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"Experimental Determination of the Hydrodynamic Loading Functions for TMB Number 7 Fairing Shape," by Donald E. Gray (January 1974)

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20034

(6)

EXPERIMENTAL DETERMINATION OF THE HYDRODYNAMIC LOADING FUNCTIONS FOR TMB NUMBER 7 FAIRING SHAPE.

by

(10) Donald E. Gray

(16) F14222

DDC

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REPORT NO. 551-H-01

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NOTATION

A_o Constant coefficient in hydrodynamic loading function; cf Equation (6)

A_n Coefficient of $\cos n\phi$ terms in hydrodynamic loading function; cf Equation (6)

B_n Coefficient of $\sin n\phi$ terms in hydrodynamic loading function; cf Equation (6)

C_R Cable fairing drag coefficient; cf Equations (1) and (3)

F   General hydrodynamic loading function for either the normal or tangential direction

n   Integer index; cf Equation (6)

R   Drag per unit length of fairing when the fairing is normal to the free stream

R_n Reynolds number based on maximum fairing thickness; cf Equation (2)

s   Fairing model submergence (wetted length)

t   Maximum fairing thickness

V   Free stream velocity

X   Normal hydrodynamic force

Y   Lateral hydrodynamic force

Z   Tangential hydrodynamic force

Γ Tangential hydrodynamic loading function; cf Equations (5) and (11)

Λ Normal hydrodynamic loading function; cf Equations (4) and (10)

ν Kinematic viscosity of fluid

ρ Mass density of fluid

ϕ Cable angle (acute angle between Z force direction and direction of motion; cf Figure 4)

ADMINISTRATIVE INFORMATION

INTRODUCTION

The Naval Ship Research and Development Center (NSRDC) established a research project under the Submarine Towed Communications Program directed toward the development of fundamental design information for future submarine towed systems. This work is in accordance with a continuing effort at the Center to improve techniques for predicting the steady-state and dynamic characteristics of cable-towed systems.

The differential equations describing the two-dimensional steady-state configuration and forces of a cable-body system are well defined within the limits of certain simplifying assumptions.[1]* Solutions to these equations can be obtained numerically through digital computation provided the body characteristics, cable loading functions, and cable drag coefficients are specified.[2] An expression representing the general form of the cable loading function has been developed at the Center.[3] However, to obtain the loading functions for a specific faired cable, the coefficients for the aforementioned expression must at present be determined experimentally. To date, experiments to determine

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*References are listed on page 23.

cable loading have been conducted on numerous faired-cable designs
(References 4, 5, 6, 7, 8, 9, and 10). The experimental approach
consists of towing a rigid faired-cable model in the David Taylor
Model Basin at various speeds, cable angles, and model submergences
and measuring the hydrodynamic forces using the DTMB Cable-Fairing
Dynamometer. Data obtained from these experiments are non-dimensionally
normalized and processed with a curve-fitting computer program to obtain
mathematical expressions for the loading functions and drag coefficients.

This report is concerned with similar experiments on the TMB
Number 7 Fairing Shape including experiments for a cable angle of zero
degrees to obtain the lower boundary value of the tangential loading
function. This report describes the subject fairing model, the cable
fairing and towing girder dynamometers, the instrumentation, the
experimental procedure and method; gives sample plots used to obtain
the loading expressions of normal and tangential forces versus model
submergence for various speeds; presents graphically, fairing drag
coefficient versus Reynolds number and normal and tangential loading
functions; and provides the mathematical expressions, with coefficients,
for the loading functions and drag coefficients.

DESCRIPTION OF FAIRING MODEL

The basic model consists of a five-segment aluminum strut having
a TMB Number 7 Fairing section shape as described in Reference 11.

2

Details are shown in Figure 1. Additional physical characteristics of the fairing model are given in Table 1.

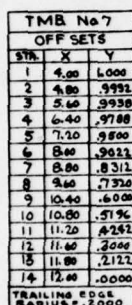TABLE 1

PHYSICAL CHARACTERISTICS OF FAIRING MODEL

Section shape	TMB No. 7
Chord, inches	12.00
Maximum thickness, inches	2.00
Section fineness ratio	6
Ratio of wetted surface area to projected frontal area	12.78
Model length (cable fairing dynamometer), inches	89.25
Model length (towing girder), inches	113.25

The model was designed to be configured for both the cable fairing and towing girder dynamometers. The configuration for the cable fairing dynamometer consisted of the long 7-1/2-foot model segment with the strut plate and is shown attached to the dynamometer in Figure 2. The configuration for the towing girder dynamometer consisted of the long model segment suspended, leading edge up, below the girder by two standard 4-1/2-foot ogive struts. The length of the model was variable by the addition of the short segments. The "full length" configuration is depicted in Figure 3. Nose and tail fairings were added for stream-lining and fillets were also added at the model/strut interfaces.
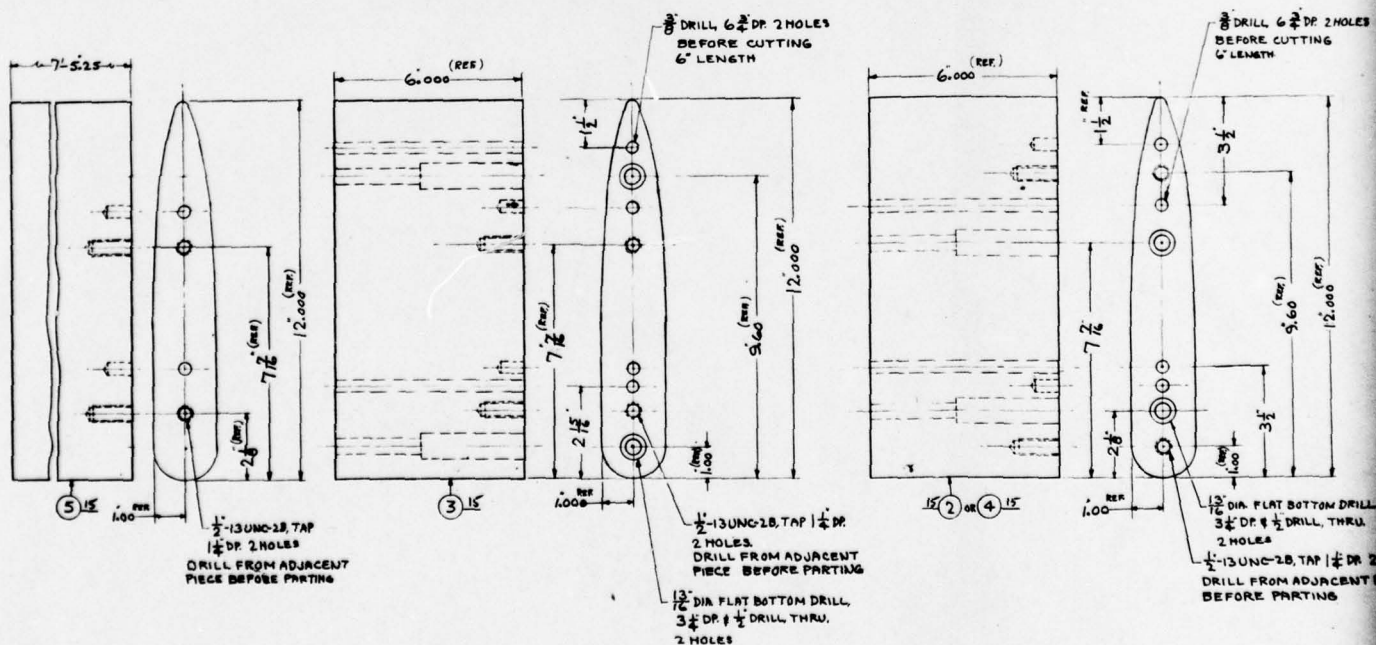
DESCRIPTION OF DYNAMOMETER AND INSTRUMENTATION

