPARTMENTAL REPORT

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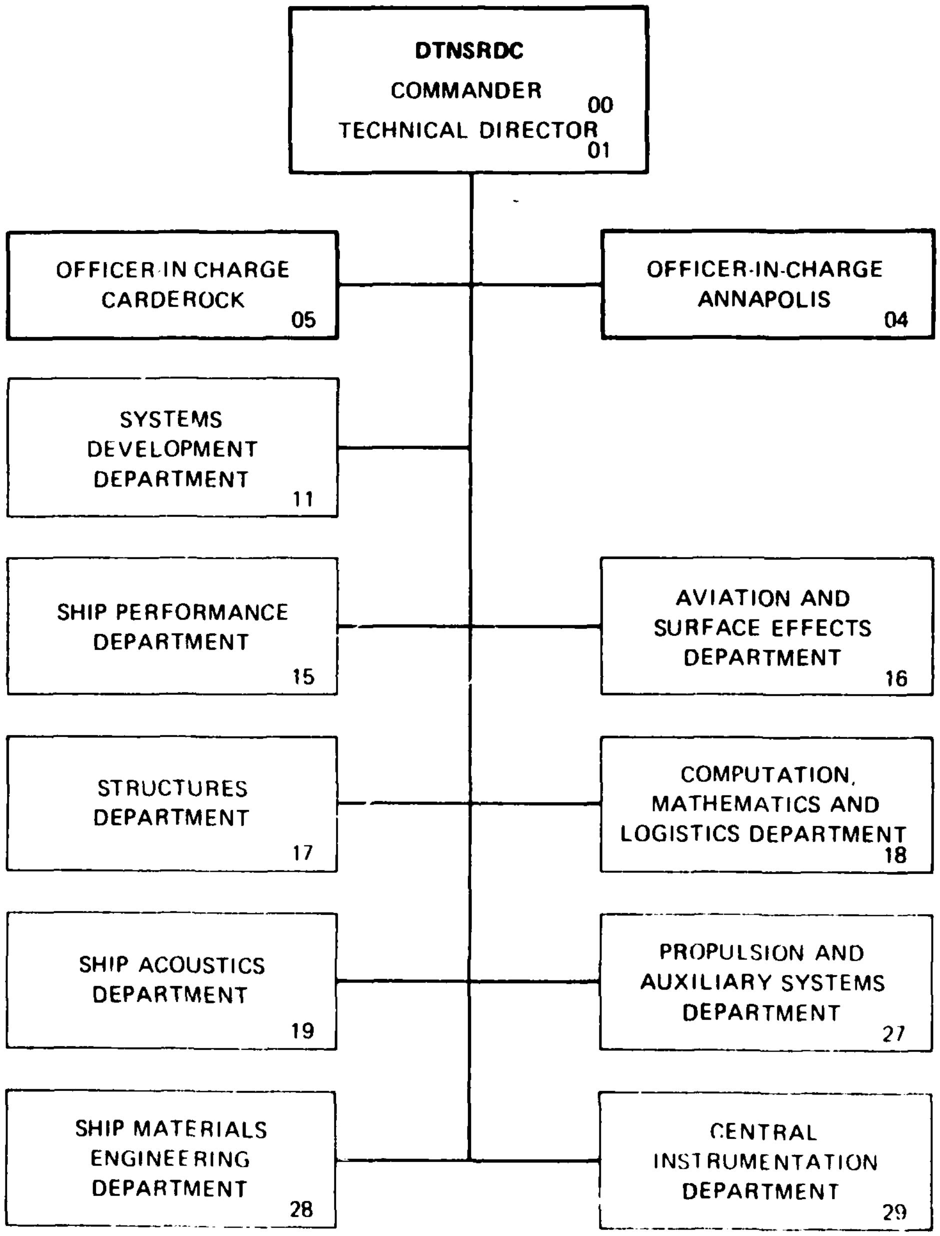

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An electromechanical oscillator was developed to simulate both surface-wave-induced motions and subsurface currents for the evaluation of current meters or other sensors that are suspended beneath surface buoys during oceanographic operations. With the oscillator, the hydrodynamic characteristics and performance of sensors may be evaluated under simulated sea conditions at amplitudes up to 4 ft (1.2 m) peak-to-peak and at periods from 3 to 30 s.

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Mechanical and operational details are described for each of three-modes of operation producing circular, vertical, and horizontal motions. Sample experimental results are presented to illustrate the quality of motion in all three modes.

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NOTATION

A	peak-to-peak amplitude of motion
C_D	drag coefficient on cylinder, in transverse flow
D_{bn}	blunt nose drag on cylinder
D_{fp}	skin friction drag on cylinder in axial flow
D_{tc}	Transverse curvature drag on cylinder in axial flow
d	diameter of cylinder
F	Total resultant force on cylinder
F_x	horizontal force on cylinder in plane of motion
F_{xH}	hydrodynamic portion of horizontal force
F_{xI}	inertia portion of horizontal force
F_y	horizontal force on cylinder transverse to plane of motion
F_z	vertical force on cylinder
F_{zH}	hydrodynamic portion of vertical force
F_{zI}	inertia portion of vertical force
g	acceleration due to gravity
m_x	virtual mass (actual plus added mass) of cylinder in horizontal direction in plane of motion
m_z	virtual mass of cylinder in vertical direction
R_n	Reynolds number
S_{wet}	wetted surface area of cylinder
T	period of oscillation
t	time

A

NOTATION (CONTINUED)

U	tow speed
W	weight in water of cylinder
W_a	weight in air of cylinder
x	horizontal position of cylinder in plane of motion
$\dot{x}$	horizontal velocity
$\ddot{x}$	horizontal acceleration
z	vertical position of cylinder
$\dot{z}$	vertical velocity
$\ddot{z}$	vertical acceleration
z_s	vertical immersion of cylinder
ν	kinematic viscosity of water
ρ	density of water
ϕ	angle of plane of motion with respect to tow direction
ω	radian frequency of motion

ABSTRACT

An electromechanical oscillator was developed to simulate both surface-wave-induced motions and subsurface currents for the evaluation of current meters or other sensors that are suspended beneath surface buoys used in oceanographic operations. The oscillator will permit evaluating the hydrodynamic characteristics and performance of sensors under simulated sea conditions at amplitudes up to 4 ft (1.2 m) peak-to-peak and at periods from 3 to 30 s. Mechanical and operational details are described for each of three modes of operation producing circular, vertical, and horizontal motions. Sample experimental results are presented to illustrate the quality of motion in all three modes.

ADMINISTRATIVE INFORMATION

This work was funded by the National Oceanic and Atmospheric Administration, Test and Evaluation Laboratory (NOAA/TEL), under NOAA Purchase Order Number 5-15238 dated 7 June 1975, David W. Taylor Naval Ship Research and Development Center (DTNSRDC) Work Unit 1-1548-073.

INTRODUCTION

Sensor arrays used to measure currents in the ocean are subjected to wave-induced motions. For example, many arrays are suspended from surface buoys that move with the surface waves. This wave action is transmitted down the suspension lines to the current sensors. Also, the surface waves induce orbital motions of the water beneath the surface. The orbital motions diminish with depth, but the effects must be taken into account for all but deeply submerged sensors. These unsteady motions may cause a sensor package to read the relative velocity incorrectly, dependent on the type of sensor and its mounting arrangement. To generate specific motions chosen to simulate those encountered in the natural environment for standardized current meter evaluations in a towing basin, an electromechanical oscillator configured as a Vertical Planar Oscillator (VPO) was developed and fabricated at the David W. Taylor Naval Ship Research and Development Center.

At present, the VPO has three interchangeable modules to provide circular, vertical, and horizontal motions of up to 1.2 m (4 ft) peak-to-peak at periods of 3 to 30 s. Over these ranges of experimental conditions, the VPM was designed to accommodate oscillatory loads of up to 650 N (160 lb). As discussed in Appendix A, these correspond to loadings expected from the largest current meters. In the future, a module may be designed and fabricated to provide elliptical motion.

