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NR76H-137

ON-WATER MOTION RELATIONSHIPS STUDY

FINAL REPORT

January 15, 1977

Contract N00600-76-C-1606
for the David W. Taylor
Naval Ship Research and Development Center

FORM 351-F REV 4-73

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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This report presents an on-water head seas motion analysis of three C/STOL and three V/STOL sea based aircraft configurations. Heave, pitch, acceleration, and slamming/wetness conditions are determined. Different forward speed conditions were studied. The effect of various configuration parameters (length, inertia, c.g. location, water plane area, etc) on head seas motion parameters was established. Sea state conditions from one to seven were studied. Fundamental sea state relationships and their effect on sea basing of aircraft are presented. Recommendations for subsequent model tank testing are indicated. (continued on other side)

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20. ABSTRACT (Cont'd. from Page 1.)

Rockwell International Report NR76H-113, "Sea Based Aircraft Habitability Criteria" dated 15 October 1976, provides a definition of the human limits for sea based aircraft. Habitability criteria including vertical, lateral and roll limits for on-water operation are included. Motion sickness limits are presented. No serious habitability limitations were uncovered for the surface following sea based aircraft concept.

ABSTRACT

This report presents an on-water head seas motion analysis of three C/STOL and three V/STOL sea based aircraft configurations. Heave, pitch, acceleration, and slamming/wetness conditions are determined. Different forward speed conditions were studied. The effect of various configuration parameters (length, inertia, c.g. location, water plane area, etc.) on head seas motion parameters was established. Sea state conditions from one to seven were studied.

Fundamental sea state relationships and their effect on sea basing of aircraft are presented. Recommendations for subsequent model tank testing are indicated.

This effort was performed under Contract N00600-76-C-1606, dated August 17, 1976 (Rockwell International Sales Order, S.O. 2395) to the David W. Taylor Naval Ship Research and Development Center (DT-NSRDC), Bethesda, Md., 20084.

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1.0 INTRODUCTION

This study of Surface Loiter Aircraft On-Water Motion Relationships has been performed under Contract N00600-76-C-1606, dated 17 August 1976, to the David W. Taylor Naval Ship Research and Development Center (DT-NSRDC). The study includes the relationship of sea state characteristics to surface loiter aircraft characteristics, a head seas on-water motion analysis and a definition of human limits including habitability criteria of sea based aircraft on-water operation.

Rockwell International Report NR76H-113, "Sea Based Aircraft Habitability Criteria," dated 15 October 1976, provides a definition of the human limits for sea based aircraft. Habitability criteria including vertical, lateral and roll limits for on-water operation are included. Heating, ventilation, air conditioning illumination and volume limits are also included. Motion sickness limits are presented. No serious habitability limitations were uncovered for the surface following sea based aircraft concept.

This report presents (1) a head seas on-water motion analysis of six selected sea based aircraft configurations (three C/STOL and three V/STOL designs), (2) sea state relationships and (3) model tank test program recommendations for subsequent study.

2.0 SUMMARY

Reference 1 (NR76H-113), "Sea Based Aircraft Habitability," established 0.1 g's RMS as acceptable for sea based on-water mission operations. 0.3 g's RMS was established as unacceptable. Based on these limit criteria, (1) all of the sea based aircraft configurations considered in the study (except the 1.25 $\overline{M}$ catamaran) meet the acceptable criteria at zero speed in head seas at all sea states and (2) most of the study aircraft configurations approach or exceed the unacceptable motion criteria at 5 to 10 knots forward speed in head seas.

Acceptable sea based on-water operations are considered possible at very low forward speeds.

Sea following craft have acceleration of 0.10 to 0.125 g's RMS at zero speed in head seas at all sea states. At zero speed, accelerations do not increase significantly as sea state increases. Increasing on-water speed does increase the accelerations significantly; depending on the physical characteristics of the craft. Short length craft (e.g., 40 feet in waterline length) start contouring the waves at lower sea states than do longer length craft. This is shown in Figure 16 where representative 40 foot length craft start contouring the waves at sea state 3, and the 170 foot length craft starts contouring the waves at about sea state 6 (V = 0 knots). As on-water speed increases to 5 knots, differences in craft length and radius of gyration in pitch (Kyy) do result in different RMS acceleration levels.

The motion of sea following craft at 5 knots are higher in relation to those at zero speed and craft characteristics become more important. All craft have acceleration levels approaching 0.3 g's RMS at 5 knots or would reach this level at about 10 knots. Configuration 2, the .7 million pound single hull has about the same accelerations at 10 knots as the smaller craft do at 5 knots. The accelerations at the C.G. (not shown) are about half of those at the cockpit at 5 knots.

Recommended design limits for small 40 feet, 40,000 pound TOGW sea based aircraft are:

$$K_{yy}/L \leq .25 \text{ (Lowest inertia possible desired)}$$

This investigation has centered on the head seas condition. For a sea following craft, this would be the usual mode of operation to minimize rolling. An on water propulsion device will be required for craft orientation and for on water mobility.

At the lower sea states, the wind and waves are from the same direction. At the higher sea states or with long swell conditions the winds and waves may not be from the same direction. For those conditions, where the wind and waves are from the same direction, a large tail will tend to keep the craft headed into the wind (and waves) without necessitating active propulsion.

This is not to say that other modes of motion are unimportant (in particular rolling), but rather that head seas are usually the best case to examine, and is usually examined first. Sea keeping design studies in only head seas have been successfully conducted on ships for many years. Before final design, however, studies involving all modes of motion of the sea based aircraft should be carried out.

These computations are for long crested irregular waves in head seas. The important motions are pitch and heave. Had short crested waves been considered, the results would not be significantly different. Pitch and heave would still be the dominant motions. There would be some lateral motion (sway, roll, and yaw) but these are considered small. The energy in the waves coming from the lateral direction for short crested head seas is too small and the wave lengths too large to excite much roll motion in craft with reasonable float spacing. There is a possibility of non-linear phenomenon inducing extremely large roll amplitudes but this requires a highly unlikely combination of circumstances involving hull shape and wave length. These conclusions do not apply to the large CTOL catamaran, as initially configured, which was found to have unacceptable head seas motions.

In non-head seas, the roll motion becomes critical, due to the problem of wing tip submergence. The actual roll motion will depend on craft configuration (float span, roll inertia, damping, etc.) and wave exiting frequency. As with any lightly damped linear system, if the wave exiting frequency is near roll resonance, large motions will result. The roll natural frequency will depend on the roll radius of gyration and the transverse hydrostatic stability of the craft. The amplitude of the roll motion at resonance is a function of the roll damping (float size and shape, and perhaps wing tip flotation and shape). The more damping, the less the motion. Any analysis of the roll response of a configuration would have to take all of the above factors into account.

Unacceptable motions and g levels do occur at the cockpit for the configurations studied at speeds above 5 knots. Crew stations near the CG have about half the cockpit g's at speeds of 5 knots. Thus, long duration missions should consider very low forward speeds (for cockpit crew stations) and about 5 knots for crew stations near the CG. This places added emphasis on designing the craft for best in flight cruise performance and not for on-water cruising. Good aerodynamic cruise is obtained with fuselage length to beam (ℓ/b) ratios of 4 to 6. However, at these ℓ/b ratios, conventional and STOL landings are more difficult and result in higher impact g's. This places added emphasis on VTOL operations to avoid these high impact g's and the weight penalties associated with hull shaping, steps, etc., needed for CTOL or STOL operation. Vertical and near vertical takeoff and landing operations need to be studied to establish desirable hull shapes and operational profiles.

Slamming and water coming over the bow have also been examined. In general, there is no slamming problem. However, all designs will have trouble with water coming over the bow in the lower sea state at 5 knots. At zero forward speed, deck wetting (water over the cockpit) is minimal. The best solution to decreasing water over the cockpit is to increase freeboard at the bow. A freeboard of 3 to 3.5 feet for small 40,000 lb craft was found to minimize water over the bow at zero speed.

This study did not consider bow shaping to minimize water over the bow or slamming. Subsequent detailed design will consider these aspects.

3.0 SELECTED SEA BASED AIRCRAFT CONFIGURATIONS

In accordance with the Statement of Work for Contract N00600-76-C-1606, three representative C/STOL and three representative V/STOL surface loiter aircraft concept designs were selected by DT-NSRDC for on-water motion analysis. These configurations represent possible design concepts for sea based aircraft but are not necessarily optimized design configurations. These design concepts were selected to examine the on-water motions of a cross section of possible sea based aircraft design configurations. The general characteristics of the selected designs are presented in Table 1.

Table 1. Selected Design Characteristics

Design Number	Type	Name	TOGW (lbs)	TOGW (KG)	Span (Ft)	Span (M)	Overall Length (Ft)	Overall Length (M)
1	CTOL	Catamaran	1.25M̄	2.76M̄	317.3	96.7	327.0	99.7
2	CTOL	Single Hull	.769M̄	1.70M̄	222.7	67.9	237.9	72.5
3	C/STOL	DT-NSRDC Model	330*	727.7	9.6	2.9	8	2.44
4	VTOL	X-Wing	25K̄	55.1K̄	30.25	9.2	50.8	15.5
5	V/STOL	Twin Boom	40K̄	88.2K̄	63	19.2	55.8	17.0
6.	V/STOL	Twin Boom	25K̄	55.1K̄	50	15.2	44.2	13.5

* 41,250 lbs. TOGW Full Scale

Configurations 1 through 3 are C/STOL concepts and 4 through 6 are V/STOL concepts.

3.1 Configuration 1, CTOL Catamaran, 1.25M̄ lb. TOGW

Configuration 1, shown in Figure 1, is a large 1.25 million pound TOGW conventional takeoff and landing catamaran sea based aircraft design. The configuration has a wing loading of 90 PSF and a wing area of 14,000 square feet. Considering an engine thrust of 80,000 lbs per engine, the takeoff thrust to weight is .256.