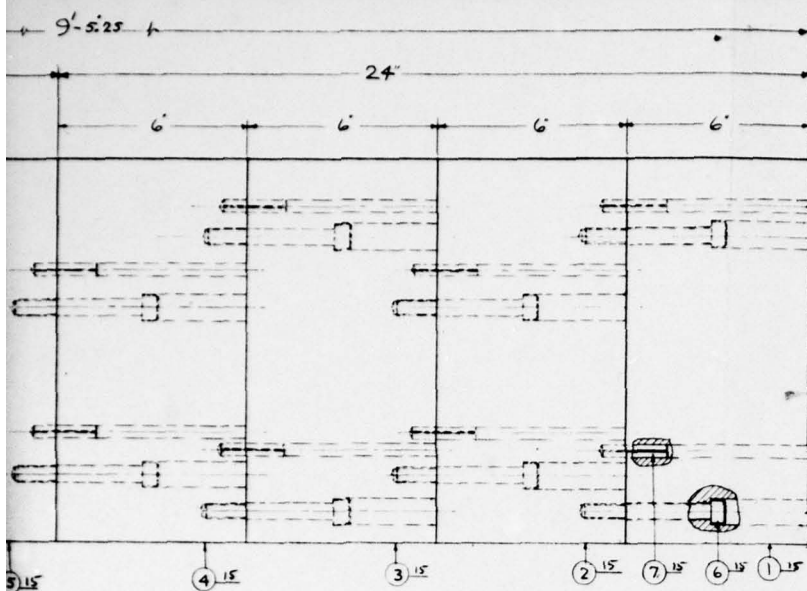The DTMB Cable Fairing Dynamometer is shown in Figure 2 with the

3

CONTOUR TO TEMPLATE
FURNISHED BY CODE 225

1" HELI-COIL

TAP FOR ½-13 UNC-2B HELI-COIL 7 HOLES
LOCATE FROM PL. 8-15

9'-5.25

7'-5.25

24"

6

6

5 15

4 15

3 15

TMB No.7		
OFF SETS		
STA.	X	Y
1	4.00	1.0000
2	4.80	.9992
3	5.60	.9938
4	6.40	.9788
5	7.20	.9500
6	8.00	.9022
7	8.80	.8312
8	9.60	.7320
9	10.40	.6000
10	10.80	.5196
11	11.20	.4242
12	11.60	.3000
13	11.80	.2122
14	12.00	.0000
TRAILING EDGE		
RADIUS = .2000		

125
√ ALL OVER EXCEPT AS NOTED

7'-5.25

6.000 (REF.)

6.000 (REF.)

⅞ DRILL, 6¾ DP. 2 HOLES
BEFORE CUTTING
6" LENGTH

⅞ DRILL, 6¾ DP. 2 HOLES
BEFORE CUTTING
6" LENGTH

5 15

3 15

2 or 4 15

½-13 UNC-2B, TAP
1¼ DP. 2 HOLES
DRILL FROM ADJACENT
PIECE BEFORE PARTING

½-13 UNC-2B, TAP 1¼ DP.
2 HOLES
DRILL FROM ADJACENT
PIECE BEFORE PARTING

1¾ DIA FLAT BOTTOM DRILL,
3¼ DP. & ½ DRILL, THRU.
2 HOLES

1¾ DIA FLAT BOTTOM DRILL
3¼ DP. & ½ DRILL, THRU.
2 HOLES

½-13 UNC-2B, TAP 1¼ DP. 2
DRILL FROM ADJACENT P
BEFORE PARTING

REVISIONS

REV.	ZONE	DESCRIPTION	BY	DATE	APP'D
I	5 D	7 TAPPED HOLES FOR ¼" HELI-COILS ADDED TO PC. 5-15		20 Apr. 66	
	1 B	PC 8 ADDED			
	1 A	PC. 9 & 10 ADDED, 1/16 DEEP RECESS ADDED TO PC 5			
II		PC 8, MAT'L 410 WAS 321			

9'-5.25

24"

6" 6" 6" 6"

5-15 4 15 3 15 2 15 7 15 6 15 1 15

SUGGESTED MACHINING PROCEDURE

1) MACHINE FROM ONE LENGTH ALLOWING ADDITIONAL LENGTH FOR PARTING OF END PIECES 1, 2, 3, & 4 (DIMENSIONS SHOWN ARE FINISHED DIM.)

2) BORE FOR ⅜" REAMED HOLES, AND ½" BOLTS STARTING WITH PIECE No. 1, ie (BORE PIECE 1 TO GIVE 6" LENGTH THEN BORE PIECE No. 2 AND PART, AND SO FORTH IN RESPECTIVE ORDER)

3) TEMPLATE SUPPLIED BY CODE 225.

17/32 DRILL ø 1¼ DIA C'BORE ⅜ DP. 7 HOLES

4"
2"
2¼
13"
4 SPACES @ 2.00 = 8.00

17/32 DRILL, 10 HOLES
SAW CUT EXCEPT AS NOTED
BREAK SHARP EDGES
1.50
3.00
.75

8 E-2295-15
SCALE: 6"=1'-0"

⅜ DRILL 6 ¾ DP. 2 HOLES
BEFORE CUTTING
6" LENGTH

STAMP PC. No. ON END OF EACH
PIECE, FILE SMOOTH AFTER
STAMPING

6.000

⅜ DRILL, 6 ¾ DP. 2 HOLES
BEFORE CUTTING
6" LENGTH

3¼
7¼
9.60
12.000
2⅛
1.00

13/16 DIA FLAT BOTTOM DRILL
3¼ DP. & ½ DRILL, THRU.
2 HOLES

½-13UNC-2B, TAP 1¼ DP. 2 HOLES
DRILL FROM ADJACENT PIECE
BEFORE PARTING

1¾
3¼
9.60
12.000
2"
1.00

13/16 DIA FLAT BOTTOM DRILL
3¼ DP. & ½ DRILL, THRU.
2 HOLES

1.00

1 15

LIST OF MATERIAL

PC. NO.	NAME OF PIECE	NO. REQ'D	MATERIAL	STD. NAVY STOCK NO.	
10	½-13UNC-2A, HEX. HD. CS. 2" LONG	7	STEEL	5305-577-5463	SHM
9	½-13UNC-2B HELI-COIL 1185-8CNX1	7	COM'L.	5340-L00-0041	SHM
8	STRUT PLATE	1	CRES 410		SHM
7	⅜ DIA ROLL PIN 2" LONG	8	CRES	5315-058-9834	SHM
6	½-13UNC-2A SCHCS. 4" LONG	8	CRES	IND. 2501/66	O
5	FAIRING	1	ALUM. 6061	IND 2500/66	OVM
4	FAIRING	1			
3	FAIRING	1			
2	FAIRING	1			
1	TMB. No. 7 FAIRING	1	ALUM. 6061	IND 2500/66	OVM

LIST OF MATERIAL - QUANTITIES FOR ONE ASSEMBLY.