In this report, the VPO is described; sample experimental results are presented to illustrate quality of motion; and data, conclusions, and recommendations are given.

DESCRIPTION OF SYSTEM

The Vertical Planar Oscillator (VPO) consists of mechanical and electrical subsystems that are described in the sections which follow.

MECHANICAL SUBSYSTEMS

The mechanical subsystems are illustrated in Figure 1,* which shows the VPO as configured for circular motion. The mechanical subsystems include a basic frame and drive unit, three interchangeable modules for circular, vertical, and horizontal motion, and various model mountings.

The basic frame provides support for the drive system and each of the three motion modules. In addition, the flanges which mount the basic frame to the towing carriage contain positioning holes that allow the plane of oscillation to be rotated about a vertical axis through a range of 90 degrees so that the motion can be set at any 15-degree interval from parallel to transverse to the tow direction. This is to simulate conditions where the wave direction is different from the current direction. The drive system consists of a 2200-W output (3 hp), direct-current electrical motor driving two upper crank arms through a 40 to 1 gearbox as shown in Figure 1. The drive beam for each module attaches

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* All figures appear at the end of the report in front of Appendix A.

to one of a series of holes in one of the crank arms. These holes are spaced to provide motion amplitudes between 0.15 and 1.22 m (0.5 and 4 ft) peak-to-peak in steps of 0.15 m (0.5 ft). Also, the drive system provides periods of 5 to 30 s at the highest amplitudes and periods as low as 3 s at the low amplitudes. The combinations of amplitude and period available can simulate a wide range of surface-wave-generated subsurface sea conditions encountered by full-scale sensor packages either being moored or towed.

Mechanical arrangements for the three modes of motion are shown in Figure 2. The circular motion module consists of a drive beam, a balance beam, and two lower crank arms. These form a rotating parallelogram such that a current meter mounted to the drive beam undergoes circular motion. A sequence for one cycle is shown in Figure 3. Weights may be added to the balance beam to counterbalance the weight of the model for smoother motion.

The vertical motion module consists of a drive beam, a slider (shown in Figure 4) with linear bearings that ride vertical guide shafts, and a mounting beam for the current meter. As in the circular mode, counter-balance weights may be suspended from the crank opposing the drive crank.

The horizontal motion module includes a rack mounted to a drive beam. This rack turns a pinion gear that is connected by a shaft to another pinion gear as shown in Figure 5. The second pinion gear drives another rack in the horizontal direction. The horizontal rack is attached to a slider with linear bearings that ride on the horizontal guide shafts as shown in Figure 6. A sequence for one cycle is shown in Figure 7. A mounting beam for the current meter is attached to the slider. Counter-balance weights are not used in this mode.

Typical mountings for a current meter are shown in Figure 8. The flange was specified by NOAA/TEL to attach a variety of current meters. For example, a small current meter is attached to a staff which fits into the center hole in the flange. The staff pierces the water surface and holds the current meter deep enough to avoid free surface interaction with the current measurements. Larger current meters such as the Vector

Averaging Current Meter (VACM) are mounted directly to the outer holes on the flange. This is acceptable because the VACM consists of a long cylinder housing electronics and a sensor at the bottom. Similar mounting arrangements may be fabricated for various model experiments. Also, though designed for use on the towing carriages, the VPO may be used in a similar arrangement in the laboratory for oscillatory experiments in air.

ELECTRICAL POWER AND CONTROL SUBSYSTEM

The electrical power and control subsystem is shown schematically in Figure 9. The motor requires 200 V, direct current in the field and from 0 to 180 V in the armature. The armature power supply (high power servo amplifier) controls the speed of the motor (between 0 and 1800 rmp). To maintain constant speed under the varying and reversing loads imposed by the mechanical subsystems, a high gain bidirectional closed loop servo control is contained in the armature system. The drive signal is supplied by a precision, 0 to 1 V power supply. Voltage corresponding to a desired speed is set into digital switches. Then as the motor runs, voltage from a tachometer on the motor shaft is fed back to the servo amplifier and compared with the drive signal voltage. The controller adjusts armature current to maintain a match between input signal and tachometer voltages. Current limits can be set to avoid the possibility of overspeed. Also, the polarity of the signal voltage may be reversed by a switch to change motor direction. Before startup, the signal voltage is shunted through an L-pad potentiometer which is then slowly turned up to supply the set voltage to the controller. This procedure prevents damage to the mechanisms from a sudden startup.

The power and control system, except for the motor and tachometer, are contained in a portable cabinet, as shown in Figure 10.

SAMPLE EXPERIMENTAL RESULTS

Experiments were conducted in the towing basin to evaluate the performance of the VPO in all three modes. Various current meters were supplied by NOAA/TEL to provide a range of loadings on the VPO and to evaluate the performance of various type current meters under oscillating conditions. Parametric variations included oscillatory periods, tow speeds and angles between the plane of motion and the current. Conditions were varied from those imposing the least load to those inducing the most severe load on the system.

Performance of the VPO in water was evaluated from measurements and observations. Measurement sensors included the tachometer on the motor, a position resolver on the gearbox output shaft, a triaxial accelerometer at the upper end of the current meter mount (shown in Figure 8), the carriage speed pickup, and the current meters. NOAA/TEL supplied the position resolver, the triaxial accelerometer, and the current meters.

For the circular mode, a strip chart recorder monitored carriage speed, motor speed and current meter accelerations. In the vertical and horizontal modes, only accelerations were monitored. These were adequate to assess the quality of the motion. An analog tape recorder recorded all measurement sensor outputs, and a small computer averaged carriage speed, measured current speed and speed deviations. NOAA/TEL was responsible for evaluation of these measurements. Hence, in this report only the strip chart recordings of the accelerations and various observations on smoothness of the motion are discussed.

As to the accuracy of the measurements, carriage speed was measured to within ± 0.01 knot; motor speed to within ± 10 rpm; position to within ± 1 deg; and accelerations to within ± 0.098 m/s^2 (± 0.01 g).

Accelerations for a typical run in the circular mode with a medium size NOAA current meter mounted on the oscillator are shown in Figure 11. The period of motion was the shortest, 5 s, that could be used for the maximum amplitude 1.22 m (4.0 ft) peak-to-peak, which was selected for this run. The tow speed was 0.7 m/s, equivalent to the maximum design current for this meter. The plane of oscillation was oriented 45 degrees to the tow direction.

Superimposed on the 0.2 Hz (5-second period) driving motion is a measurable 3-Hz motion. In terms of acceleration, the 3-Hz signal is a maximum of 11.78 m/s^2 (1.2 g) peak-to-peak in the horizontal, 2.45 m/s^2

(0.25 g) in the vertical and 9.81 m/s^2 (1.0 g) in the side directions. In terms of displacements from the fundamental motion, these represent 33, 7 and 28 mm (1.3, 0.27, 1.1 in.), respectively. These maxima, which would be compared with the 1.2 m (4 ft) peak-to-peak motion of the fundamental, occur at top- and bottom-dead-center of the drive stroke. At other portions of each cycle, these motion deviations were greatly diminished. In all other conditions evaluated in the experiments, the deviations from the driving motion were less than or equal to those shown in Figure 11. After these initial tests the smoothness of the circular motion was greatly improved by correcting a slight misalignment between the drive unit output shaft and the pivot shaft for the lower crank arms. No acceleration measurements have been made since the modifications.

In the experiments in the vertical and horizontal modes, the vertical accelerometer malfunctioned. Thus, in Figure 12, only horizontal accelerations are shown for motion in the vertical mode. The oscillatory period and amplitude were similar to those in Figure 11 except that the current meter was the largest the VPO was designed to handle. The horizontal acceleration in the plane of the oscillator contains high-frequency, low-amplitude mechanical noise that could not be analyzed from the strip chart. The horizontal acceleration transverse to the plane of the oscillator contains 10.5 Hz bursts with a maximum amplitude of 4.51 m/s^2 (0.46 g), peak-to-peak, which is a displacement of 1 mm (0.04 in.). The vertical motion, although not measured, was observed to be smooth. Again, other conditions evaluated yielded smaller or equal deviations from driving motion when compared with those shown in Figure 12.