TOGW 1.25 · 10^6 LBS

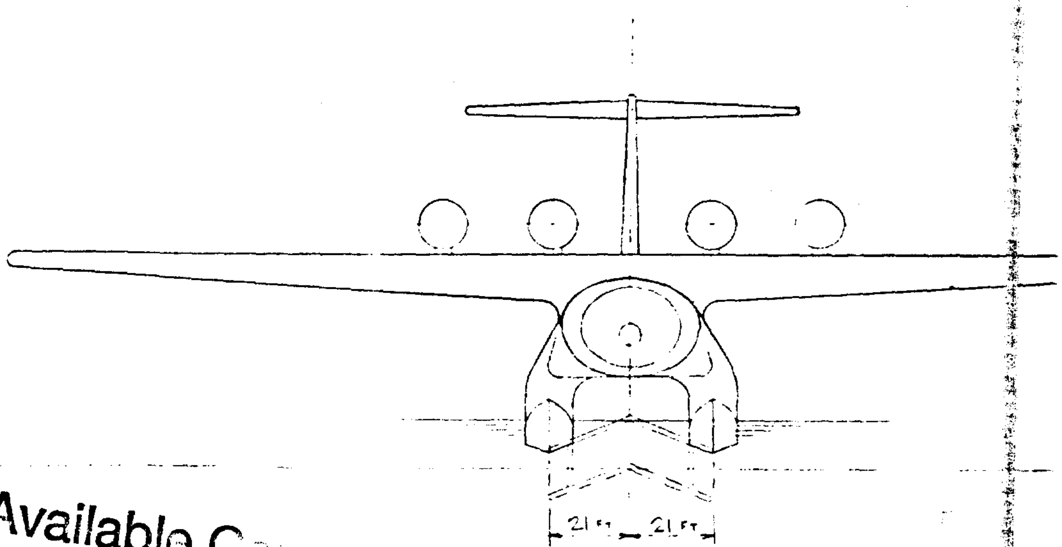
SPAN 317.3 FT

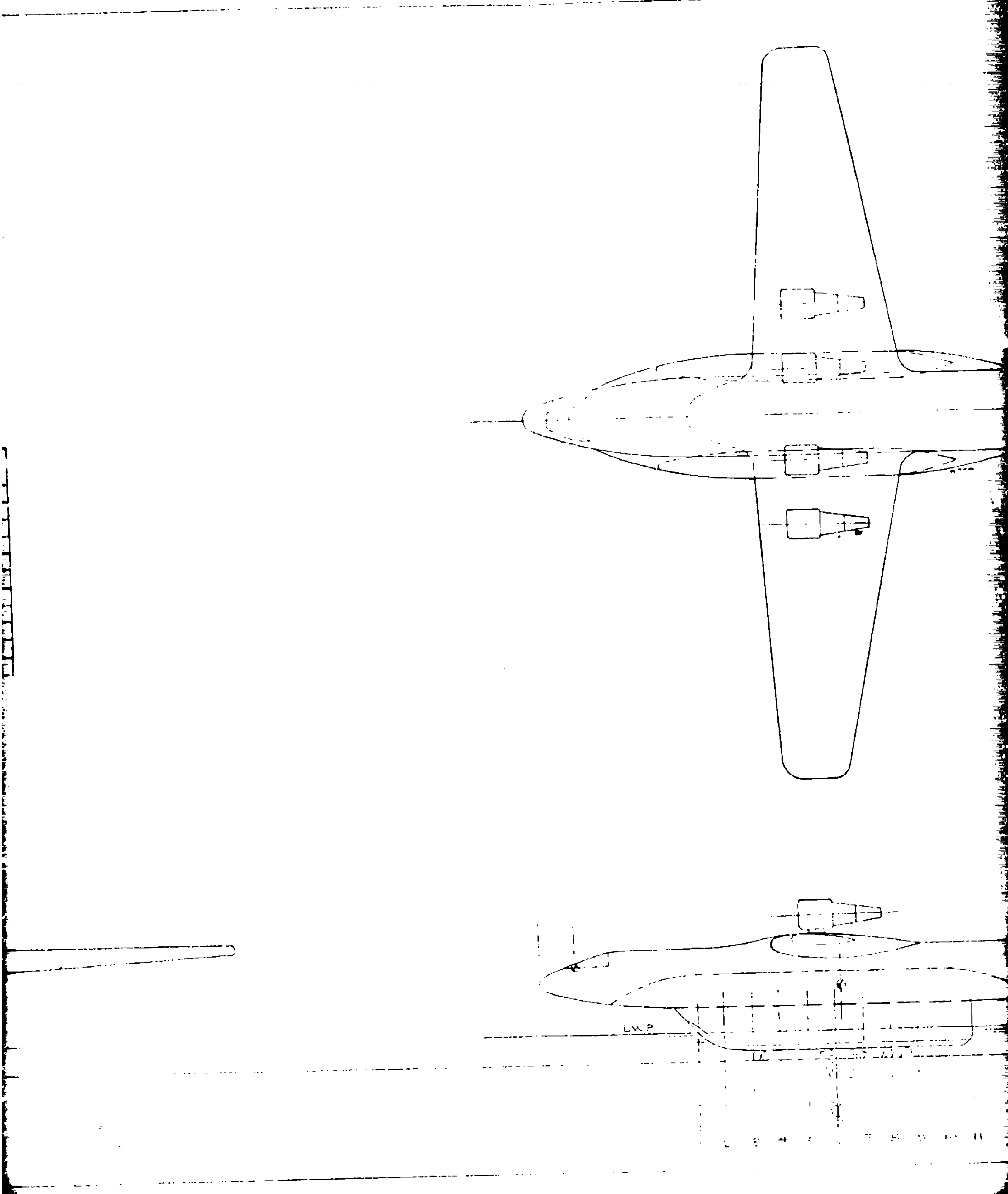
LENGTH OVERALL 327.0 FT

DATA FOR SEAKEEPING PROGRAM

NO OF STATIONS	11.0	PER FLOAT
LENGTH	120.0 FT	PER FLOAT
BEAM	12.0 FT	PER FLOAT
DRAFT	9.75 FT	PER FLOAT
X_{CG}	-3.3 FT	
Z_{CG}	-10.0 FT	
k_{YY}	705.0 IN	
COCKPIT LOCATION	115.0 FT FWD OF ℄	
	30.0 FT FREEBOARD	

STN NO	BEAM (FT)	DRAFT (FT)	SECTIONAL AREA (FT²)	DIST. BTWN STNS (FT)
1	0	0	0	↓
2	7	6.6	39.2	
3	10	7.5	65.0	
4	12	9.75	105.0	STNS
5	↑	↑	↑	SPACED
6				12 FT
7				APART
8	↓		↓	
9	12	↓	105.0	
10	6.98	9.75	61.15	↓
11	0	0	0	





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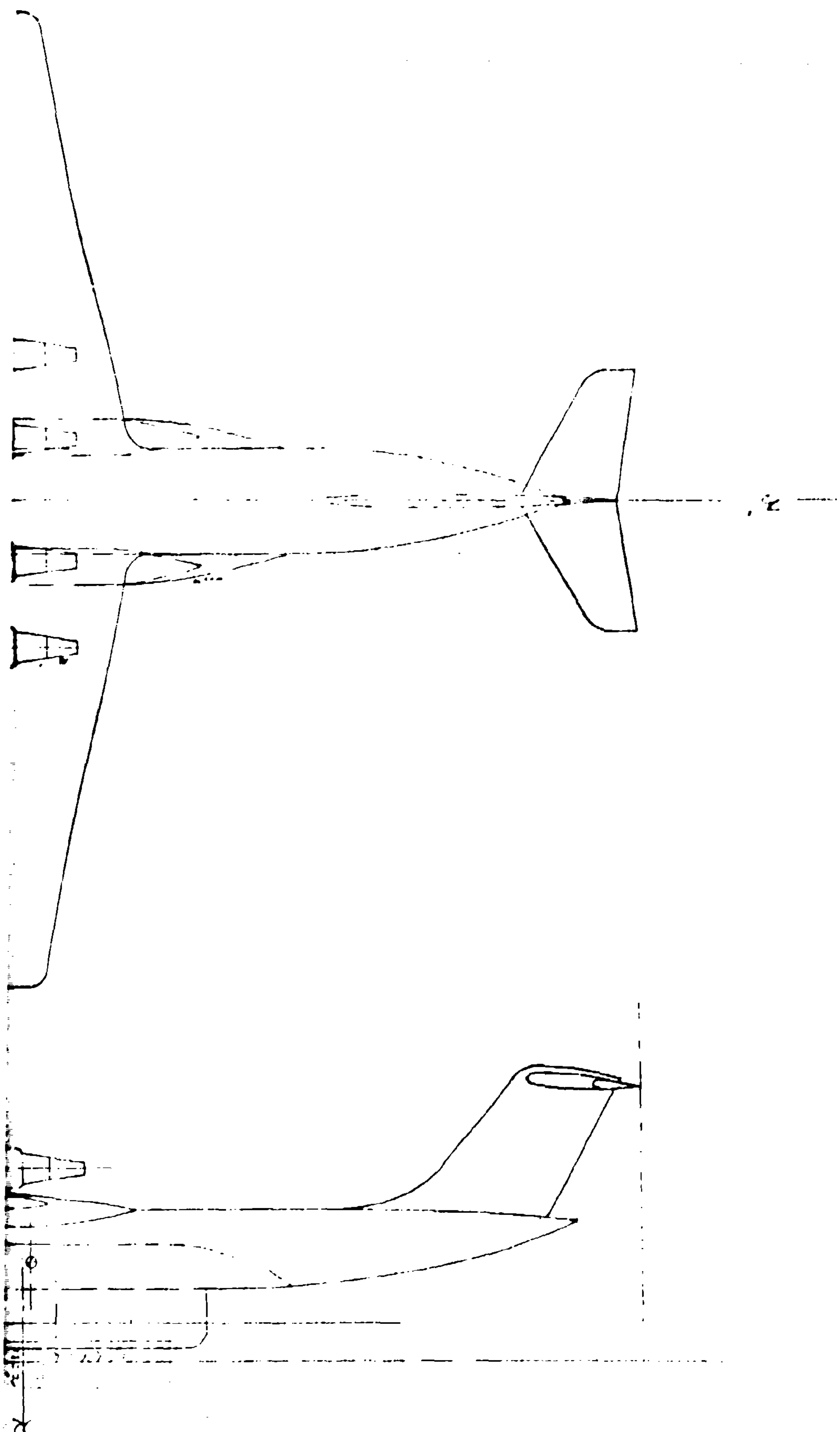

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COI

180

CTC
CAT

SCA

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FIGURE 1

CONFIGURATION 1

1801 - 018

CTOL

CATAMARAN - [illegible]

SCALE 1 - 1/200 [illegible]

[illegible] 6

3.2 Configuration 2, CTOL Single Hull, .769M Lb TOGW

Configuration 2, shown in Figure 2, is a large 769,000 pound TOGW conventional takeoff and landing single hull sea based aircraft design. The configuration has a wing loading of 124 PSF and a wing area of 6,200 square feet. Considering an engine thrust of 41,100 lbs per engine, the takeoff thrust to weight is .214.

3.3 Configuration 3, C/STOL DT-NSRDC Model, 330 Lb TOGW

Configuration 3, shown in Figure 3, is a David W. Taylor Naval Ship Research and Development Center (DT-NSRDC) model configuration presently undergoing model basin tests. The model is a 1/5th scale model with a weight of 330 lbs. The full scale weight is 41,250 lbs.

3.4 Configuration 4, VTOL X-Wing, 25K Lb. TOGW

Configuration 4, shown in Figure 4, is a stopped rotor helicopter design with two outboard fans for forward flight and two internal inboard engines. The two internal inboard engines drive the outboard fans in forward flight on decoupling with the rotor. Static on water roll stability is provided by an active roll control mechanism not shown on the drawing. This could be provided with a small propeller mounted on a shaft below the helicopter. An engine start APU would be used for continuous on-water power for roll stabilization.

3.5 Configuration 5, V/STOL Twin Boom, 40K Lb TOGW

Configuration 5, shown in Figure 5, is a Type A class V/STOL configuration for use aboard vertical support ships and on-water. The concept includes a thrust augmented wing for vertical takeoff and landing and a propulsive wing concept for cruise flight. The configuration has a wing loading of 72.5 PSF and a wing area of 552 square feet.

3.6 Configuration 6, V/STOL Twin Boom, 25K Lb. TOGW

Configuration 6 is a scaled version of Configuration 5 (except for the cockpit area) and is representative of a Type C class V/STOL configuration for use aboard destroyers and on-water. The configuration has a wing loading of 71.4 PSF and a wing area of 350 square feet (see Figure 6).

3.7 Configuration Head Seas Seakeeping Data

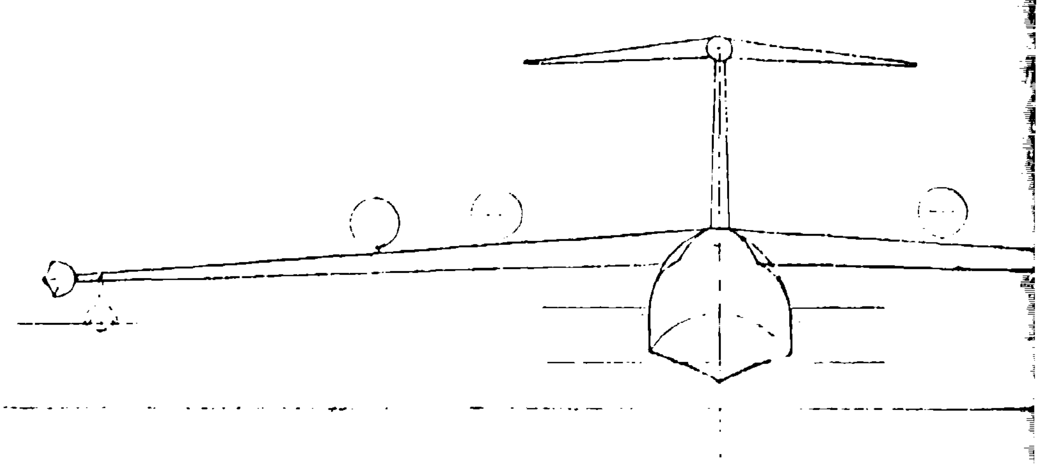
The head seas on-water motion analysis was performed using the data contained in Figures 1 through 6 for the six respective configurations of Table 1. The head seas on-water motion analysis data is summarized in Table 2. Note that the pitch radius of gyration (Kyy) of configurations

TOGW	769000 LBS
SPAN	222.7 FT
LENGTH OVERALL	237.9 FT

DATA FOR SEAKEEPING PROGRAM

Nº OF STATIONS	17
LENGTH	170.0 FT
BEAM	25.0 FT
DRAFT	17.12 FT
X_{CG}	3.38 FT
Z_{CG}	−7.0 FT
k_{YY} [illegible]	[illegible].9 IN
COCKPIT LOCATION	85.2 FT FWD OF ℄ 16.5 FT FREEBOARD

STN Nº	BEAM (FT)	DRAFT (FT)	SECTIONAL AREA (FT²)	DIST BTWN STNS (FT)
1	0	0	0	
2	14.6	3.5	26	
3	20.0	4.0	40	
4	25.0	4.8	69	
5		5.1	82	
6		5.6	95	STATIONS
7		6.2	114	SPACED
8		7.0	127	10.625
9		7.12	139	APART
10		7.10	101	
11		6.36	87	
12		5.52	69	
13		5.2	65	
14	25.0	4.0	50	
15	22.5	2.5	38	
16	18.0	1.7	29	
17	0	0	0	



TWN
(FT)