CABLE FAIRING DYNAMOMETER
T.M.B. NO. 7 FAIRING
DETAILS

DRAWN 3/23/66
CHECKED
REVIEWED
APPROVED V. Miller
DATE 3-31-66
SCALE 6"=1'-0"

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN
WASHINGTON, D.C. 20007

E-2295-15 II

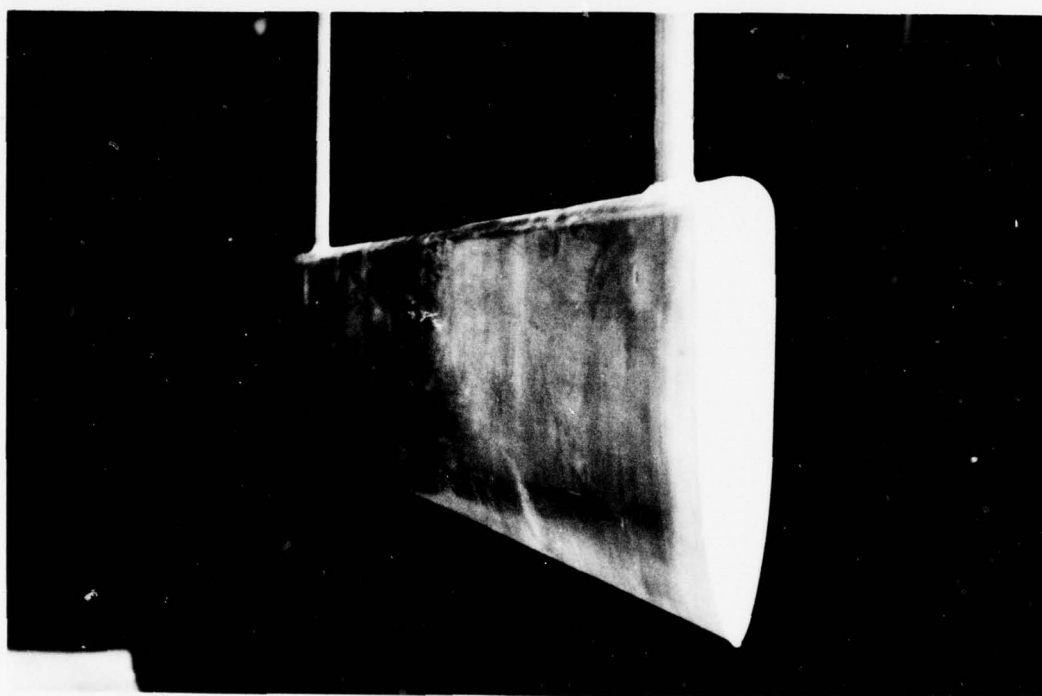Figure 1 - Fairing Model Drawing

4
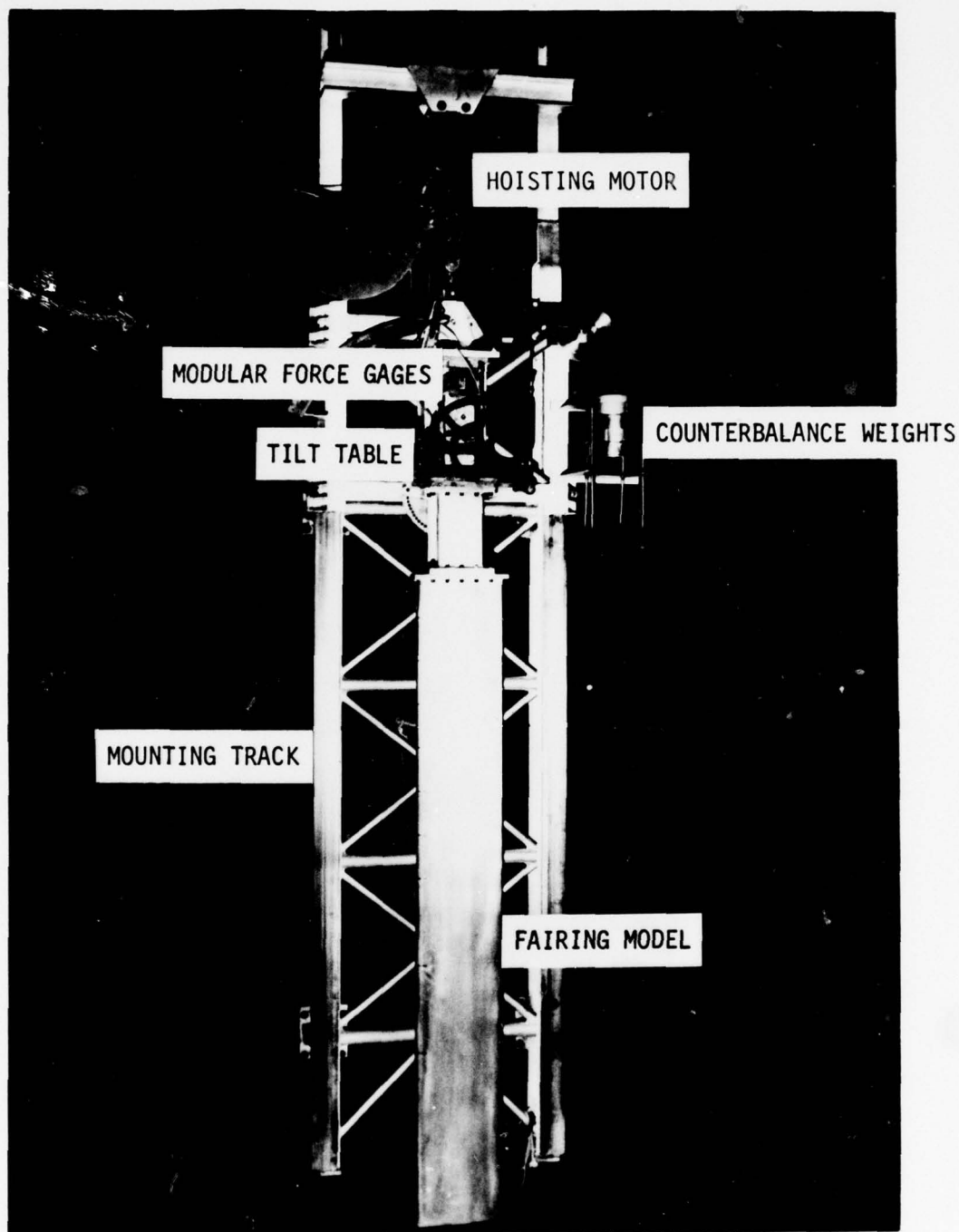
PSD 321140

Figure 2 - Cable Fairing Dynamometer with Model Attached

5
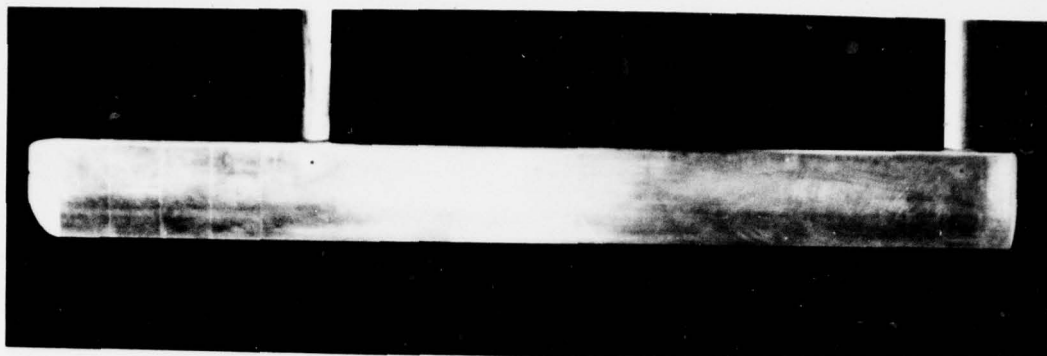
PSD 338419

Figure 3a - Side View

PSD 338498

Figure 3b - Quarter View

Figure 3 - "Full Model" Configuration with Ogive Struts

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fairing model attached. The normal force, X, lateral force, Y, and tangential force, Z, on the model, as depicted in Figure 4, are sensed by separate 4-inch-cube modular force gages of the type described in Reference 12. Interchangeable gages with capacities ranging from 50 to 1000 pounds are available so that high accuracy can be maintained over a range of speeds. However, the dynamometer structure limits each of the three component forces to 500 pounds.

The dynamometer tilt-table angle is adjustable so that the model cable angle, ϕ, relative to the free stream may be varied from 30 degrees to 90 degrees in 5-degree increments. The vertical position of the model and tilt table also is adjustable by means of an electric hoist so that model submergence may be varied from zero to approximately 7 feet. A weight-pan system provides a means of counterbalancing the model weight on the gages at each submergence and cable angle. Model yaw angle also is adjustable to provide proper alignment with the flow.