In Figure 13, horizontal accelerations are shown for horizontal motion. The oscillatory period and amplitude are similar to those for Figure 12 for the large current meter. Superimposed on the driving acceleration of 1.96 m/s^2 (0.20 g) peak-to-peak in the horizontal direction at a period of 5 s is a varying 9-Hz acceleration with a maximum of 9.32 m/s^2 (0.95 g) peak-to-peak. In terms of displacement this represents a deviation from the desired motion, 1.2 m (4 ft) peak-to-peak, of 2.9 mm (0.11 in.). The transverse acceleration shown contains high frequency, low-amplitude noise that could not be analyzed from the strip chart.

Other conditions yielded smaller or equal deviations from the desired motion when compared to those shown in Figure 13.

The data discussed above and observations of the motion both indicated that the VPO operates smoother, with less high-frequency deviation from the desired motion in the vertical and horizontal modes than in the circular mode.

During the experiments the mechanical subsystems were altered to change modes between vertical and horizontal. Each of these changes was accomplished within two hours.

CONCLUSIONS AND RECOMMENDATIONS

The following may be concluded from the discussions of results:

1. Observations and measurements of the motion indicate that, with hydrodynamic loadings up to maximums described in Appendix A, the Vertical Planar Oscillator operates smoothly in all three modes. In terms of displacement, maximum deviations of up to 3 percent of the fundamental motion occur in the circular mode. Most of these deviations were eliminated by minor modifications. The deviations are much smaller in the vertical and horizontal modes.

2. Procedures for changing between modes are found to be simple and straightforward.

Operation and handling of the VPO would be improved by the following:

1. Addition of a chain with sprockets top and bottom to link the crankshafts to eliminate toggling at top- and bottom-dead-center in the circular mode.

2. Addition of counterbalance weights to make motion smoother in the circular mode.

3. Welding of plates to the support and drive beams to increase the load bearing capability of the VPO.

4. Construction of a handling and storage dolly to save time and money during rigging. At present, parts have to be removed and the VPO laid on its side when not in use.