ONS
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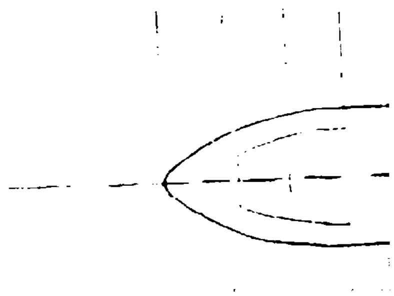
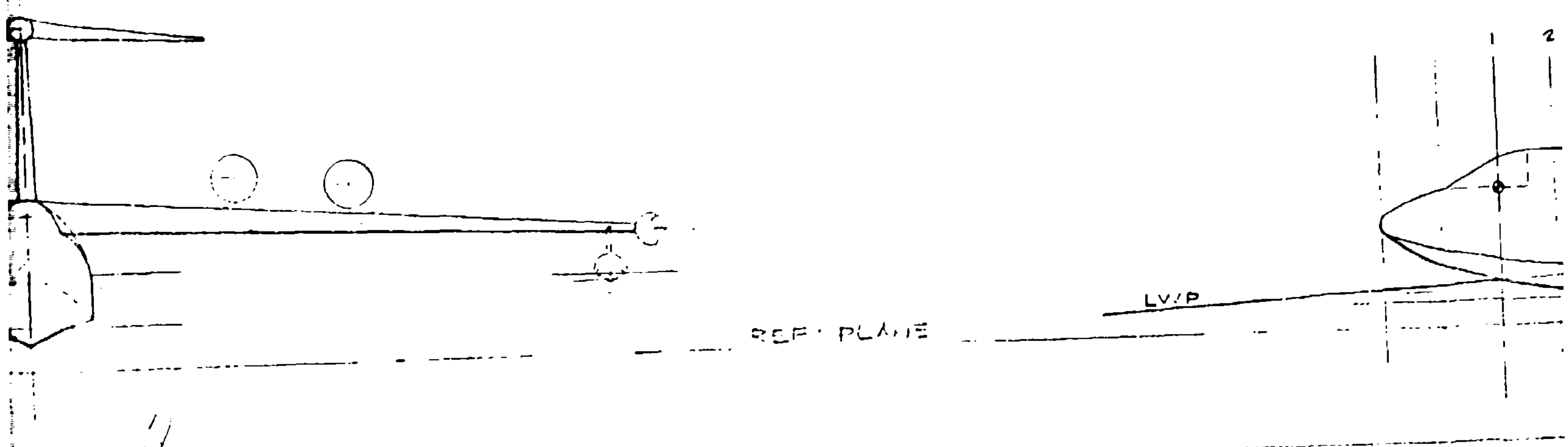
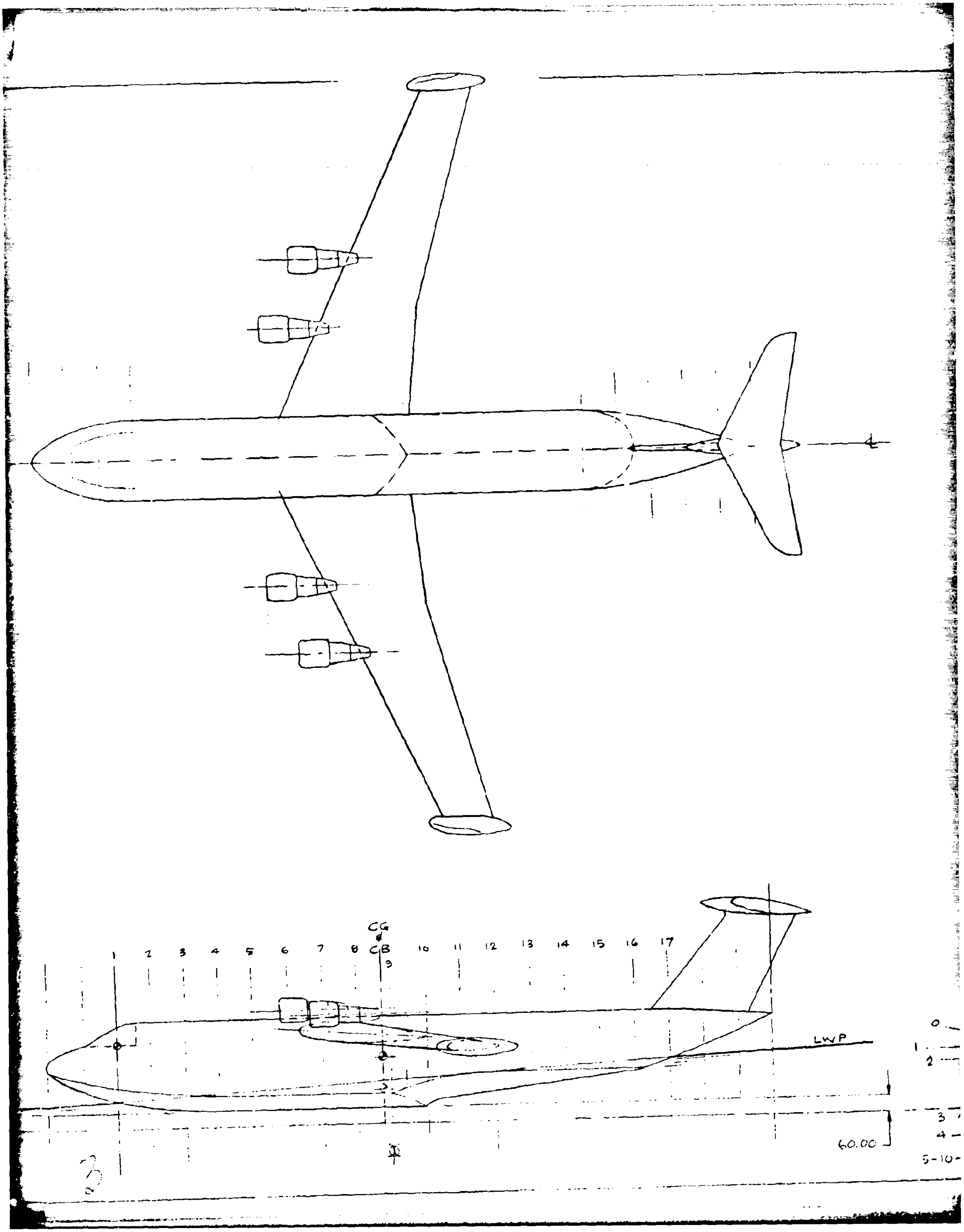
625
RT







CG
CB
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
LWP
0
1
2
3
4
60.00

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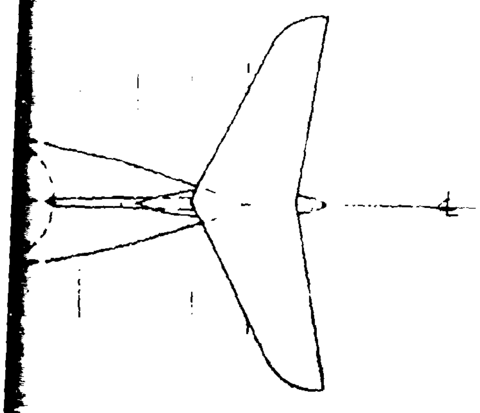