Instrumentation used with the cable fairing dynamometer included a 50-pound-capacity gage for the X force, a 1000-pound-capacity gage for the Y force, and a 50-pound-capacity gage for the Z force; a three-channel modular-force-gage control unit, two integrating digital voltmeters for readout of the X and Z forces and a strip-chart recorder for monitoring the Y force. A magnetic pickup and digital counter were used to indicate towing carriage speed and a digital printer was used to record the X force and Z force. The instrumentation console used is shown in Figure 5.
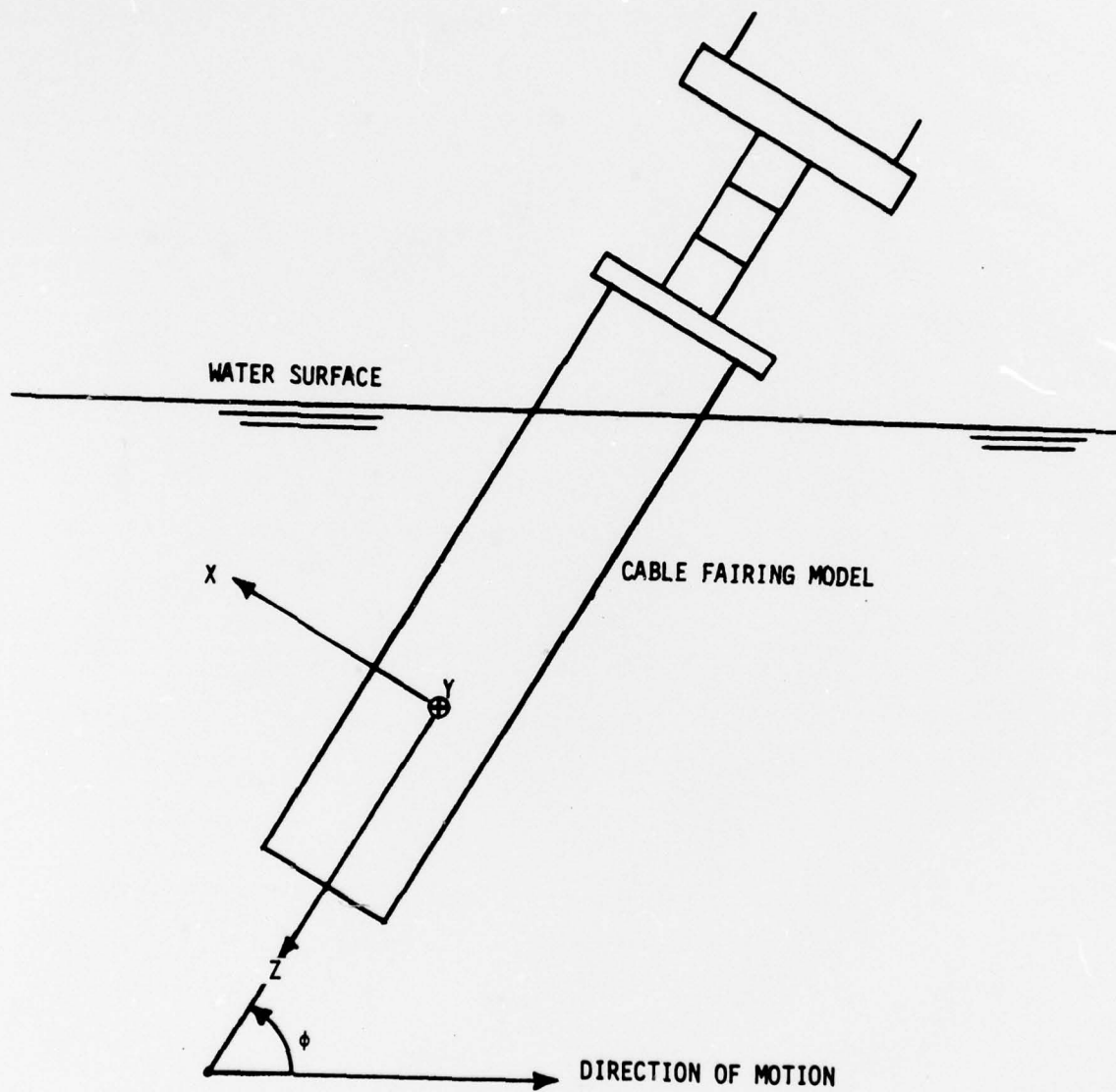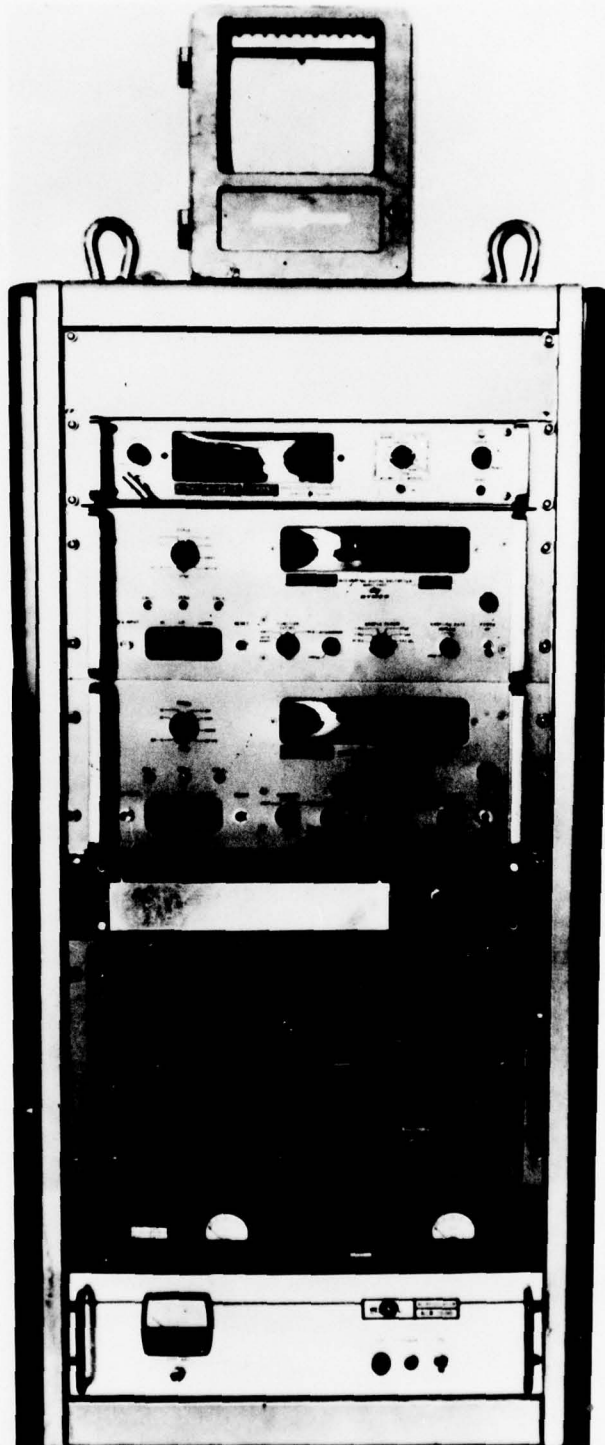
7

WATER SURFACE

CABLE FAIRING MODEL

X

Y

Z

ϕ

DIRECTION OF MOTION

Figure 4 - Force Coordinate System

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PSD 338499

Figure 5 - Instrumentation Console for Cable Fairing Dynamometer

The estimated accuracy of the force measurement system is ±0.25 pound for the X and Z forces and ±5 pounds for the Y force. The accuracy of the speed measurement is ±0.05 knot.