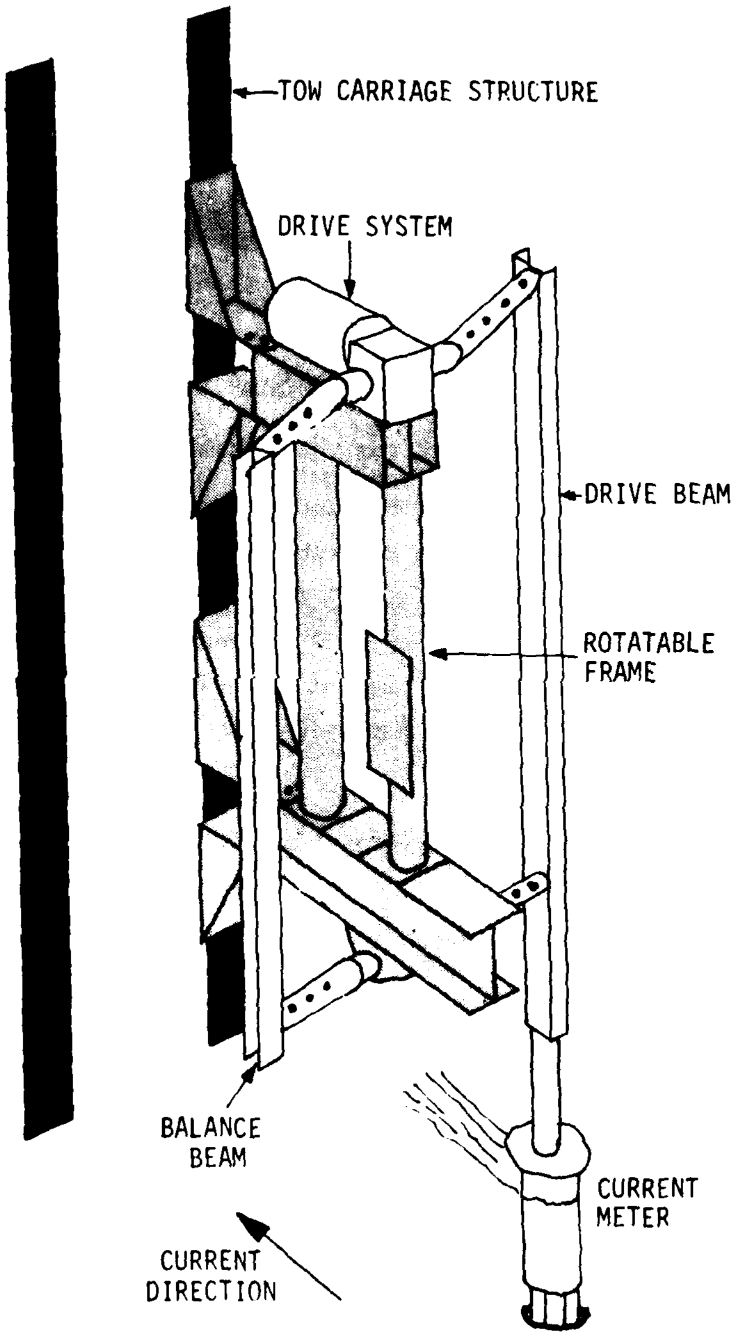


Figure 1 - Vertical Planar Oscillator
Configured for Circular Motion

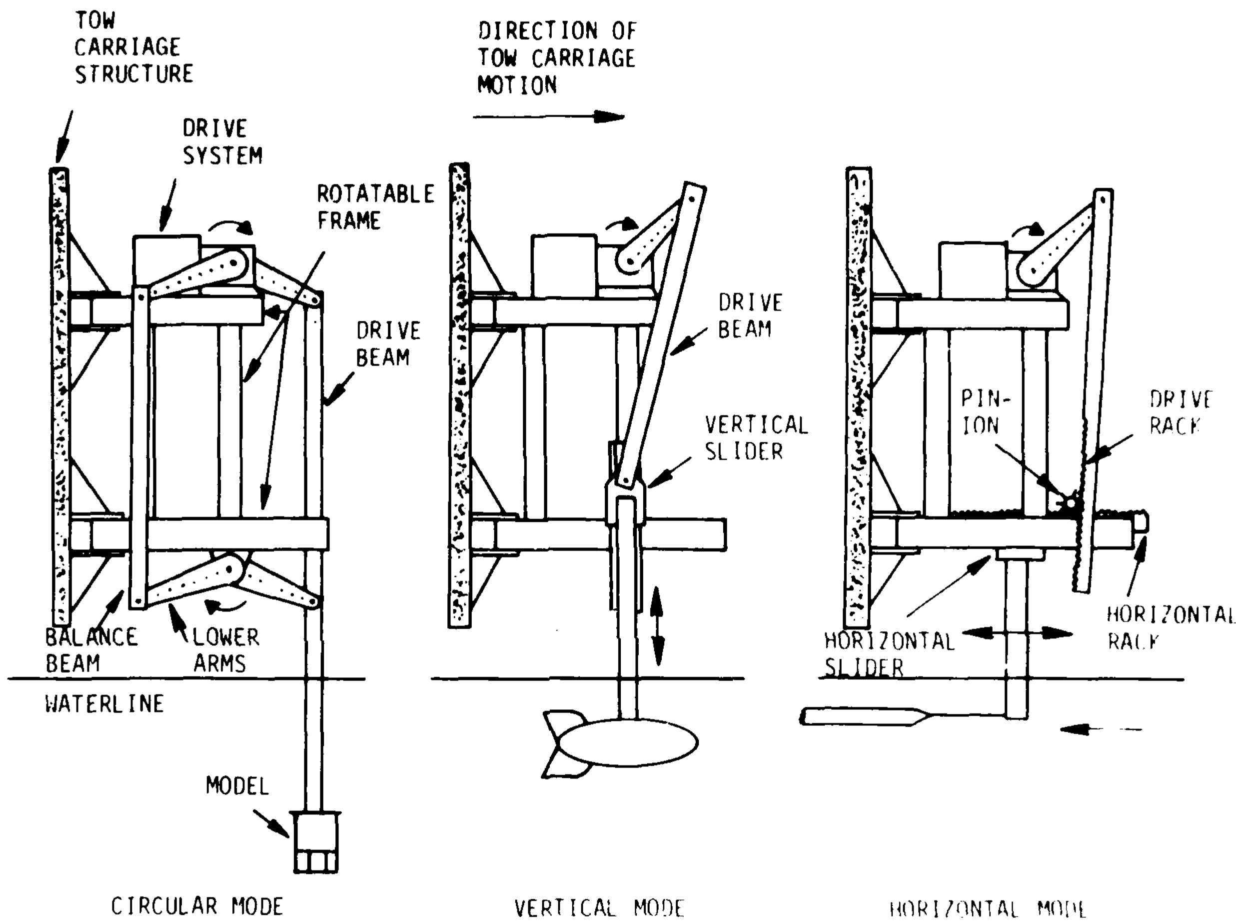


Figure 2 - Mechanical Arrangements for Three Modes of Motion-Starboard Side View

Figure 3a - Drive Beam at
Top Dead Center

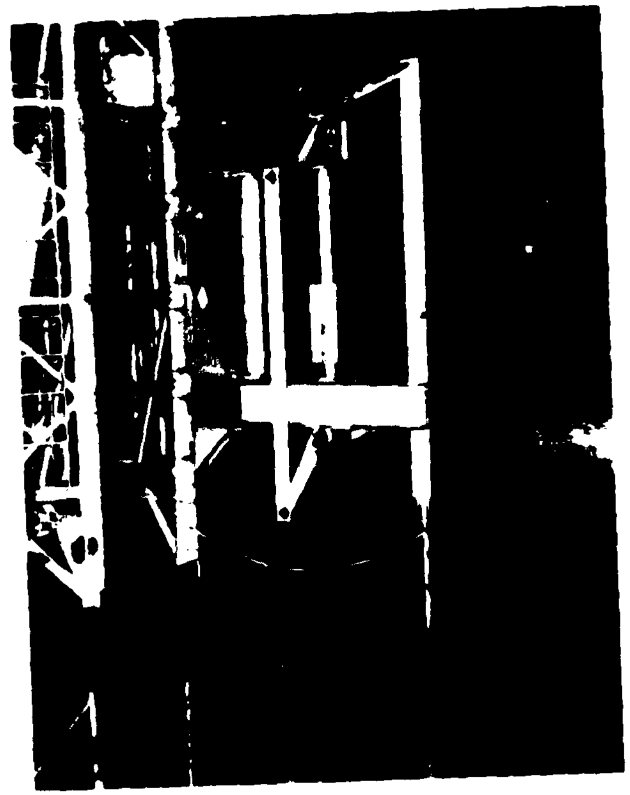


Figure 3b - Drive Beam Approaching
Bottom Dead Center

Figure 3 - Sequence for Circular Motion

Figure 3 (Continued)