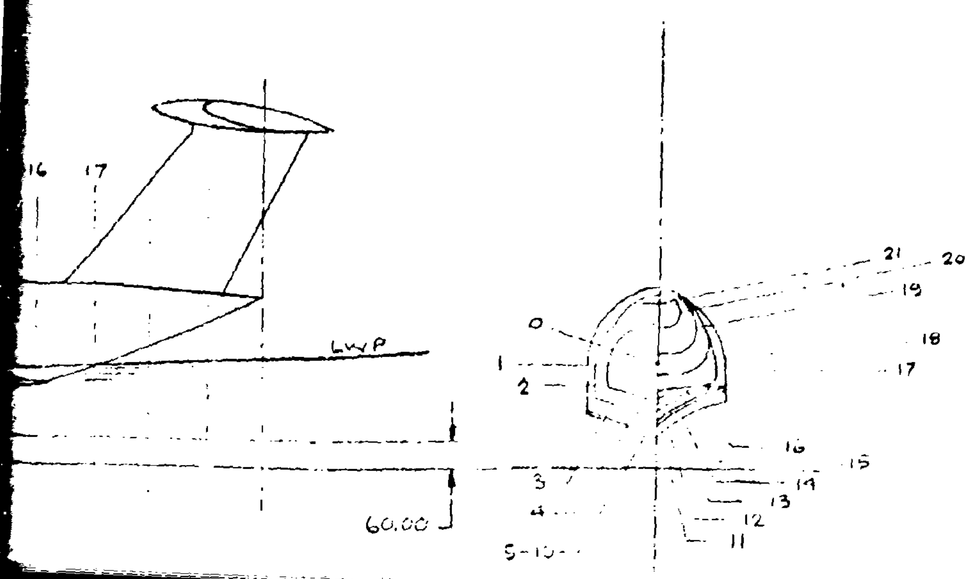


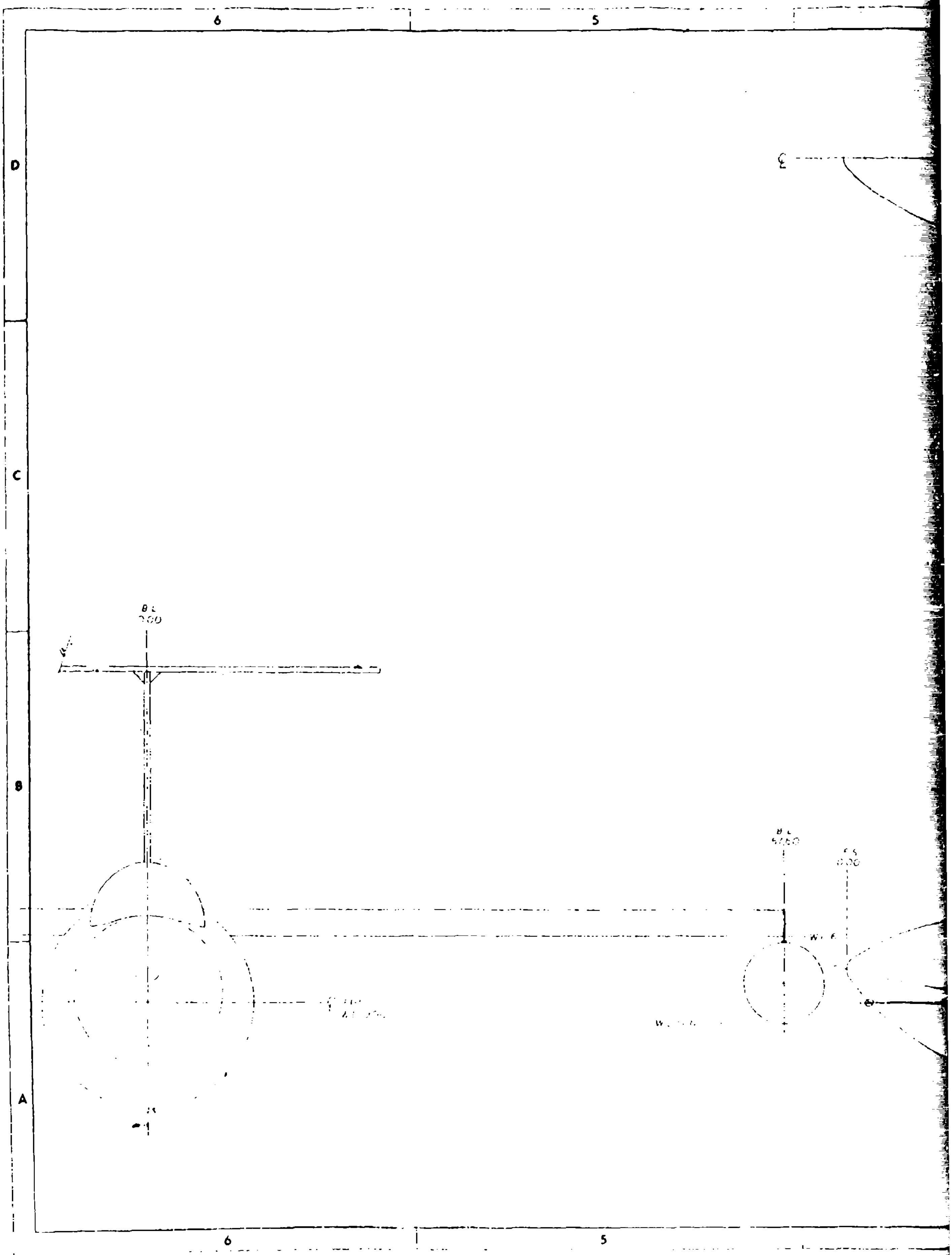
FIGURE 2

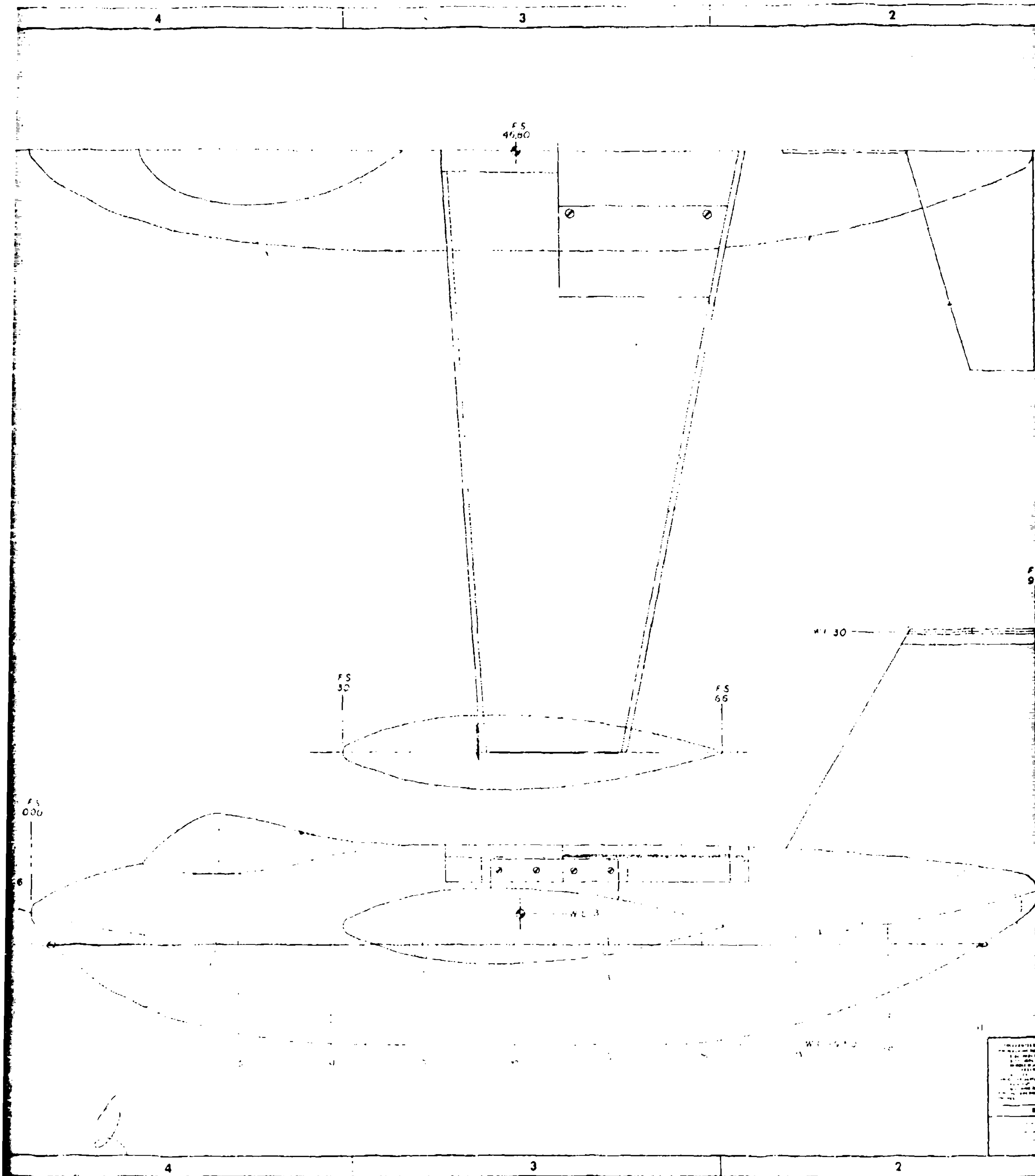
CONFIGURATION 2

8

1801-015
CTOL
SINGLE HULL - 769000 LBS.
SCALE :- 1/240 (1" = 20 FT)
I INGLIS 9/30/76

4


6
5
D
C
B
A


4
3
2
FS 46.60
FS 96
WL 30
FS 30
FS 66
FS 0.00
WL 3

NR 76H-137

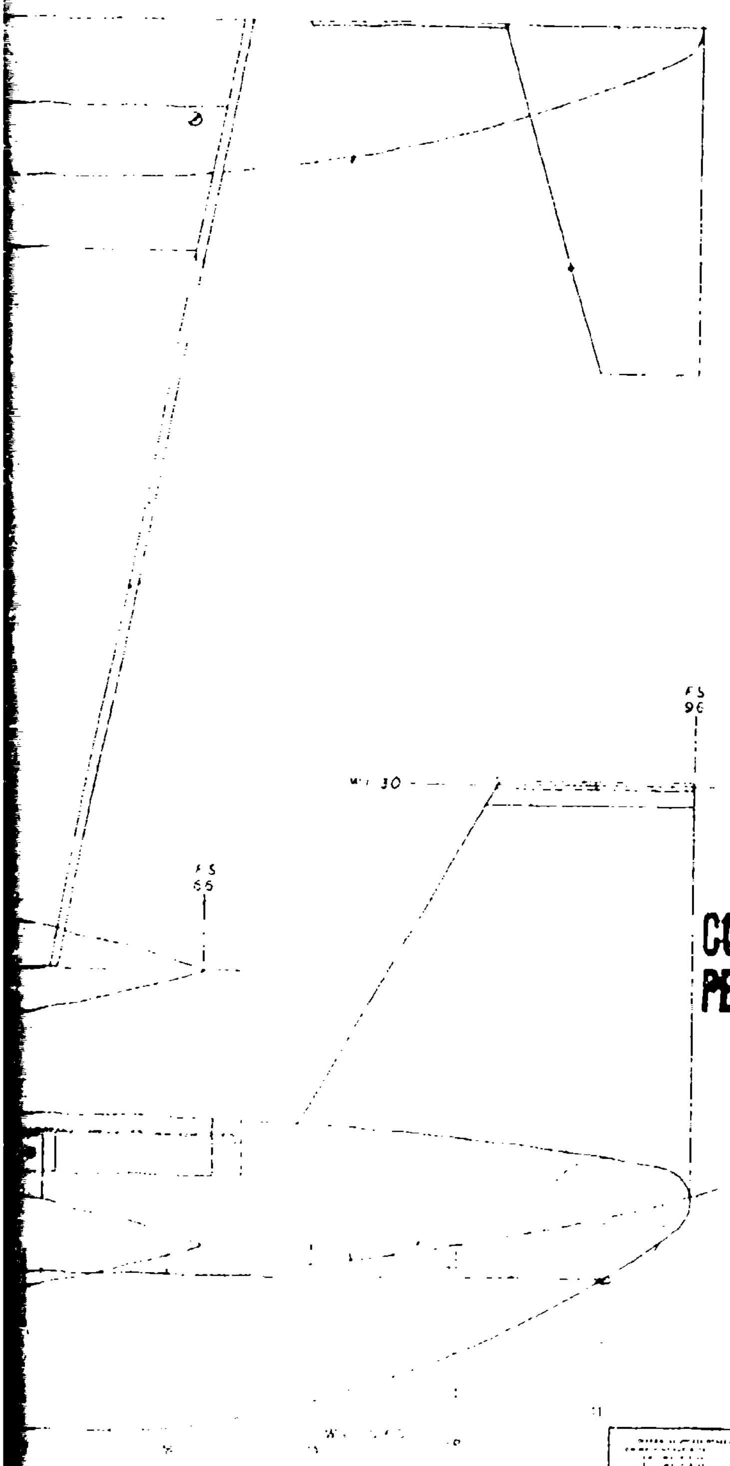


FIGURE 3

CONFIGURATION 3

BEAM .... 84 IN

DRAFT .... 21 IN AT FS 0, 53 IN AT FS 706

LOAD WATER PLANE AREA .... 44410 IN^2

LOAD WATER PLANE CG .... FS 260

CB .... FS 318, 2 IN BELOW LWP

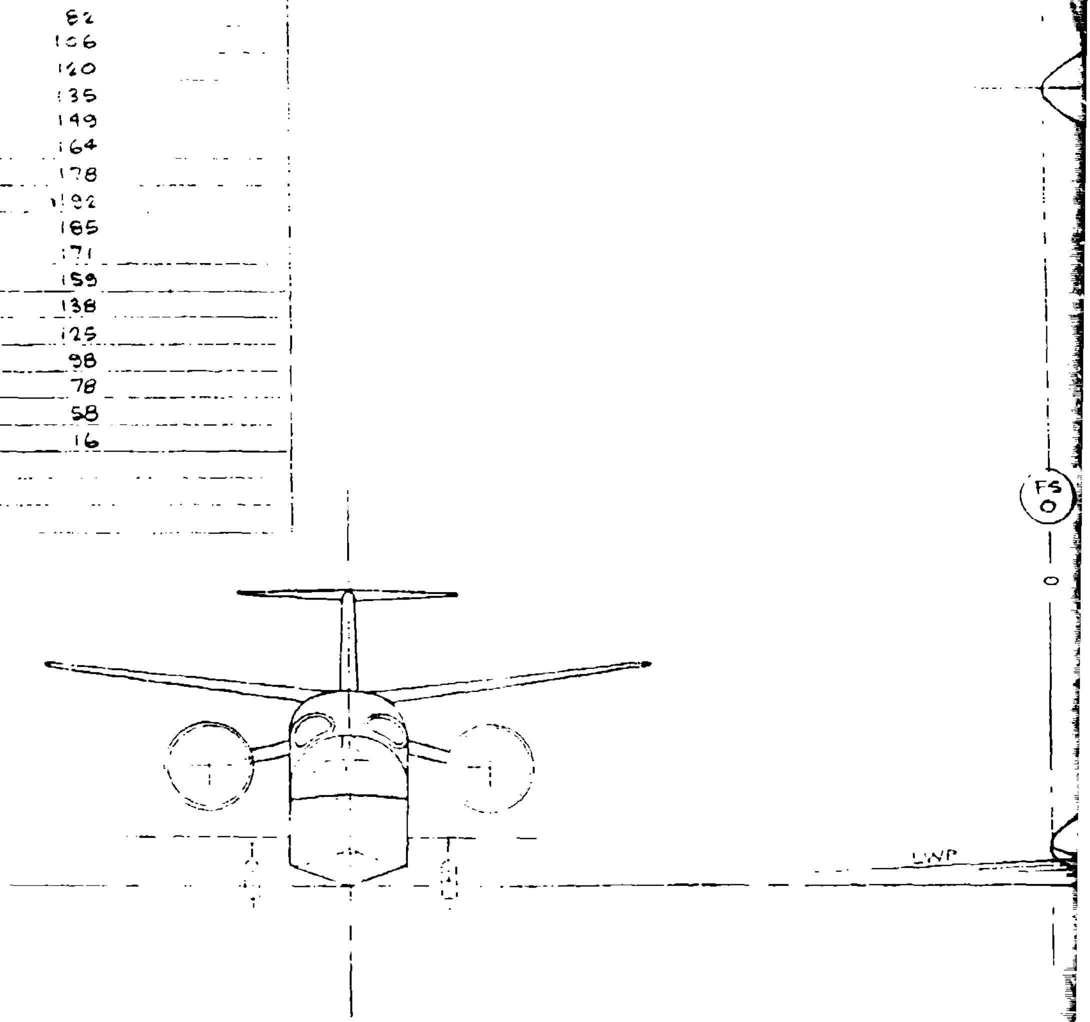
CG .... FS 318, 64 IN ABOVE REF PLANE

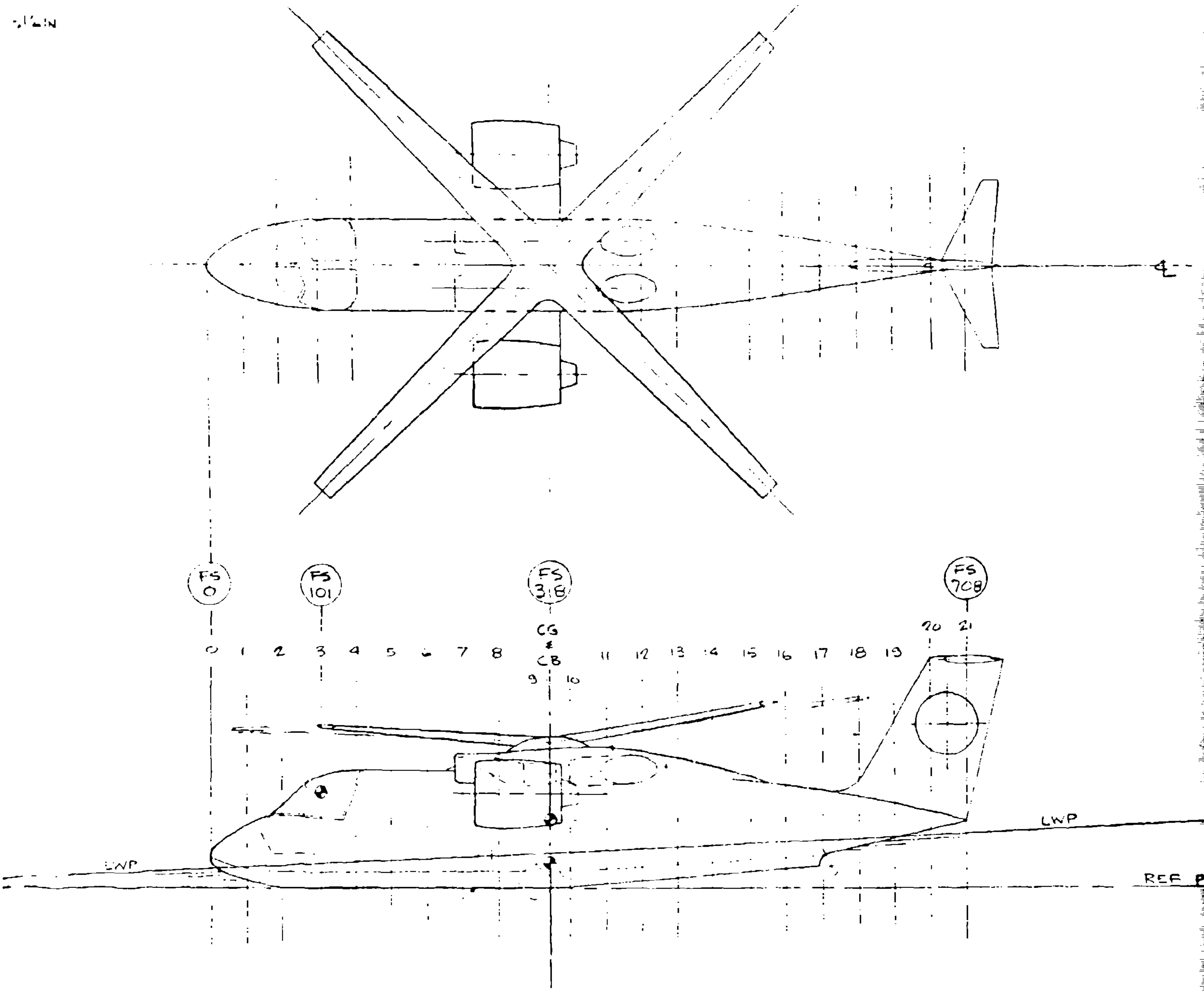
COCKPIT LOCATION .... FS 101, 66 IN FREEBOARD