The towing girder dynamometer is of the floating-frame weighing type and is illustrated diagrammatically in Figure 6. The dynamometer girder carries a long horizontal floating beam in pendulum fashion on two pairs of vertical arms terminating in flexible springs. A counterweight at the upper end of a vertical swinging arm mounted on the girder and attached to the floating beam maintains the beam in equilibrium at any position between the limit stops. The model resistance is transmitted as a horizontal force through the upper flexible link to the T-shaped balance, where it is balanced by weight, W. When the model resistance is not equal exactly to a unit weight, W, the difference is taken up by the resiliency of the flexible spring supports; the exact amount being recorded on the drum through the lower link and recording arm shown. A variable strength electro-magnetic dampener is incorporated to minimize model surge motions. The drag measurement is estimated to be accurate to ±1.5 percent.

EXPERIMENTAL PROCEDURE

The model was first towed with the cable-fairing dynamometer in the high-speed basin at various cable angles ranging from 30 degrees to 90 degrees in approximately 10 degree increments. At each cable angle, the model submergence was varied from 24 inches to 84 inches
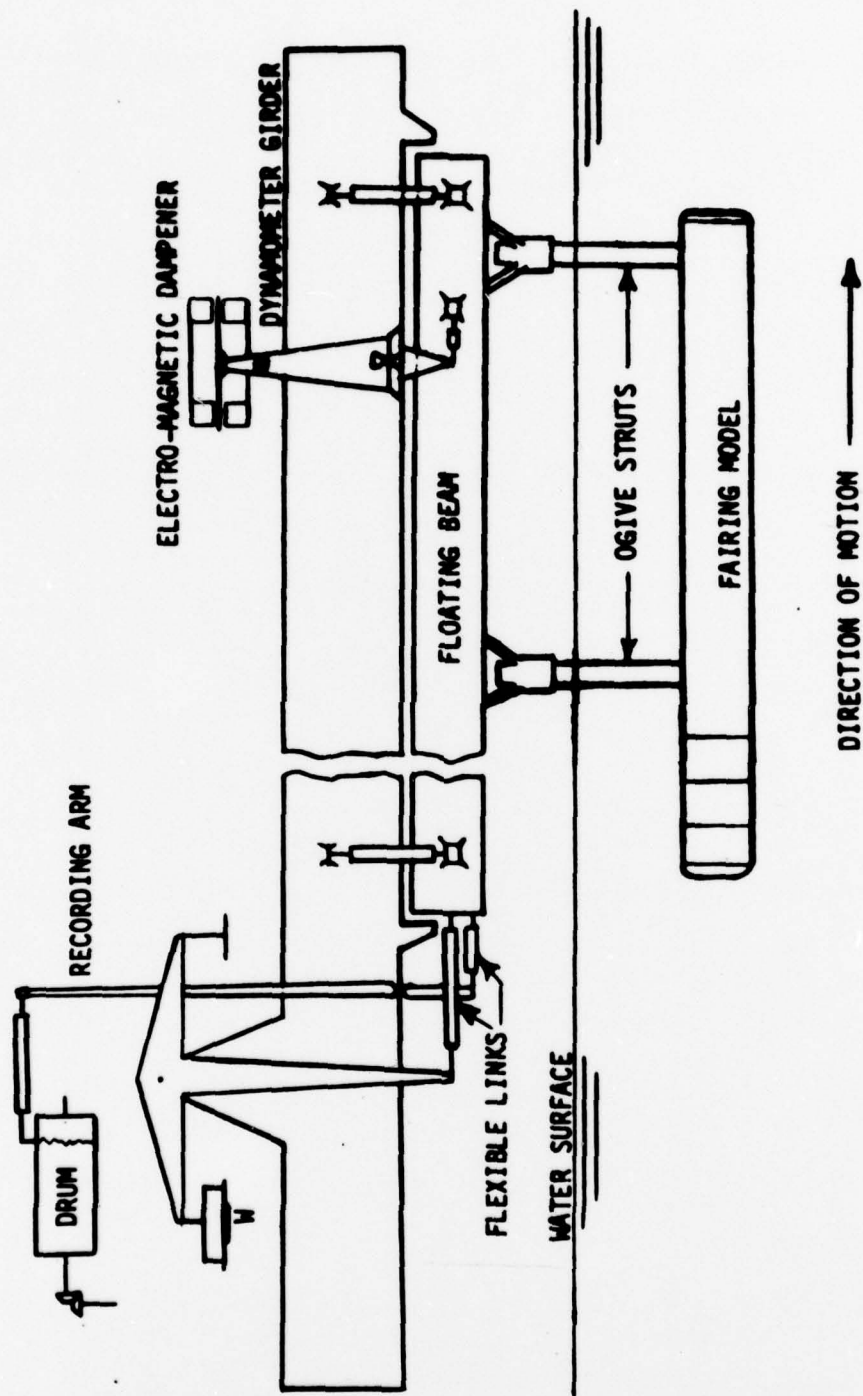
ELECTRO-MAGNETIC DAMPENER

DYNAMOMETER GIRDER

RECORDING ARM

FLOATING BEAM

DRUM

W

FLEXIBLE LINKS

WATER SURFACE

OGIVE STRUTS

FAIRING MODEL

DIRECTION OF MOTION

Figure 6 - Schematic Arrangement of Towing Girder Dynamometer

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in multiples of 6 inches for towing speeds of 5 and 8 knots. Additional
speeds of 2, 3, 4, 6, 10, and 13 knots also were run at a cable angle
of 90 degrees over the aforementioned submergence range. The X, Y,
and Z forces and towing speed were measured for each run condition.
The Y force reading was used mainly as a basis for aligning the model
with the flow to minimize the Y force. It also provided a means of
monitoring model lateral oscillations at each run configuration.

The model also was towed from the floating girder dynamometer in
the deep-water basin to obtain zero degree cable angle data. The
procedure consisted of first towing the long model segment at speeds
of 5, 8, and 13 knots and measuring the total drag force at each speed.
Subsequent runs were conducted adding each of the four 6-inch segments
in turn and measuring the total drag force at each speed.

HYDRODYNAMIC FORCES

The measured hydrodynamic forces were generated by a three-
dimensional surface-piercing model. Therefore, the data contain
both end effects and surface effects. The desired two-dimensional
hydrodynamic forces were derived from these data by the following method.
The X and Z forces were plotted as a function of model submergence
(wetted length) for each angle and speed. As model submergence is
increased, a length is reached after which both the X and Z forces
became linearly dependent on submergence for a constant speed and
angle, i.e., end and surface effects became essentially constant.

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Slopes of the linear portion of the force-submergence curves were determined by the method of least squares for each angle and speed. Typical plots are given in Figures 7 and 8 for the X and Z forces, respectively. These slopes, $\frac{\Delta X}{\Delta S}$ and $\frac{\Delta Z}{\Delta S}$, represent the two-dimensional hydrodynamic forces per unit length acting on the fairing model and are tabulated as Table 2.

TABLE 2

TWO-DIMENSIONAL HYDRODYNAMIC FORCES

Cable Angle, degrees	Speed, knots	Normal, pounds per foot	Tangential, pounds per foot
30.62	5	0.5266	0.5460
	8	1.0267	1.2368
40.58	5	0.6842	0.4868
	8	1.5344	1.0652
50.50	5	0.8641	0.4655
	8	1.8782	0.9044
60.12	5	1.1964	0.3630
	8	2.4649	0.7266
70.10	5	1.4026	0.2255
	8	No data, large lateral oscillations	
79.82	5	1.3077	0.2071
	8	2.8169	0.2715
	13	6.8185	0.4742
79.92	5	1.2942	0.1997
	8	2.8169	0.2715
	13	6.8185	0.4742
90.00	5	1.2915	0.0152
	8	2.8386	-0.0175
	13	6.6157	0.0108