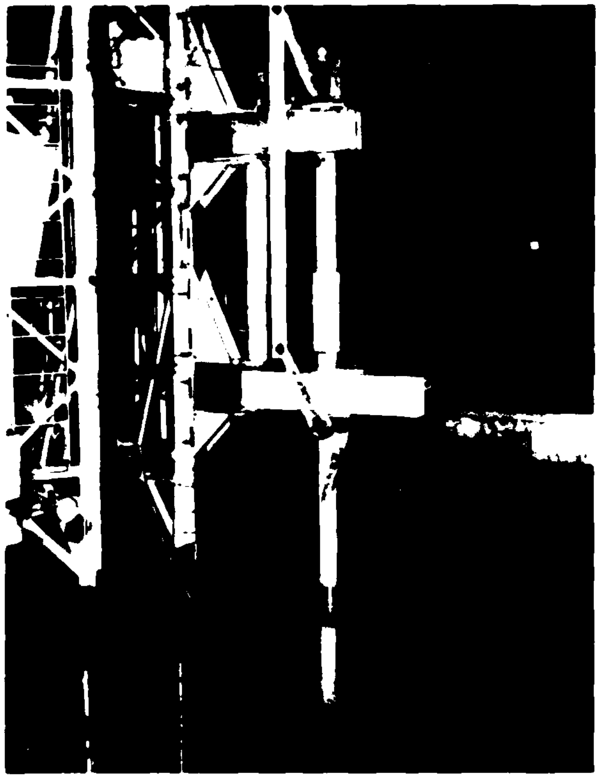


Figure 3c - Drive Beam at
Bottom Dead Center

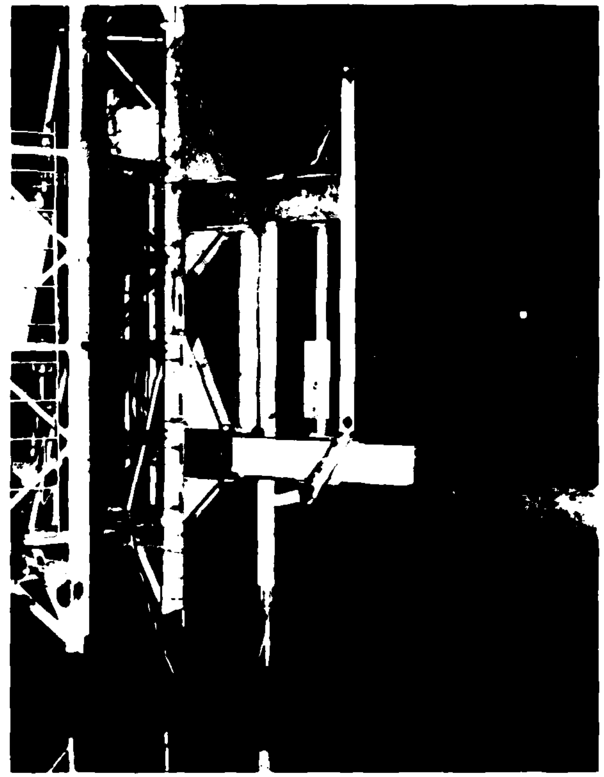


Figure 3d - Drive Beam Approaching
Top Dead Center

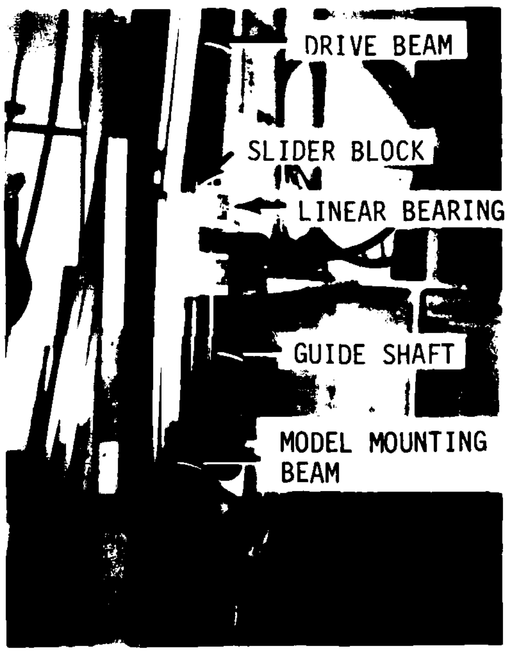


Figure 4 - Vertical Motion Module Details

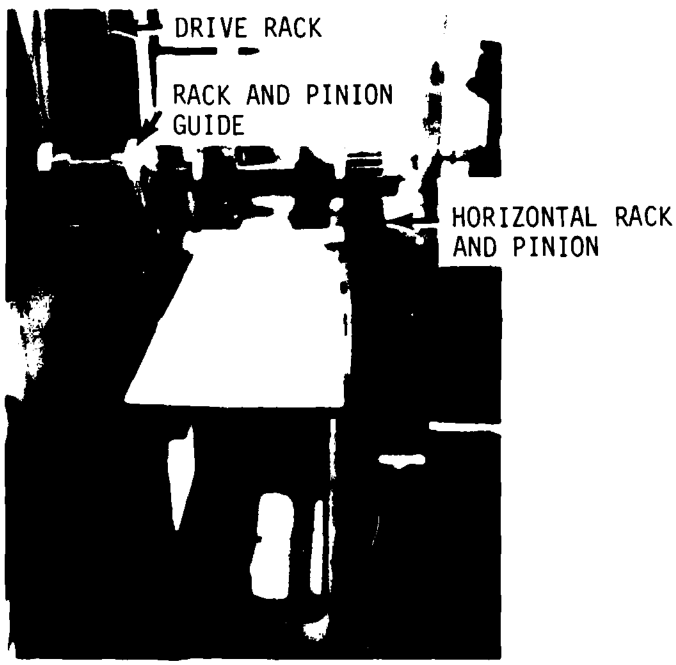


Figure 5 - Horizontal Motion, Rack and Pinion Details

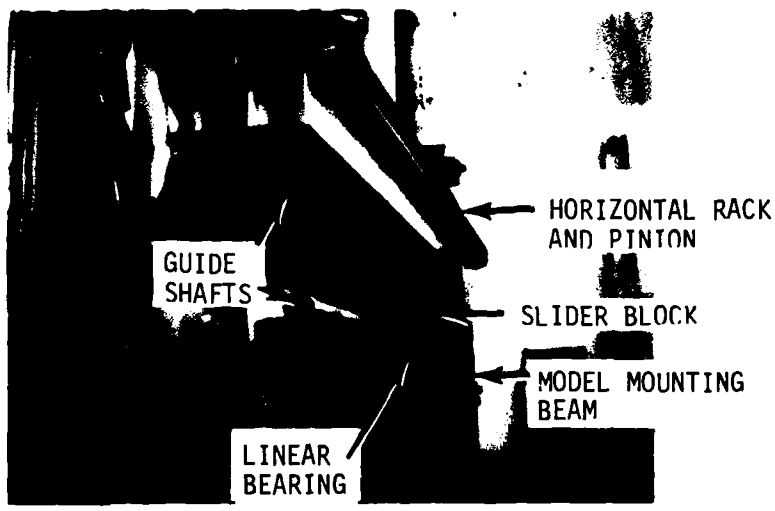


Figure 6 - Horizontal Motion, Slider Details

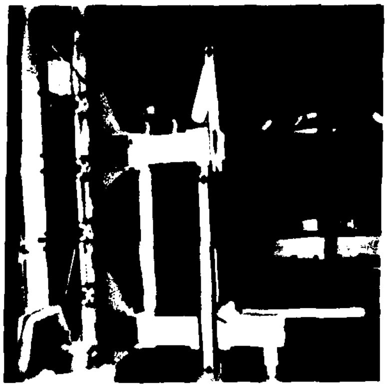


Figure 7a - Drive Beam at Top Dead Center Rack Forward

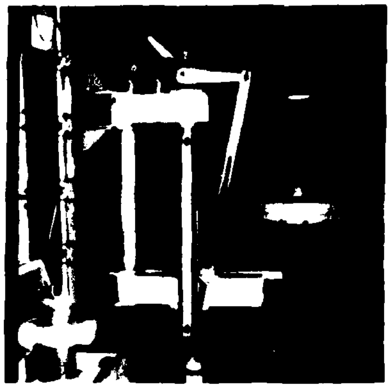


Figure 7b - Drive Beam Approaching Bottom Dead Center, Rack Midposition