MAX TAKE OFF GROSS WT .... 40000 LBS

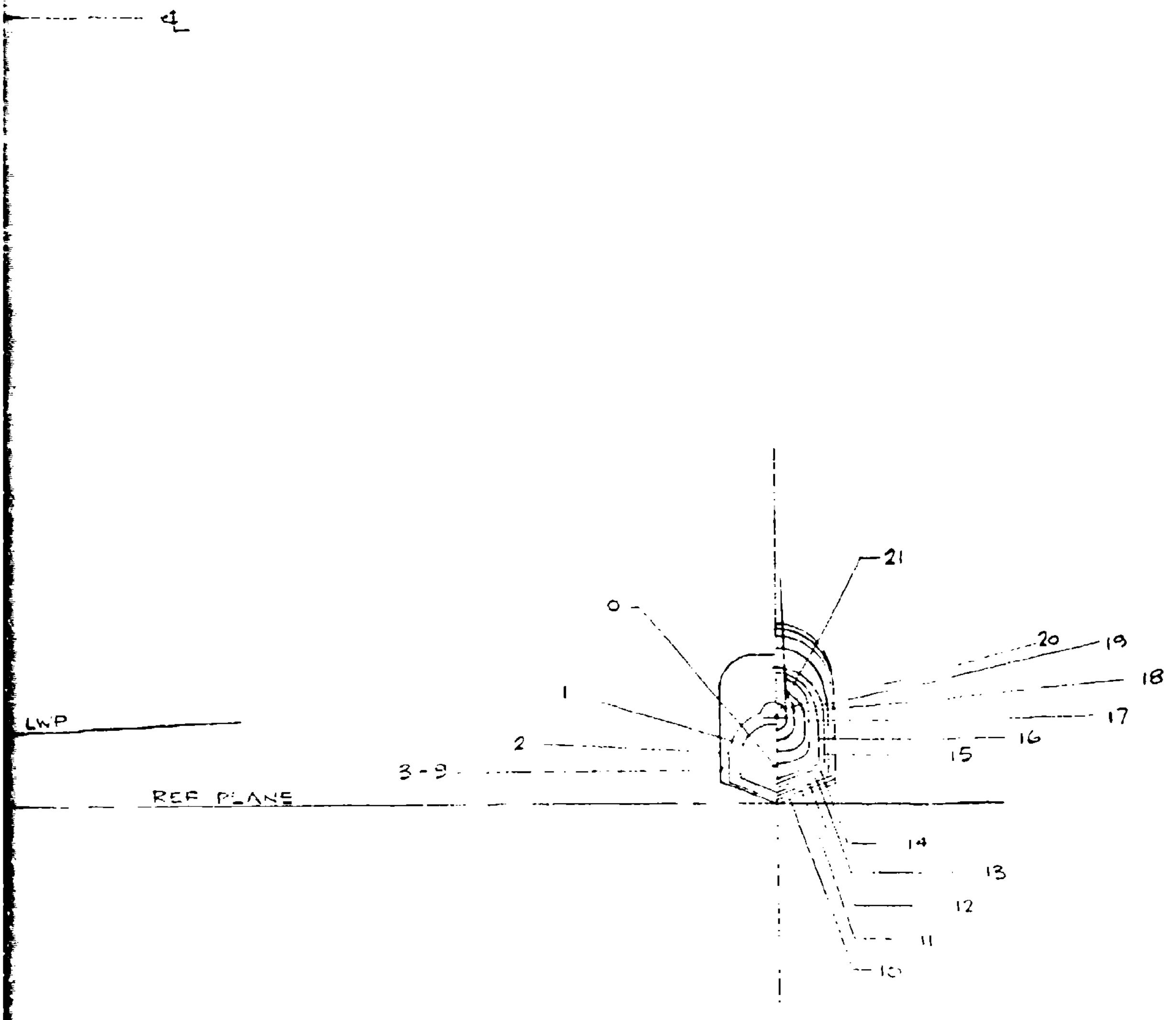
RADIUS OF GYRATION .... k_{xx} = 18.48 IN, k_{yy} = 17.40 IN, k_{zz} = 24.12 IN

21 SECTIONS EQUALLY SPACED BETWEEN FS 0 & FS 708	
SECT^N NO	AREA (IN^2) BELOW LWP
0	
1	33
2	82
3	106
4	120
5	135
6	149
7	164
8	178
9	192
10	185
11	171
12	159
13	138
14	125
15	98
16	78
17	58
18	16
19	
20	
21	





℄
FS 0
FS 101
FS 318
FS 708
CG & CB
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
LWP
LWP
REF



1/78 SCAL

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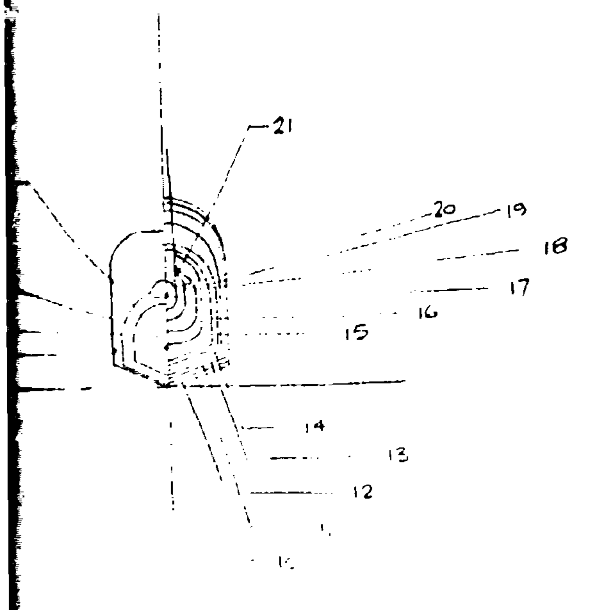