DRAG COEFFICIENT

The fairing drag coefficient, C_R, and corresponding Reynolds number, R_n, were determined for each speed using the following expressions:
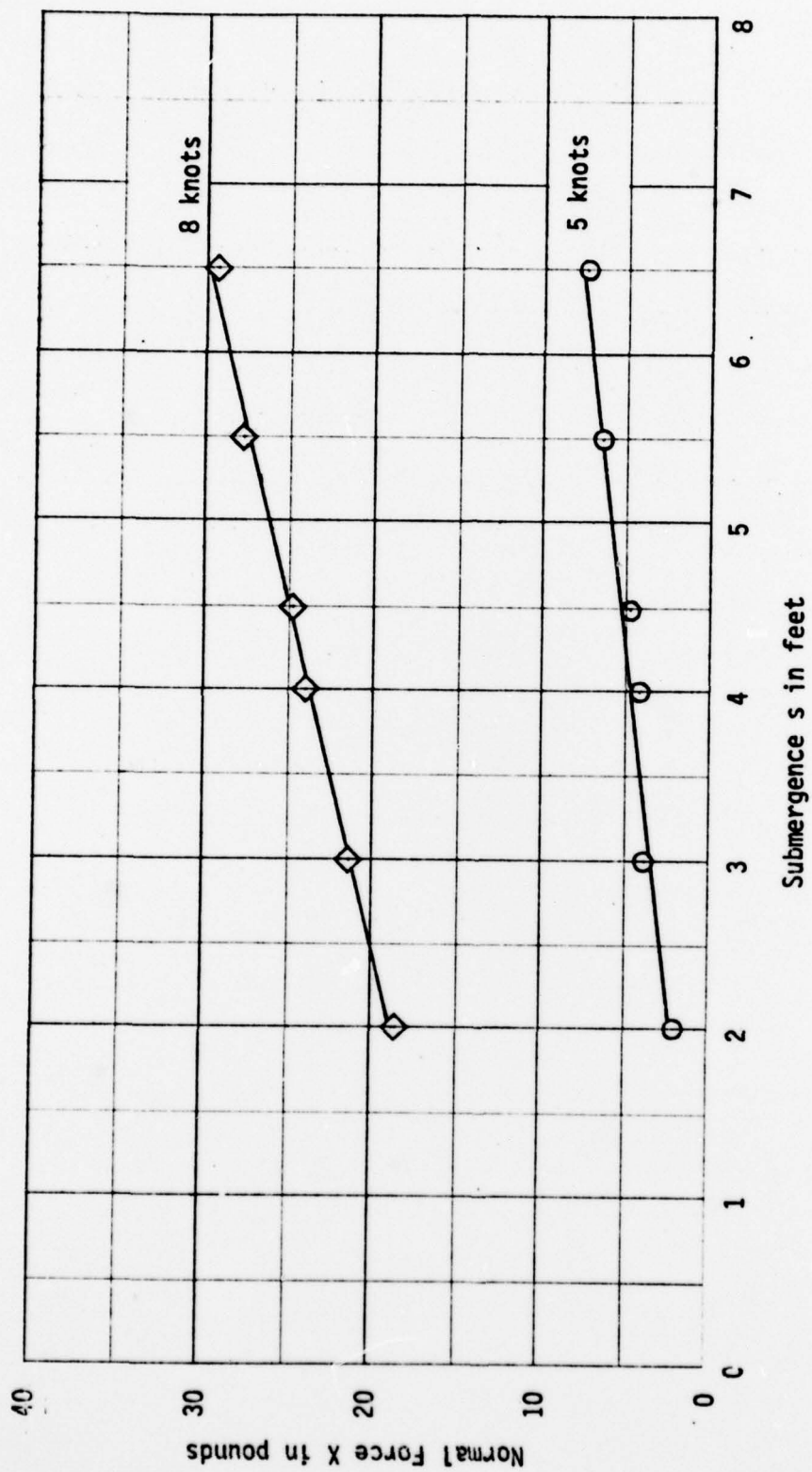
13

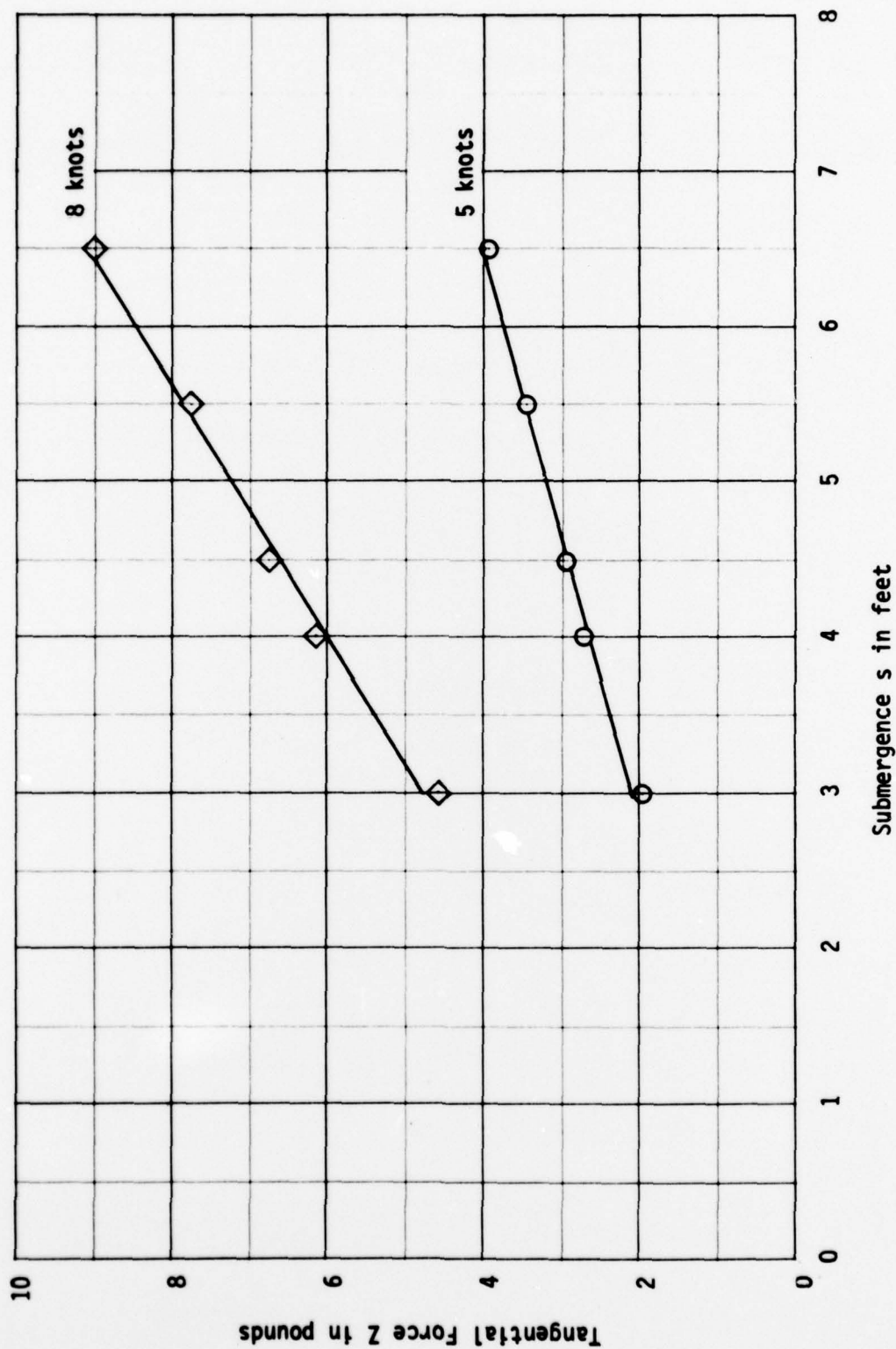Figure 7 - Normal Force Versus Submergence for a Cable Angle of 60.12 Degrees

Figure 8 - Tangential Force Versus Submergence for a Cable Angle of 30.62 Degrees

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$$C_R = \frac{R}{(1/2)\rho t V^2} \quad , \tag{1}$$

and

$$R_n = \frac{Vt}{\nu} \quad . \tag{2}$$

The resulting Reynolds numbers and drag coefficients are given in Table 3. Applying a least-squares fit to the data in Table 3 yields the following expression for the variation of drag coefficient with Reynolds number:

$$C_R = 3.74 \, R_n^{-0.296} \tag{3}$$

The curve representing this expression is given in Figure 9.