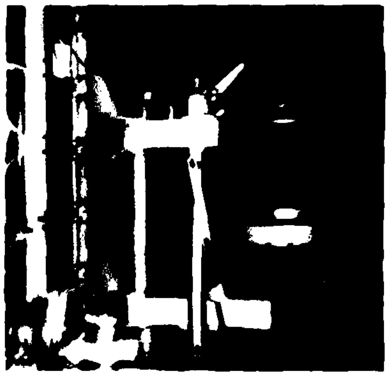


Figure 7c - Drive Beam at Bottom Dead Center Rack Aft

Figure 7d - Drive Beam Approaching Top Dead Center, Rack Midposition

Figure 7 - Sequence for Horizontal Motion

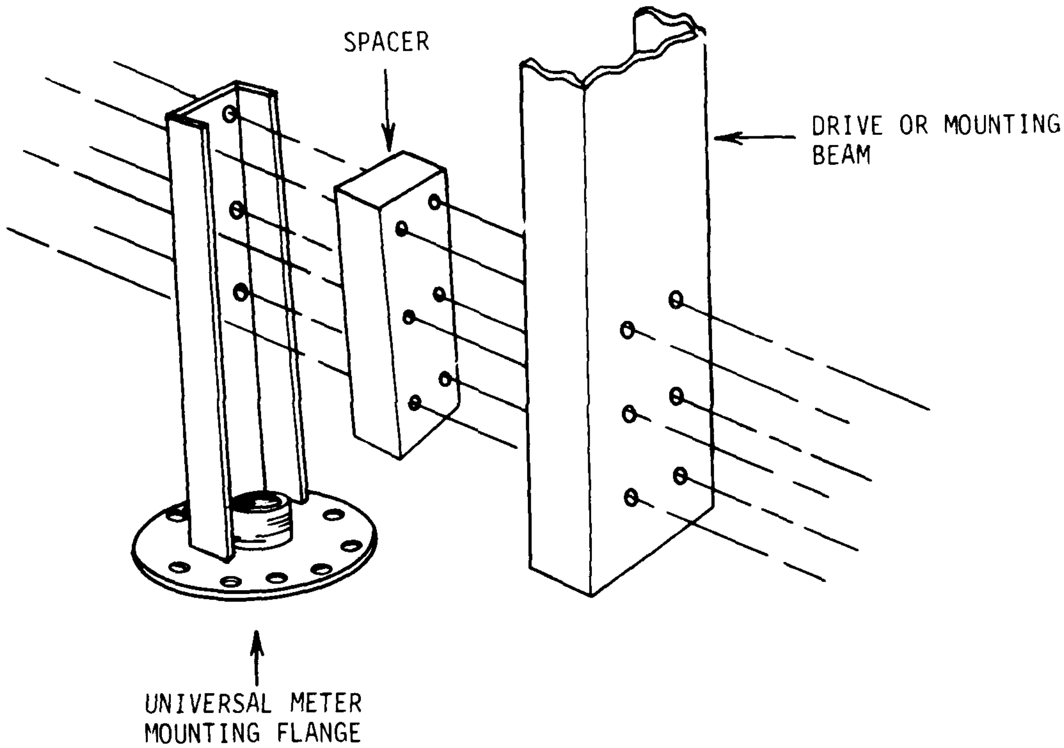


Figure 8 - Mountings for Current Meters

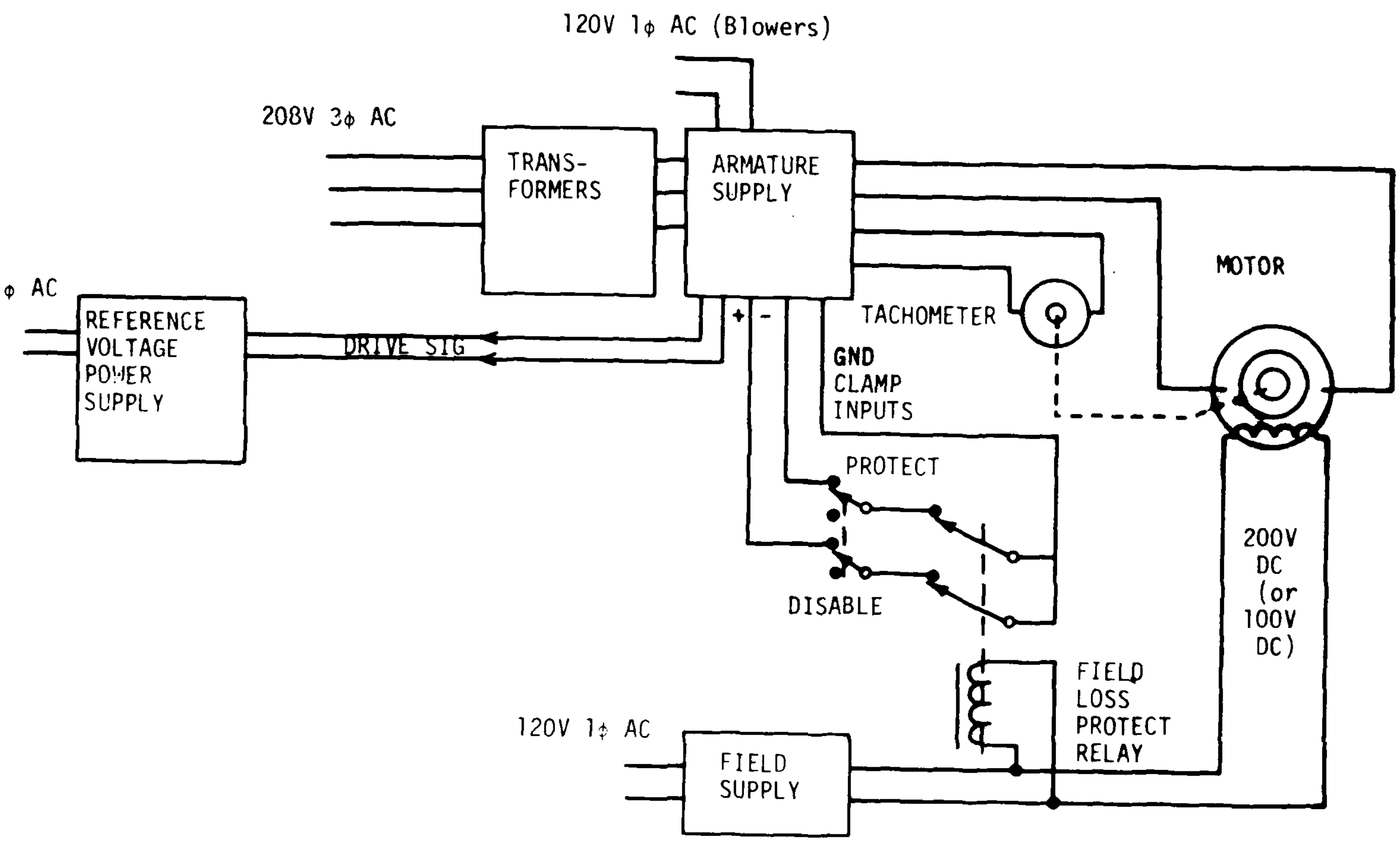


Figure 9 - Electrical Power and Control, Schematic Drawing

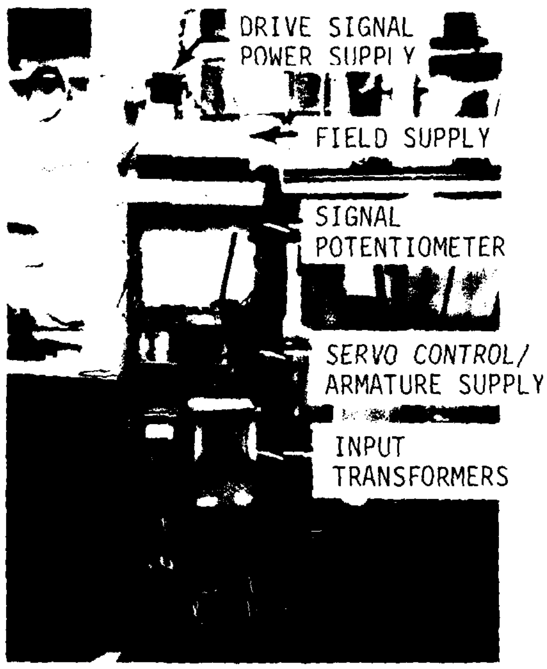
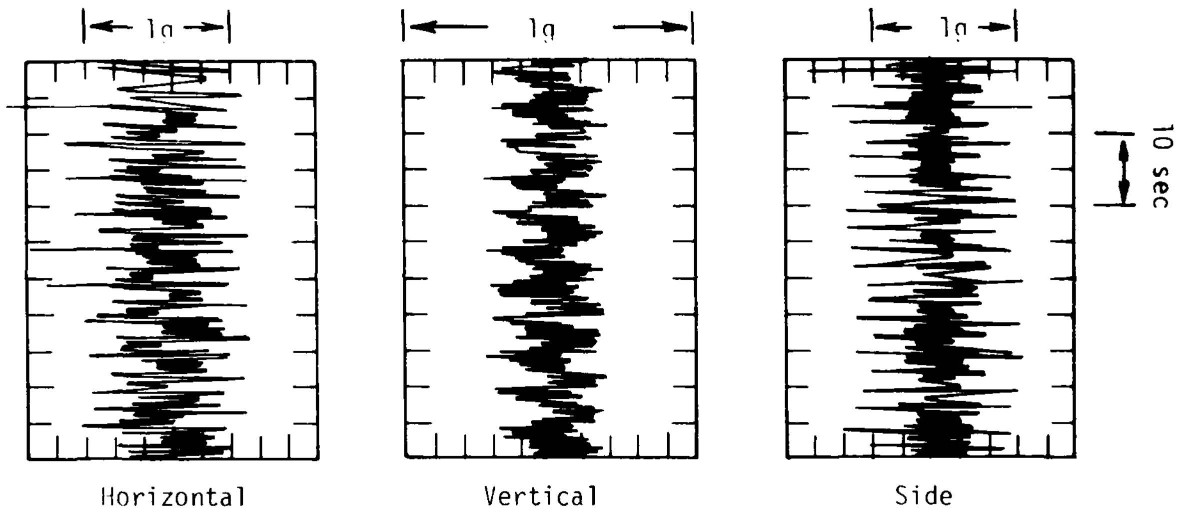


Figure 10 - Control Cabinet



NOTE: 1.0 g - 9.81 meters/sec^2

A = 1.2 m p-p, U = 70cm/s, T = 5 sec, ϕ = 45 deg.

Figure 11 - Acceleration Traces for Circular Mode with Marsh-McBirney Meter in Water