FIGURE 4

CONFIGURATION 4

1801-017
SEA LOITER V/S
"X"- WING

1/78 SCALE 0 50 300 IN

TOGW 40000 LBS

SPAN 756 IN

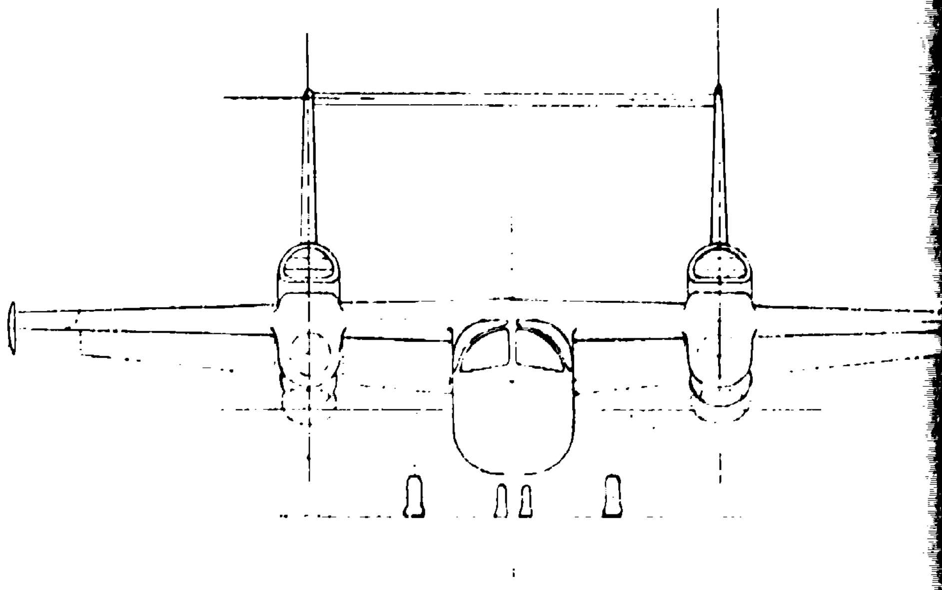
LENGTH (OVERALL) 670 IN

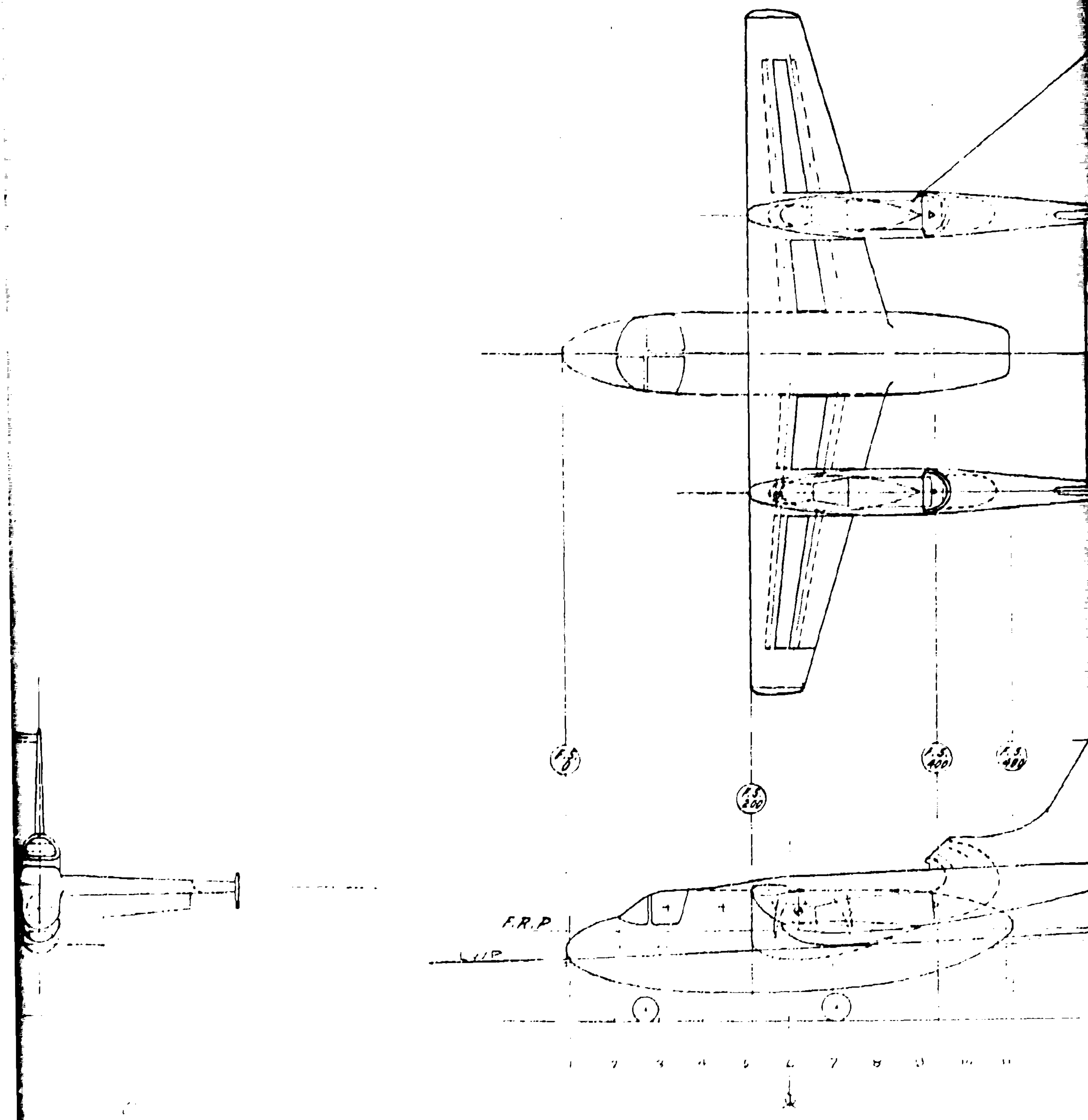
DATA FOR SEAKEEPING PROGRAM

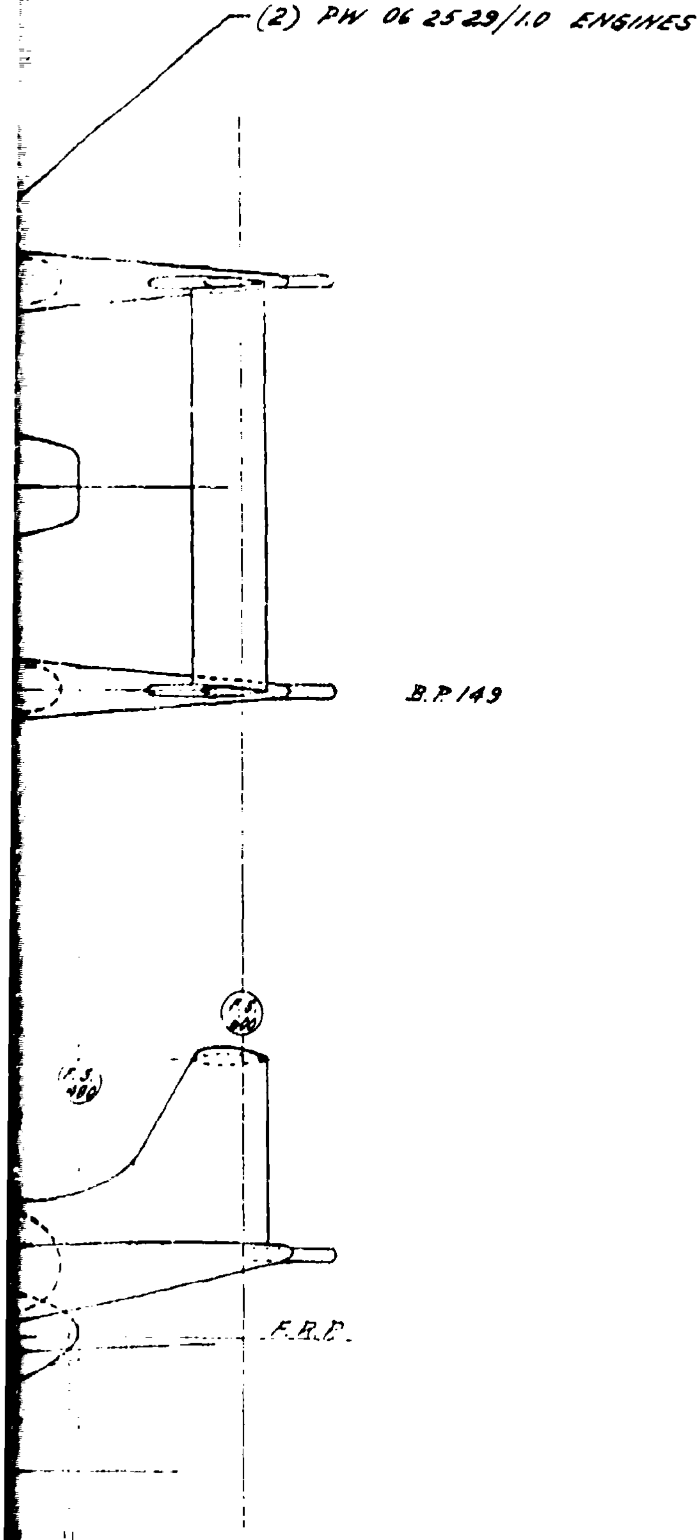
NO OF STATIONS 11.0

LENGTH	47[illegible] IN	(39.17 FT)
BEAM	88.0 IN	(7.33 FT)
DRAFT	42.0 IN	(3.5 FT)
Y_{CG}	− 6.5 IN	(− 0.542 FT)
Z_{CG}	− 40.0 IN	(− 3.33 FT)
K_{YY}	104.3 IN	([illegible] FT)
COCKPIT LOCATION	66.0 IN FWD OF ℄; 34.0 IN FREEBOARD	

STN NO	BEAM (IN)	DRAFT (IN)	SECTIONAL AREA (IN²)	DIST. BTWN STNS (IN)
1	0	0	0	
2	62	19	912	
3	80	31	2108	
4	88	35	2800	STNS SPACED 47 IN APART
5	86	39	3160	
6	88	42	3400	
7	88	44	3520	
8	88	43	3440	
9	85	40	3080	
10	68	26	780	
11	0	0	0	




F.S. 0
F.S. 200
F.S. 400
F.R.P



WING

S_W	552 FT^2
AR	6.7
λ	0.35
Λ_{LE}	0°
t/c	18% sc

HORIZONTAL TAIL

S_H	110 FT^2
AR	5.3
λ	1.0
Λ_{LE}	0°
t/c	12.5%

AUGMENTER (EA. PANEL)

A_2	4649 IN^2
A_0	310 IN^2
A_2/A_0	15
l/d	1.5
ϕ	1.65

VERTICAL TAIL

S_V (EA)	95 FT^2
AR	1.56
λ	0.38
Λ_{LE}	30°
t/c	10.5

FIGURE 5

CONFIGURATION 5

1801 - 013
V/STOL SEABASED AIRCRAFT
PROPULSIVE WING TWIN BOOM
40000 LBS TOGW
SCALE :- 1/80

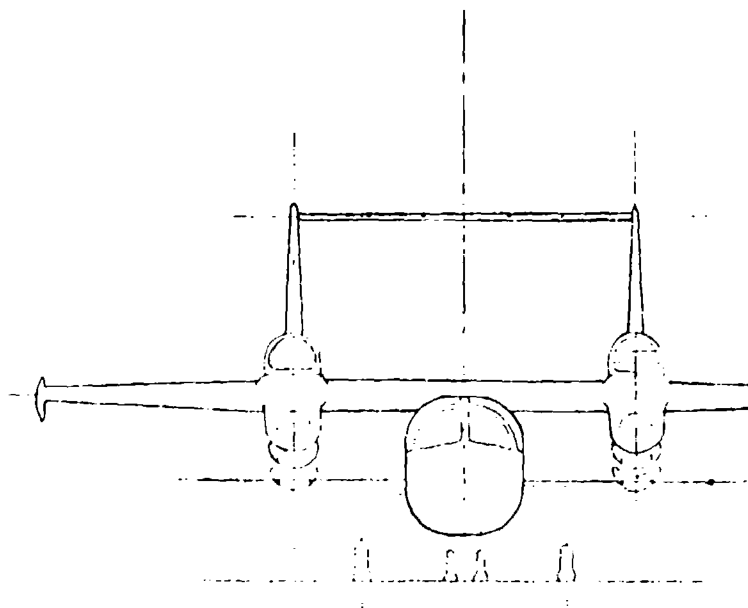
C. GREER 9/8/76

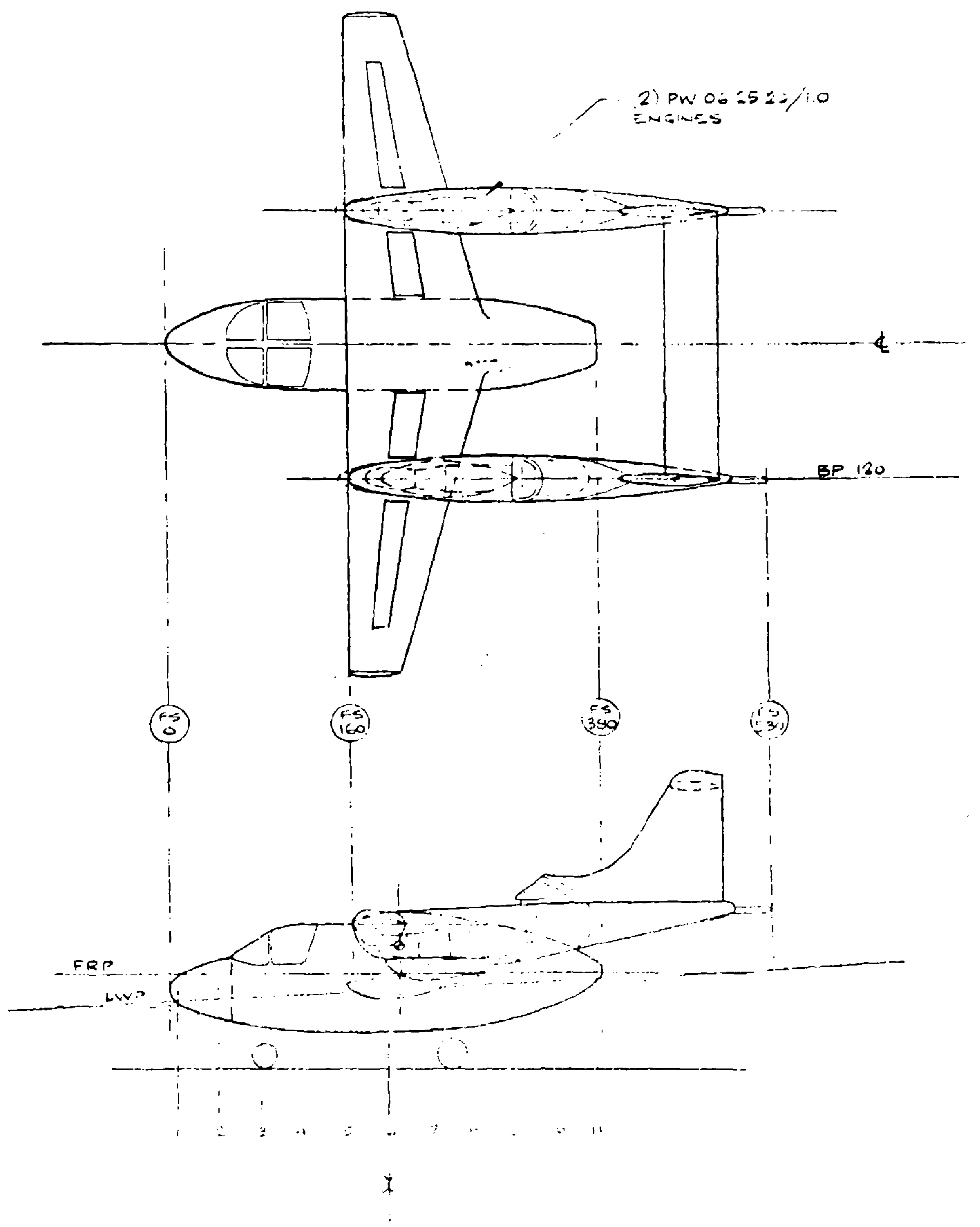
TOGW	25000	LBS
SPAN	600	IN
LENGTH (OVERALL)	530	IN

DATA FOR SEAKEEPING PROGRAM

Nº OF STATIONS	11.0	
LENGTH	370.0 IN	(30.83 FT)
BEAM	80.0 IN	(6.67 FT)
DRAFT	37.0 IN	(3.08 FT)
Y_{CG}	− 7.1 IN	(− .592 FT)
Z_{CG}	−40.0 IN	(−3.33 FT)
K_{YY}	121.4 IN	(10.12 FT)
COCKPIT LOCATION	115.0 IN FWD OF ℄ 30.0 IN FREEBOARD	

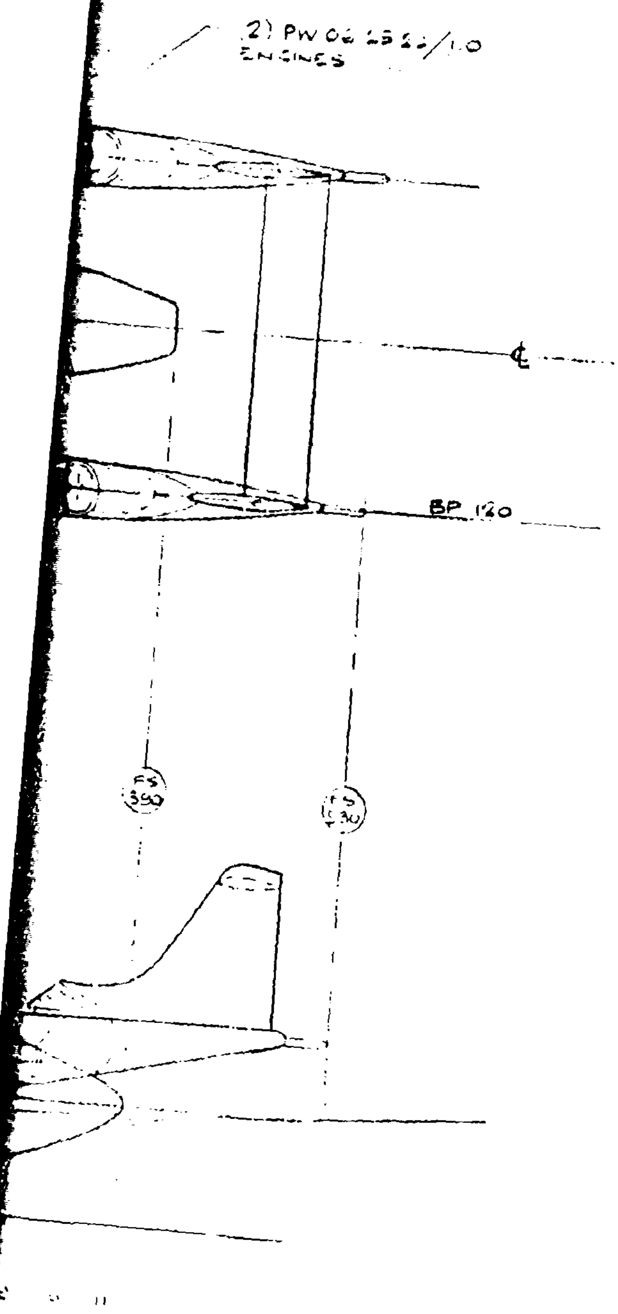
STN Nº	BEAM (IN)	DRAFT (IN)	SECTIONAL AREA (IN²)	DIST. BTWN STNS (IN)
1	0	0	0	STNS SPACED 37 IN APART
2	60	17	714	
3	73	25	1625	
4	80	31	2294	
5	80	35	2590	
6	80	37	2738	
7	80	39	2886	
8	80	36	2664	
9	77	31	2201	
10	62	20	840	
11	0	0	0	





ENGINES
BP 120
FS 0
FS 160
FS 390
FRP

NR 76H-137



WING

S_w	350 FT^2
AR	7.2
λ	0.35
Λ_{LE}	0°
t/c	18% SC

AUGMENTER (EA PANEL)

A_2	2910 IN^2
A_0	194 IN^2
A_2/A_0	15
ℓ/d	1.5
φ	1.65

HORIZONTAL TAIL

S_H	69 FT^2
AR	4.87
λ	1.0
Λ_{LE}	0°
t/c	15.5%

VERTICAL TAIL

S_V (EA)	59 FT^2
AR	1.56
λ	0.28
Λ_{LE}	30°
t/c	10.5

FIGURE 6

CONFIGURATION 6

1801-019
V/STOL SEA BASED AIRCRAFT
PROPULSIVE [illegible], TWIN [illegible]
25000 LB [illegible] TOGW
SCALE [illegible]

5 and 6 indicate that as configurations are scaled down in weight from 40,000 lb TOGW to 25,000 lb TOGW, the moment of inertia decreases from 95,000 slug-ft^2 to 80,000 slug-ft^2 and K_{yy} increases from 8.72 to 10.12. Here, weight is decreasing faster than the moment of inertia with a consequent increase in radius of gyration.