TABLE 3

REYNOLDS NUMBERS AND DRAG COEFFICIENTS

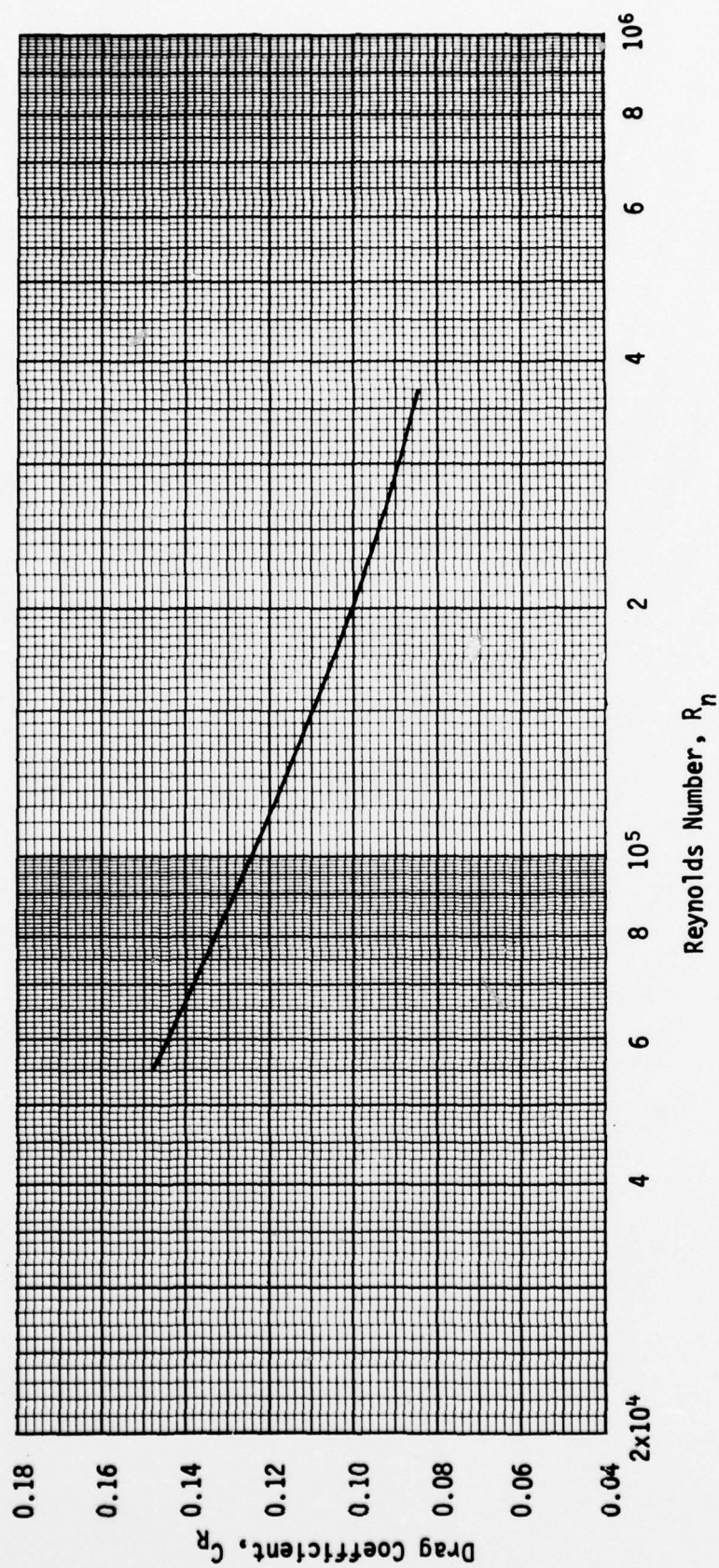| Speed, knots	$R_n \times 10^{-5}$ *	C_R
2	0.562	0.145
3	0.844	0.133
4	1.125	0.122
5	1.406	0.111
6	1.687	0.107
8	2.250	0.096
10	2.812	0.092
13	3.656	0.085
*NOTE: Basin water temperature was 74 degrees Farenheit		

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Figure 9 - Drag Coefficient Versus Reynolds Number, R_n

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HYDRODYNAMIC LOADING FUNCTIONS

The hydrodynamic loading functions are defined as the ratios of
the steady-state, two-dimensional, hydrodynamic forces acting on an
element of fairing at angle ϕ to the drag per unit length of fairing
when the fairing is normal to the free stream, R (where R is the drag
at ϕ = 90 degrees). Therefore, the normal and tangential loading
functions at an angle ϕ are respectively

$$\Lambda(\phi) = \frac{X(\phi,R_n)}{X(90,R_n)} = \frac{X(\phi,R_n)}{R(R_n)} \quad , \tag{4}$$

and

$$\Gamma(\phi) = \frac{Z(\phi,R_n)}{R(R_n)} \quad , \tag{5}$$

where, $0^0 \le \phi \le 90°$.

As expressed in Equations (4) and (5), these loading functions are
assumed to be dependent only on the cable angle for a given fairing
geometry. The loading functions variation with cable angle may be
represented analytically by selected combinations of the first few
terms of the infinite series,[3]

$$F(\phi) = A_0 + \sum_{n=1}^{\infty} A_n \cos n\phi + \sum_{n=1}^{\infty} B_n \sin n\phi. \tag{6}$$

The following method was used to generate the particular trigono-
metric expressions for both the normal and tangential loading functions.
The two-dimensional hydrodynamic forces per unit length given in Table 2

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were normalized by dividing by the corresponding R value at each
Reynolds number obtained from Equation (7).

$$R = 1.87 \ \frac{\rho v^2}{t} \ R_n^{1.704} \tag{7}$$

This expression represents the values of R resulting from the least
squares fit of C_R versus R_n, Equation (3), and was derived by solving
Equation (2) for V; substituting this expression and Equation (3)
into Equation (1) for V and C_R, respectively; and solving the resulting
expression for R.

A curve-fitting process using the method of least squares was
performed on the two sets of resulting loading values. The process
consisted of generating the coefficients for selected combinations
of terms in Equation (6) for which the following loading boundary
conditions were satisfied:

$$\Lambda(0^\circ) = 0, \tag{8A}$$

$$\Lambda(90^\circ) = 1, \tag{8B}$$

$$\frac{d\Lambda(90^\circ)}{d\phi} = 0, \tag{8C}$$

and

$$\Gamma(90^\circ) = 0. \tag{9}$$

The expressions resulting for $n \leq 2$ are

$$\Lambda(\phi) = 0.2675 + 0.4650 \sin \phi - 0.2675 \cos 2\phi \qquad (10)$$

and

$$\Gamma(\phi) = -2.3034 + 2.4536 \cos \phi + 2.4712 \sin \phi$$
$$+ 0.1678 \cos 2\phi - 0.8232 \sin 2\phi \qquad (11)$$