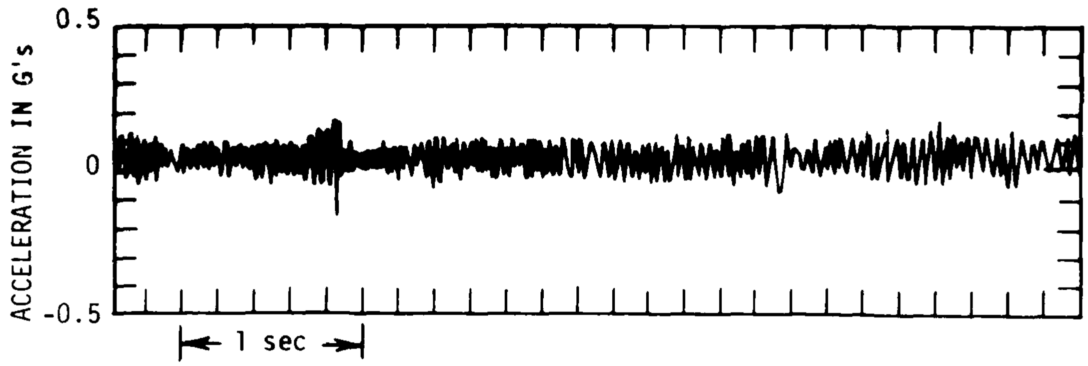


Figure 12a - Horizontal in the Plane of Oscillation

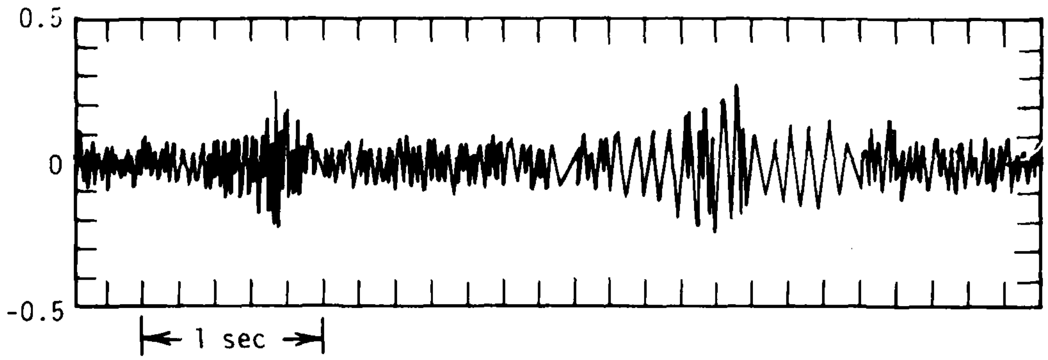


Figure 12b - Transverse to the Plane of Oscillation

A = 1.2 m p-p, U = 70cm/s, T = 5 s

Figure 12 - Horizontal Acceleration Traces for Vertical Mode with Vector Averaging Current Meter in Water

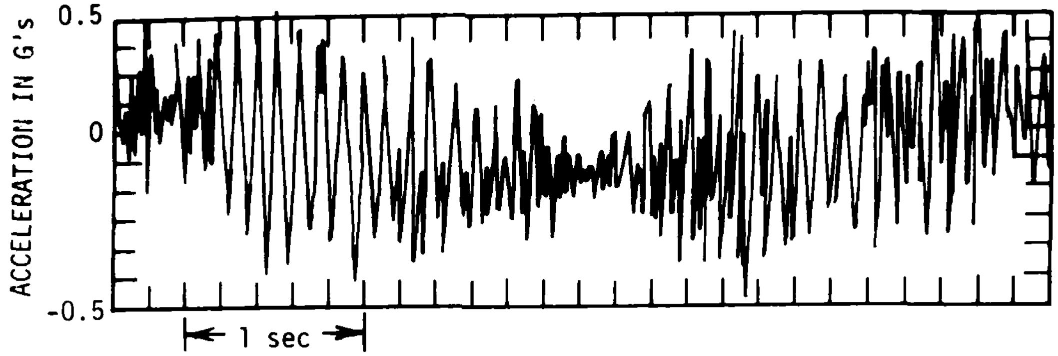


Figure 13a - Horizontal in the Plane of Oscillation

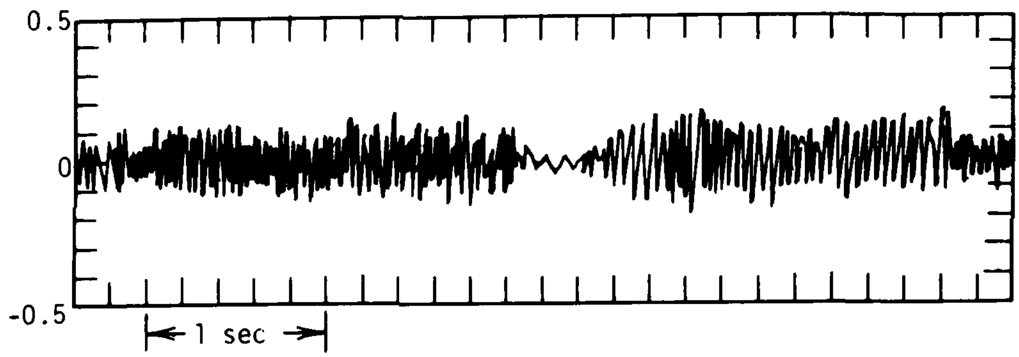


Figure 13b - Transverse to the Plane of Oscillation

A = 1.2 m p-p, U = 70cm/s, T = 5 s, ϕ = 45 deg

Figure 13 - Horizontal Acceleration Traces for Horizontal Mode with Vector Averaging Current Meter in Water

APPENDIX A

ESTIMATE OF FORCES ON LARGEST INSTRUMENT

The largest and heaviest instrument expected to be evaluated for NOAA/TEL has the physical parameters shown in Figure A.1.

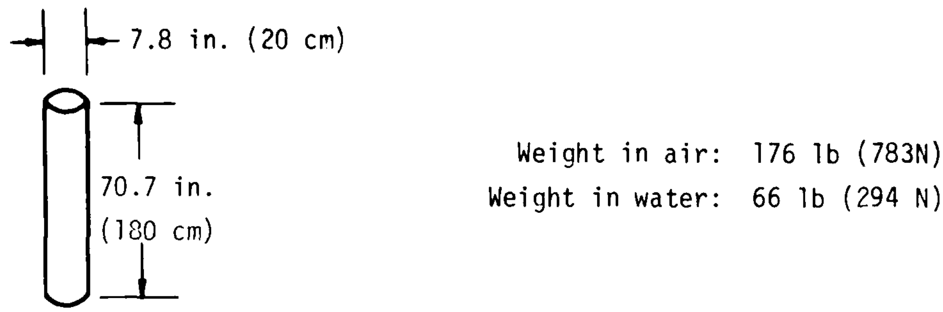


Figure A.1. Physical Parameters for Worst Case Instrument

The condition expected to produce the maximum loading are the maximum amplitude of motion of 1.2 m (4 ft) peak-to-peak in circular motion, the minimum period of 5 s and the tow speed of 68 cm/s (2.24 ft/s). Also, the entire instrument is just submerged at the end of the stroke and partially submerged throughout the remainder of a cycle. The weight of attachments for the instrument was assumed to be 111 N (25 lb).

For simplicity, the plane of the oscillation is first assumed to be aligned parallel to the flow. Side forces generated when the plan of oscillation is at an angle to the flow will be computed later. The motions and forces have the sign conventions shown in Figure A.2.

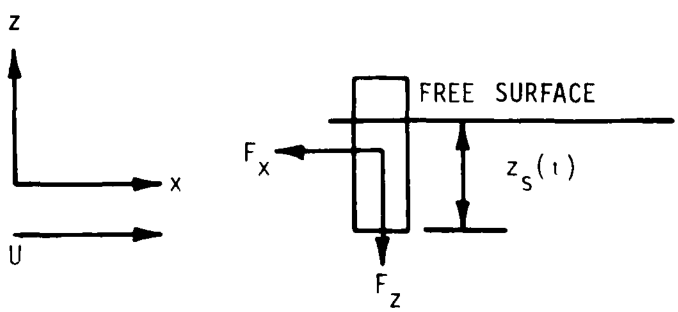


Figure A.2. - Notation

The equations of motion in the x and z directions include:

the displacements

$$x = \frac{A}{2} \sin (\omega t + \pi/2) \tag{1}$$

$$z = \frac{A}{2} \sin \omega t$$

the velocities

$$\dot{x} = \frac{A\omega}{2} \cos (\omega t + \frac{\pi}{2})$$

$$\dot{z} = \frac{A\omega}{2} \cos \omega t \tag{2}$$

and the accelerations

$$\ddot{x} = \frac{-A\omega^2}{2} \sin (\omega t + \frac{\pi}{2})$$

$$\ddot{z} = \frac{-A\omega^2}{2} \sin \omega t \tag{3}$$

where A is the peak-to-peak amplitude of motion,

t is time,

T is period of the motions,

U is flow (or tow) speed, and

ω is radian frequency (ω=$2\pi/T$).

The motion is slow enough that quasi-static equations of the following form may be used to approximate the forces

$$F_x = F_{xH} + F_{xI}$$

and $$F_z = F_{zH} + F_{zI} + W \tag{4}$$

where the subscripts H and I refere to hydrodynamic and inertia forces, respectively, and W is the weight in water of the instrument and attachments.