Note also that the pitch radius of gyration of Configuration 4, the X-wing is taken at the same value of Configuration 6, the twin boom fixed wing aircraft. These values were estimated based on inputs from manufacturers of single rotor helicopters to be comparable (in pitch) to that of fixed wing aircraft.

4.0 HEAD SEAS ON WATER MOTION ANALYSIS

The head seas on-water motion analysis consisted of determining the sea keeping parameters of six different configurations (sectional area and water plane area distributions, center of buoyancy, metacentric height, etc.) and performing a regular waves, head seas computerized analysis of heave, pitch, acceleration (of the cockpit and c.g.) and cockpit wetness. The computerized analysis was based on the computer program described in Reference 2 The computer program provides predicted seakeeping behavior in regular waves and in a seaway (irregular waves). The initial form of the computer program was presented in 1969 by Dr. Robert Beck (see Reference 3).

Table 2 summarizes the physical characteristics that most directly influence seakeeping performance for the six configurations under consideration. Both model and full scale (F.S.) data is provided on configuration No. 3, the David Taylor-Naval Ship Research and Development Center (DT-NSRDC) design. All terms are defined in Section 7.0, Definitions.

Acceptable on-water motions are primarily influenced by the following parameters:

(i) $\frac{K_{YY}}{L}$ the ratio of the radius of gyration to the water line length of the hull or float. A value of $\leq .25$ is desirable for acceptable pitch motion.

(2) L the waterline length. The longer the waterline length, the less the craft is influenced by short length waves. As the sea state increases, even long craft (e.g. 200 feet in length) are influenced and eventually these craft will contour the waves too. Super tankers and large ships of course don't contour the waves. Extreme bending moments must be counteracted if the craft does not follow the wave contour. This bending moment is proportional to the wave height associated to the wave length that equals the waterline length of the craft (see Appendix 1).

(3) $\overline{GM}$ the metacentric height. A positive $\overline{GM}$ is required for inherent static stability. Roll is most critical (GM_R). Configurations 3 through 6 are all unstable in roll without wing tip floats. Configuration 4 has no roll static stability and is dependent on an active roll control device. The metacentric height in roll, $\overline{GM}_R$, shown in Table 2 is for the hull only.

Of particular interest to head seas pitching motion is the relationship of the radius of gyration in pitch, K_{YY} to the waterline length, L (see last row of Table 5). Configurations 2 through 5 all have a ratio of K_{YY}/L of .22 to .24. Configuration 6, the 25,000 lb V/STOL twin boom has a K_{YY}/L ratio of .33. Configuration 1, the 1.25 $\overline{M}$ lb CTOL Catamaran has a K_{YY}/L ratio of .49, considered unacceptable for good head seas pitch motions. A good value of K_{YY}/L is considered to be .25. The combination of high radius of gyration (high mass inertia), high c.g. and short float length (120 feet) and limited beam (12 feet) for configuration 1, result in a poor combination of design characteristics for head seas pitch motion (see Section 5.0). A doubling of float length and water plane area for configuration 1 would decrease K_{YY}/L to .25. This change is considered necessary to provide acceptable pitch motions in head seas for configuration 1.

The predicted heave, pitch and acceleration motions of the six study configurations are shown in Figures 7, 8 and 9. The actual characteristics of these configurations as run on the computer varied somewhat from design conditions. These characteristics are shown in Table 6 for reference. Significant differences are discussed in the following pages. The heave motions at the c.g. (Figure 7) are almost identical for all comparable weight craft. Configurations 3 through 6 are comparable in weight, heave frequency and length and the heave motions are very similar. They represent "pure wave following concepts" where the significant heave is equal to the significant wave height for all sea states.

For reference, a FF 1040 (DE 1040) of 2620 tons (5.24$\overline{M}$ lbs) and 414.5 ft length at 20 knots heave curve is shown. As indicated, heave is reduced in proportion to the length of the craft as weight increases.

Figure 8 shows significant pitch at head seas for all six study configurations at zero and 5 knots forward speed. Configuration 2 has the best pitch characteristics and configurations 1 and 6 the worst. Configurations 3, 4 and 5 show curves of significant pitch vs significant wave height that are very typical of wave following concepts. The RMS wave slope is about 6 to 7 degrees from sea states 6 to 7 (see Appendix 1). For reference, a curve of significant pitch for a DE 1040 is also shown.

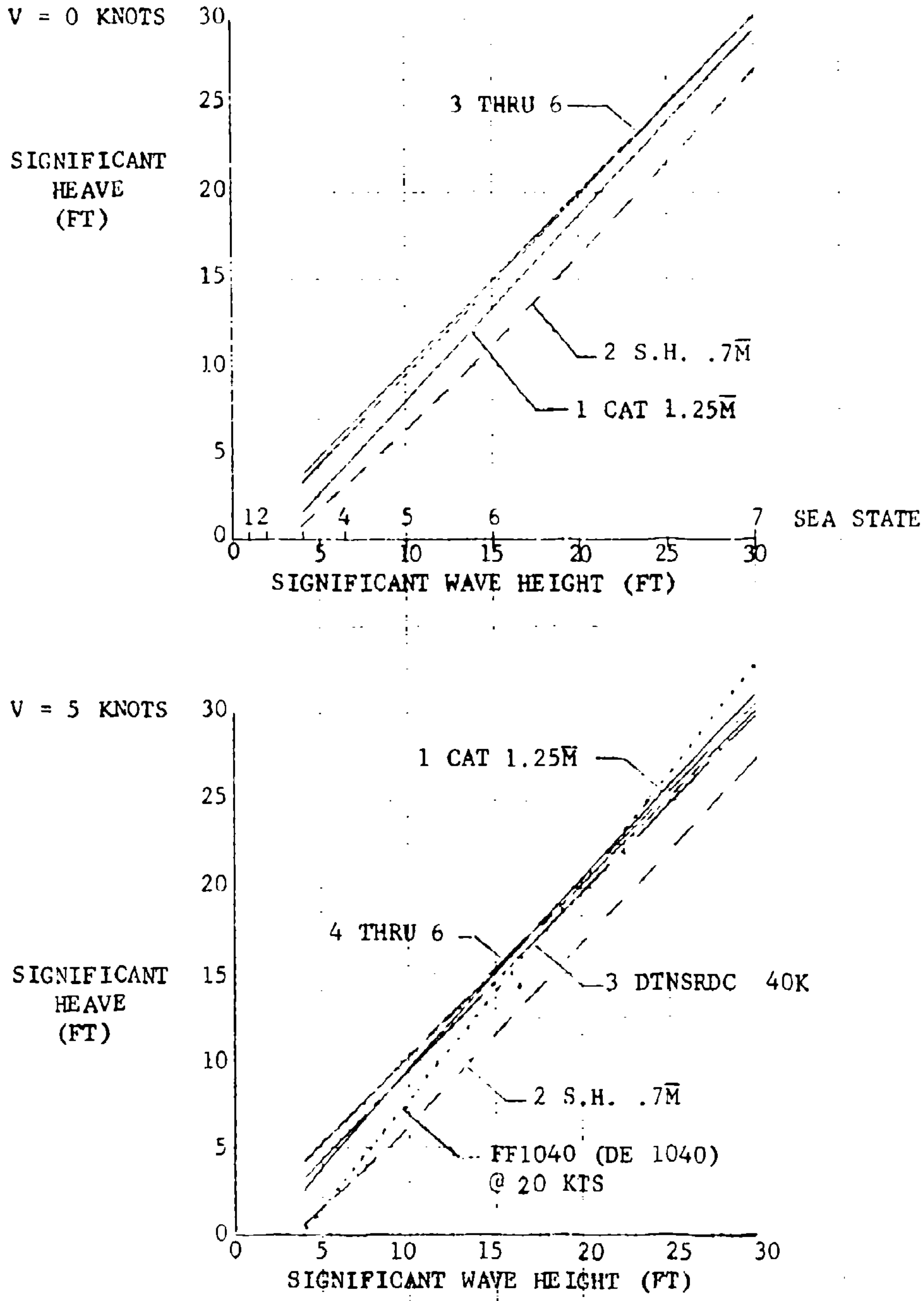
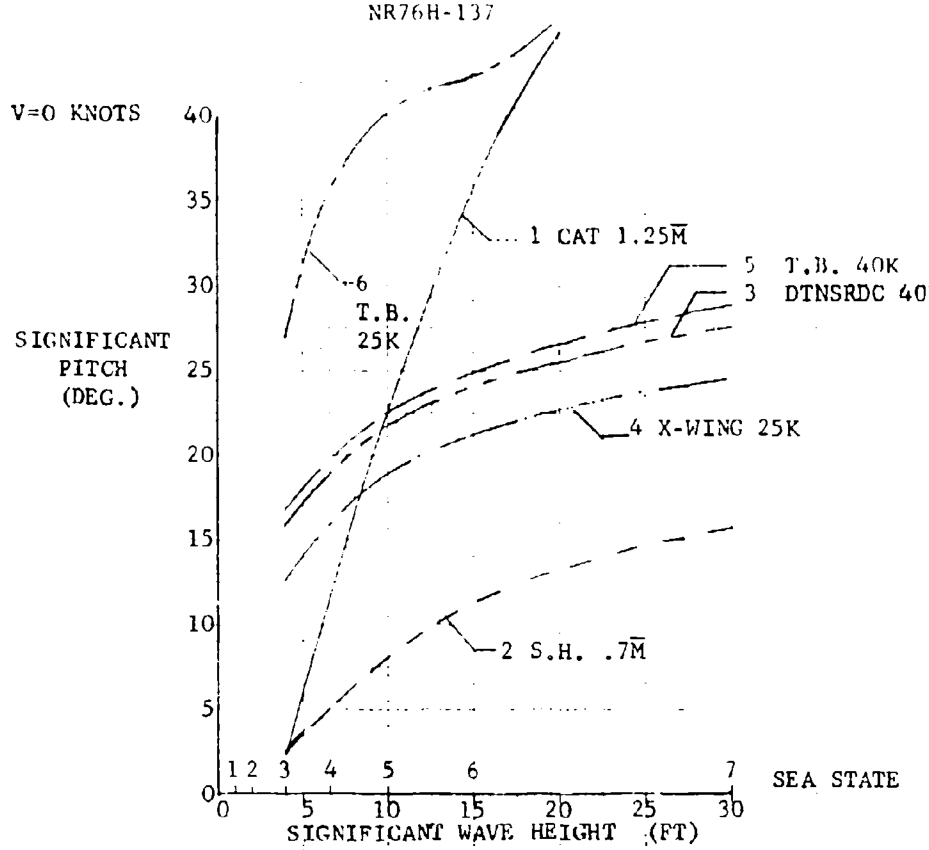