where Λ and Γ are the normal and tangential loading functions, respectively. The foregoing expressions are plotted in Figures 10 and 11.
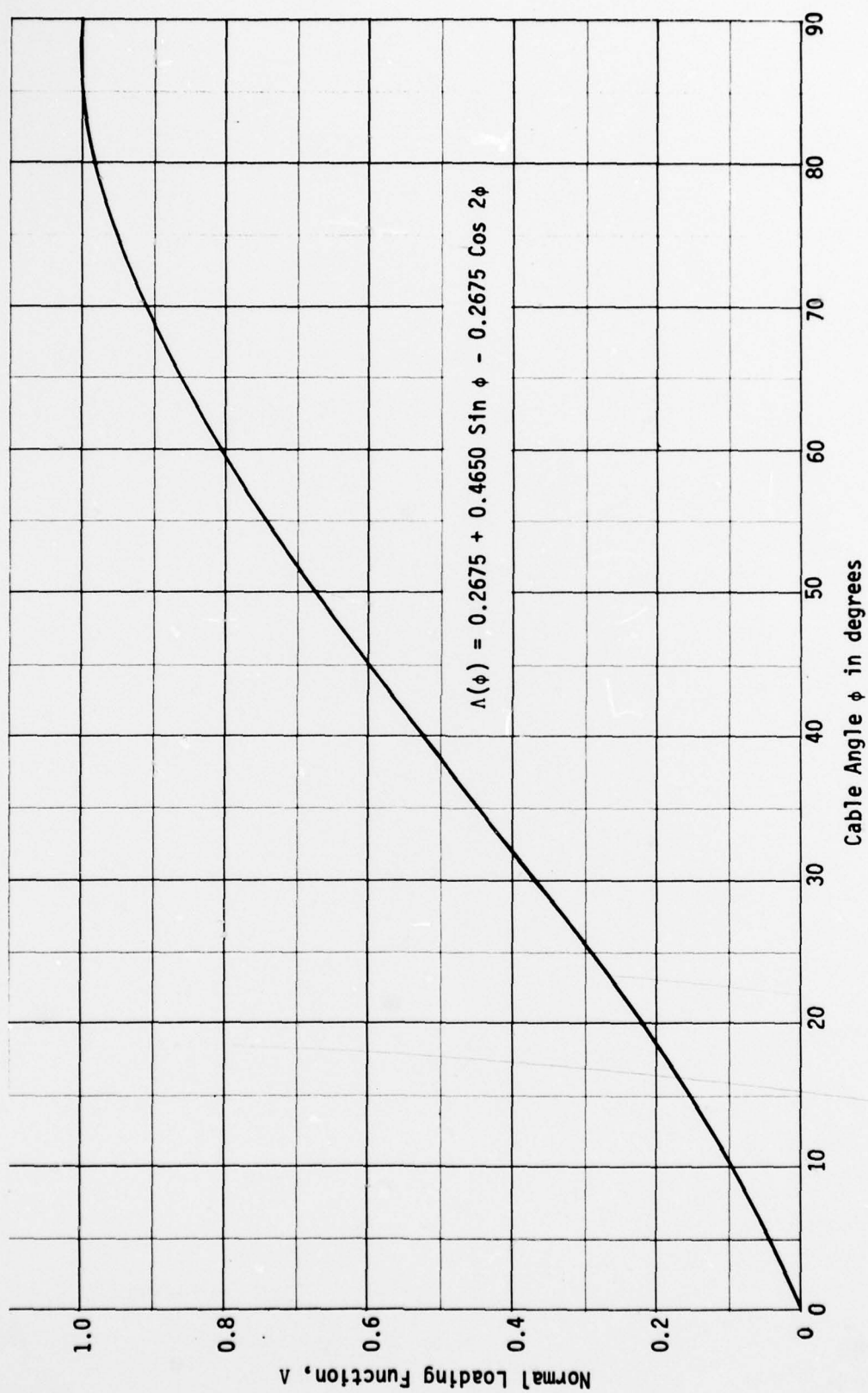
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Figure 10 - Normal Loading Function Versus Cable Angle

$\Lambda(\phi) = 0.2675 + 0.4650 \, \text{Sin} \, \phi - 0.2675 \, \text{Cos} \, 2\phi$

Cable Angle ϕ in degrees

Normal Loading Function, Λ

$$\Gamma(\phi) = -2.3034 + 2.4536 \cos \phi + 2.4712 \sin \phi$$
$$+ 0.1678 \cos 2\phi - 0.8232 \sin 2\phi$$

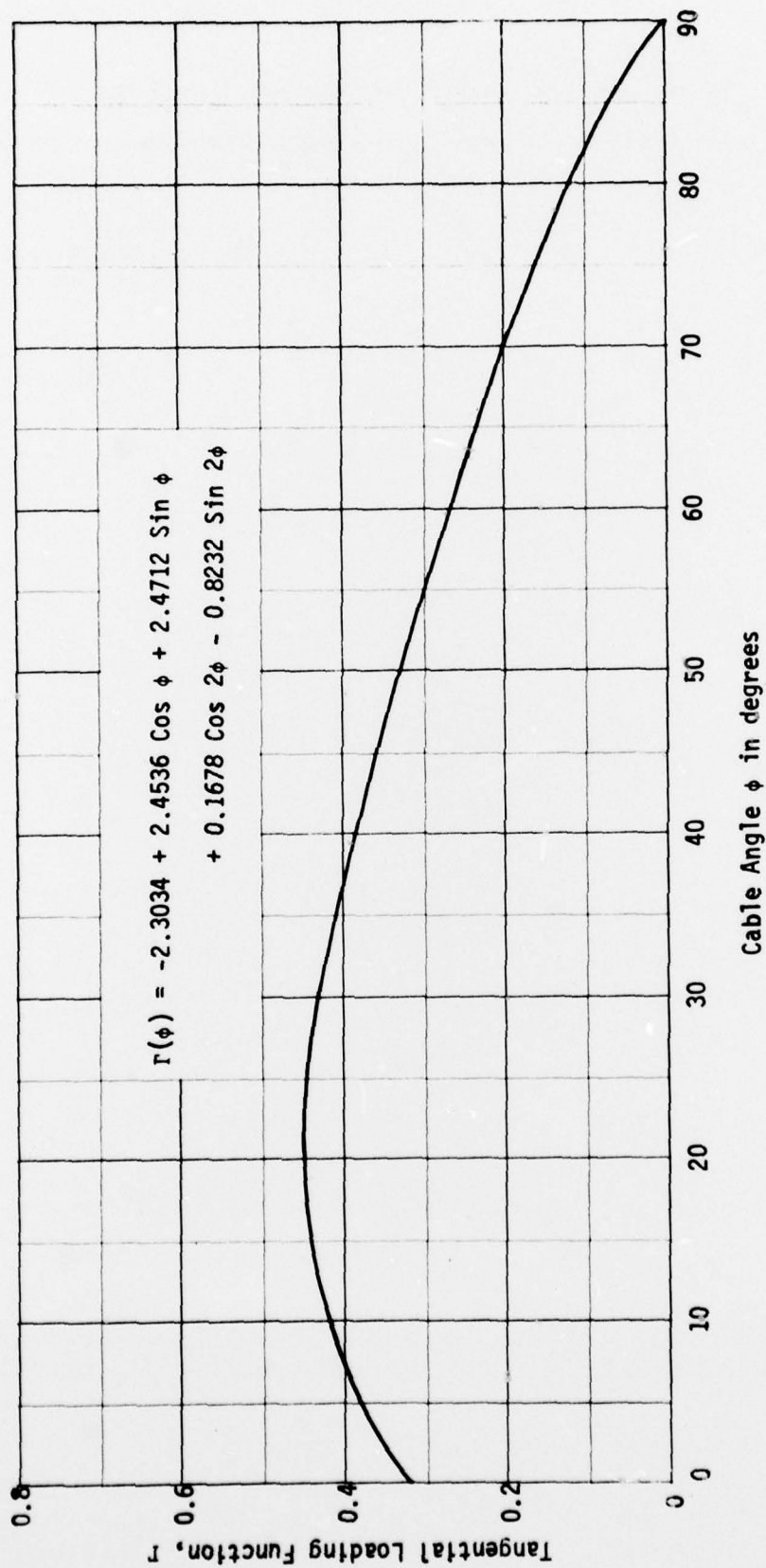Cable Angle ϕ in degrees

Tangential Loading Function, Γ

Figure 11 - Tangential Loading Function Versus Cable Angle

REFERENCES

1. Pode, L., "Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream," David Taylor Model Basin Report 687 (March 1951)

2. Cuthill, E.H., "A FORTRAN IV Program for the Calculation of the Equilibrium Configuration of a Flexible Cable in a Uniform Stream," Naval Ship Research and Development Center Report 2531 (February 1968)

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