Approximations for the hydrodynamic forces are taken from Hoerner[1]. For the horizontal force

$$F_{xH} = \tfrac{1}{2}\rho(U + \dot{x})^2 \, z_s \, d \, C_D \tag{5}$$

where

d is diameter of the instrument,

C_D is drag coefficient (1.2 in Hoerner),

z_s is the submerged length of the cylinder,

ρ is the density of water,

and F_{xH} is negative except when $\dot{x} < -U$

On the other hand F_{zH} has the following three terms:

(1) Flat plate skin friction, given by Hoerner[1] as:

$$\frac{D_{f\rho}}{\tfrac{1}{2}\rho \dot{z}^2 S_{wet}} = \frac{1.328}{\sqrt{R_n}} \tag{6}$$

Where R_n is Reynolds number ($R_n = z_s \dot{z}/\nu$),

S_{wet} is the wetted surface area, excluding the ends ($S_{wet} = \pi d z_s$),

and ν is kinematic viscosity of water. This equation may be rewritten as follows:

$$D_{fp} = -0.664\pi\rho\nu^{\frac{1}{2}} \, z_s{}^{\frac{1}{2}} \, \dot{z}|\dot{z}|^{\frac{1}{2}}$$

(2) Transverse curvature drag, given by Hoerner[1] as

$$\frac{D_{tc}}{\tfrac{1}{2}\rho \dot{z}^2 S_{wet}} = \frac{2z_s}{dR_n} \tag{7}$$

which may be rewritten as

$$D_{tc} = \pi\rho z_s \, \nu\dot{z}$$

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1 Hoerner, S.F., "Fluid Dynamic Drag," published by Author, New Jersey (1967).

(3) Blunt nose drag, given by Horner[1] as

$$\frac{D_{bn}}{\frac{1}{2}\rho \dot{z}^2 S_{nose}} = 0.83 \tag{8}$$

where S_{nose} is the area of the nose ($S_{nose} = \pi d/4$). This may be rewritten as

$$D_{bn} = -\frac{\pi}{8} \rho d^2 \dot{z} \ (0.83)$$

The vertical hydrodynamic force is the combination

$$F_{ZH} = D_{fp} + D_{tc} + D_{bn} \tag{9}$$

The inertial forces are given as follows

$$F_{xI} = m_x \ddot{x}$$

$$\text{and} \quad F_{zI} = m_z \ddot{z} \tag{10}$$

where the virtual masses (actual plus hydrodynamic, or added masses) are given by

$$m_x = \frac{W_a}{g} + \frac{\pi}{4} d^2 z_s \rho$$

$$m_z = \frac{W_a}{g} + \frac{\pi}{6} d^3 \rho$$

where W_a is the weight of the instrument plus attachments in air.

In the above equations, the weight in water is given as

$$W = W_a - \frac{\pi}{4} d^2 z_s \rho g$$

The horizontal and vertical forces are plotted as functions of time for one cycle of motion under the most severe oscillatory conditions outlined in Figure A.3. Also the magnitude of the resultant force

$$|F| = \sqrt{F_x^2 + F_z^2}$$

is plotted.

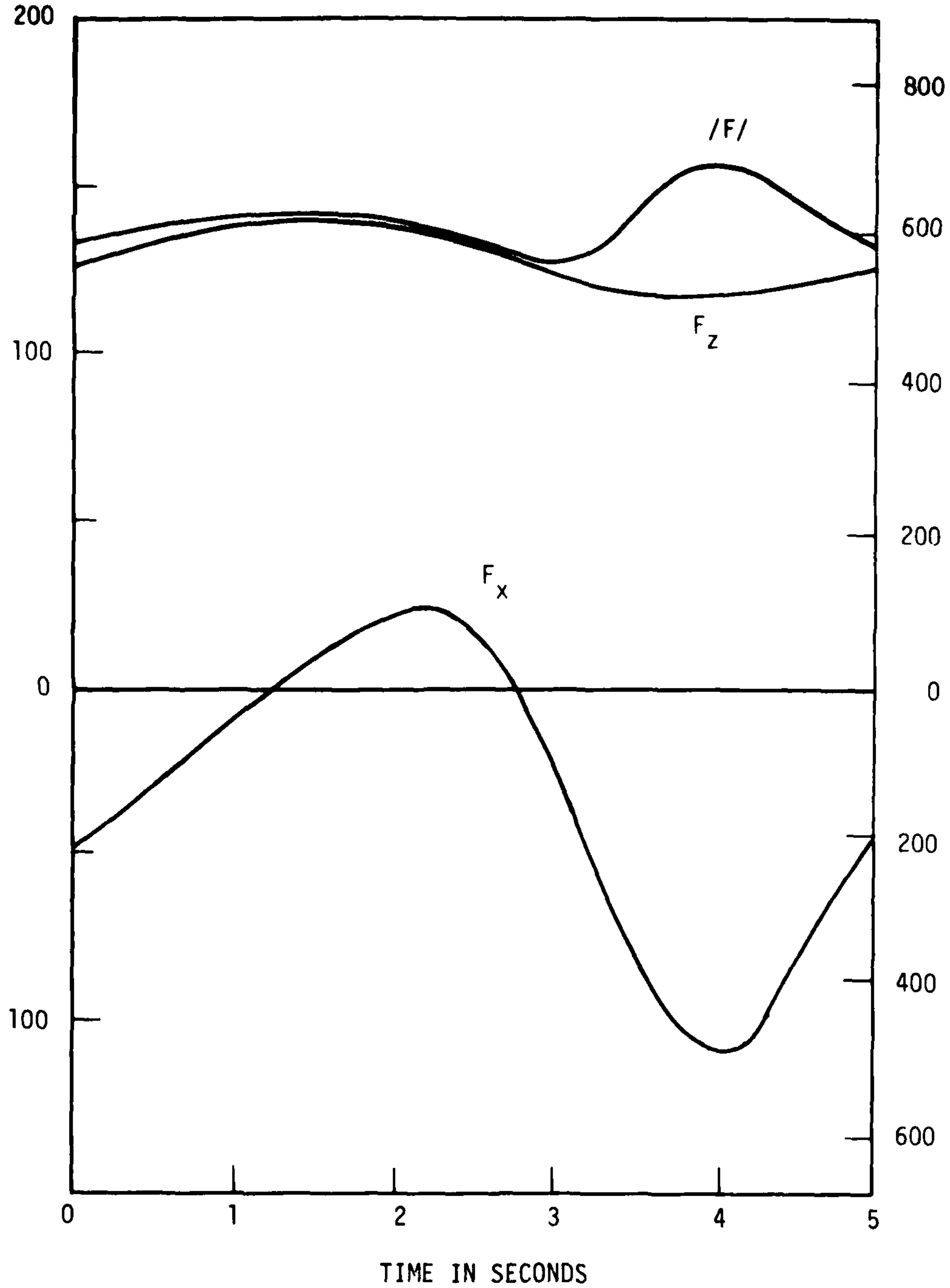

Figure A.3 - Estimate of Forces on Worst Case Instrument

When the plane of motion is rotated as shown in Figure A.4, the resulting side force F_y is purely hydrodynamic and is given by

$$F_y = \frac{1}{2}\rho d z_s (U\sin\phi)^2$$

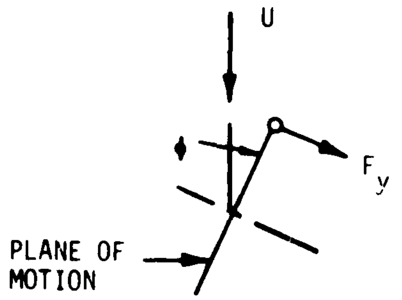

Figure A.4 - Side Force on Meter at an Angle of Attack

The maximum side force occurs at 90 degrees and for the conditions outlined above

$$F_{ymax} = 99 \text{ N } (22.3 \text{ lb})$$

These forces were used to set conditions for the in-air checkout of the Vertical Planar Oscillator in the circular, vertical, and horizontal modes.

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