Figure 7. Significant Heave - Head Seas



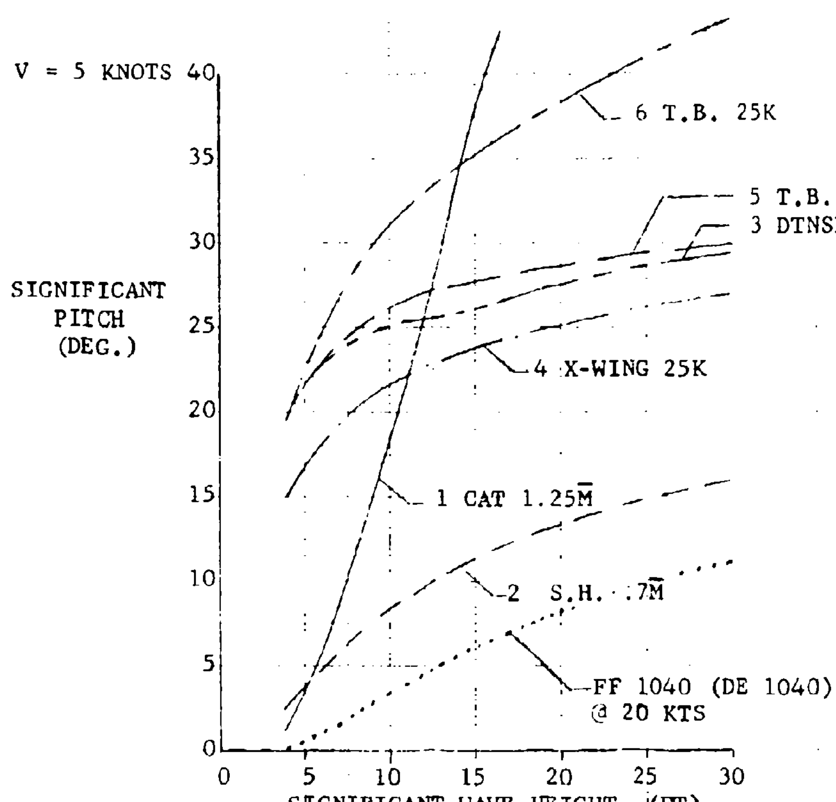


Figure 8. Significant Pitch - Head Seas

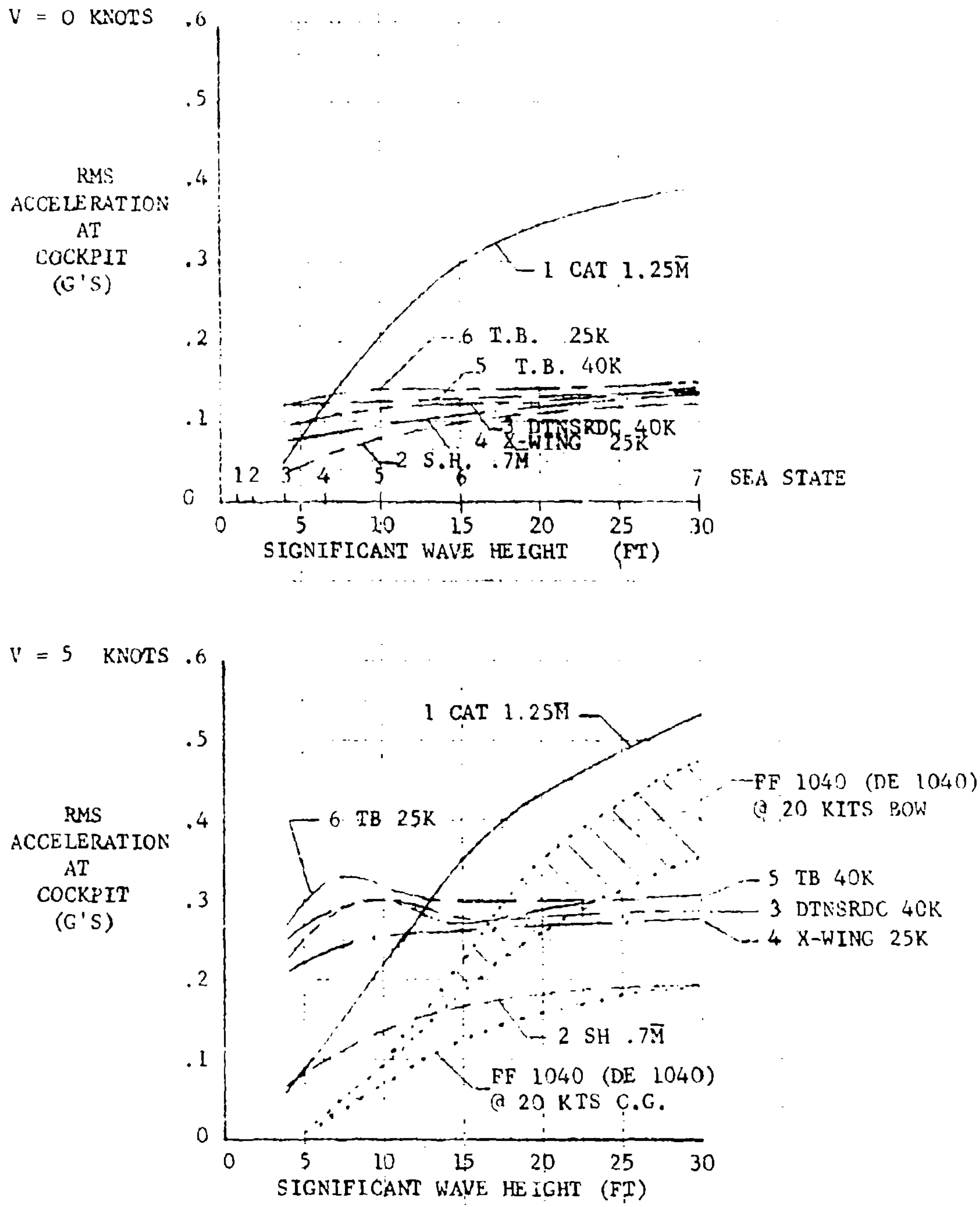


Figure 9. RMS Acceleration at Cockpit - Head Seas

Figure 9 is the RMS acceleration motions of the cockpit locations in g's for the study configurations at zero and 5 knots forward speed. Configuration 2 has the lowest accelerations for all sea states of the configurations studied. This is due to its size and length. Except for configurations 1 and 2, all configurations fall in a band of about .1 to .15 RMS g's at V = 0 and .25 to .30 g's RMS at V = 5 knots. As will be shown subsequently, proper configuration design can provide a head seas RMS acceleration of .1 g's at V = 0 knots and .2 to .24 RMS g's at V = 5 knots independent of sea state in the surface following mode. This is for a craft length of 40 to 45 feet. Craft size does not appreciably decrease RMS g's at the cockpit at zero speed except at very low sea states.

The g's shown here are for the cockpit station locations of the respective craft. The actual crew station locations during on water operations would be more centrally located and reflect the g levels close to the center of gravity (C.G.). The g's at the C.G. are all below 0.10 RMS at zero speed for all sea states (see Figure 10). Depending on craft length and damping RMS g's at the C.G. can be as low as .05. For reference, the wave surface g's are shown in Figure 10 at zero speed and approach .125 g's RMS at the higher sea states.*

This wave surface g curve shown represents the g's of a very small craft (e.g. lifeboat) would receive while riding on the wave surface. The craft shown have lower RMS g levels due to damping and craft size.

On-water speed has a greater effect in increasing g level than any other parameter. Compared with zero speed, five knots more than doubles the g's encountered. For example, for the DT-NSRDC model at four foot significant wave height (Sea State 3), the RMS g's jump from .1 to .265. Bow shaping may in part reduce these g's, but not appreciably. Speed is considered to be the primary contributor. Again, g's at the C.G. are lower than the cockpit g's at 5 knots and are more acceptable for crew operations.

For reference, accelerations at the C.G. and bow for an FF 1040 (DE 1040) in head seas at 20 knots is shown (see Figure 9, V = 5 knots).

* At very low sea states (below 3) wave surface g's actually increase considerably over the values shown in Figure 10. These g levels do not represent craft motion g's and were not shown.

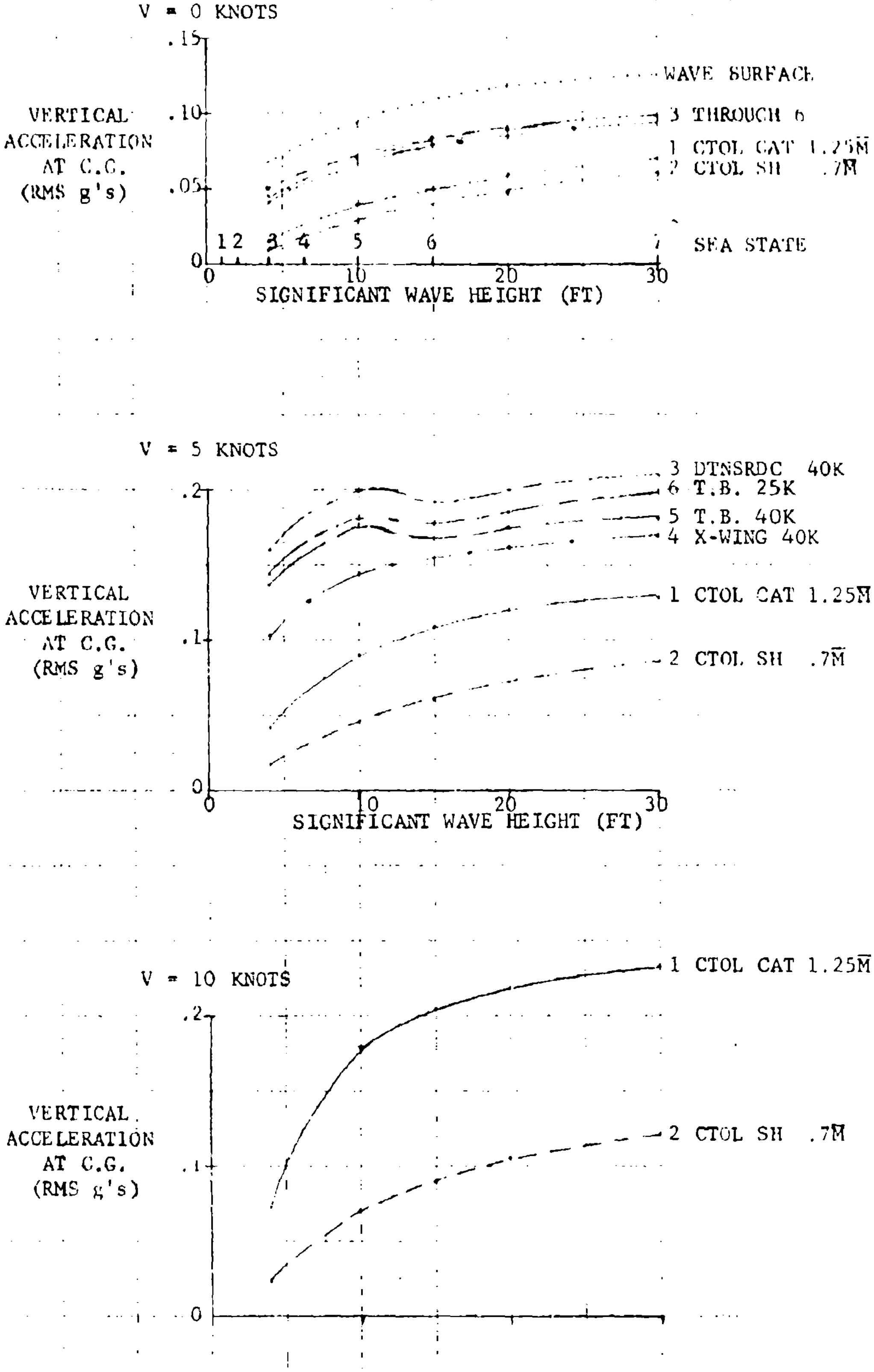


FIGURE 10. RMS VERTICAL ACCELERATION AT C.G. - HEAD SEAS

Table 2. Head Seas On-Water Motion and Stability Data

Parameter \ Configuration	1 CTOL Catamaran	2 CTOL Single Hull	3 C/STOL DT-NSRDC Model	4 VTOL X-Wing	5 V/STOL Twin Boom	6 V/STOL Twin Boom	3 (F.S.) C/STOL DT/NSRDC Full Scale
W or Δ (lbs)	1.25 $\bar{M}$	.769 $\bar{M}$	330	25 $\bar{K}$	40 $\bar{K}$	25 $\bar{K}$	41.25 $\bar{K}$
L/B/T (ft)	120/12/9.75	170.4/25/7.12	7.38/1.58/.8	43/6.25/2.5	39.2/7.3/3.5	30.8/6.7/3.1	36.9/7.9/4.0
A_ω / V $\frac{(ft^2)}{(ft^3)}$	2700/19,531	3920/12,016	10.6/5.16	260.4/391	244.4/625	175/391	265/645
Z_{CG}/Z_{CB} (ft)	-20/3.93	-7/3	-.34/.25	-.92/3.2	-1.44/3.33	-1.25/3.33	-1.45/1.25
C_b	.798	.344	.559	.581	.622	.617	.559
Float Half Span (Ft)	21	107.5	4.8	0	12.4	10.0	24.0
$I_{M_{YY}}/I_{M_{XX}}$ (Slug-ft^2)	$\frac{1.33 \times 10^8}{1.23 \times 10^8}$	$\frac{.36 \times 10^8}{.32 \times 10^8}$	32.0/29.5	80,000/30,000	95,000/85,000	80,000/70,000	70,000/56,440
K_{YY}/K_{XX} (ft)	58.6/56.2	38.8/36.6	1.76/1.66	10.12/6.20	8.74/8.27	10.12/6.20	8.84/8.34
$I_{A_{YY}}/I_{A_{XX}}$ (ft^4)	2x10^6/1.2x10^6	8x10^6/2x10^6	39.8/2.21	37,685/848	24,840/998	11,280/580	27,562/1242
$\overline{GM}_P/\overline{GM}_R$ (ft)	121.9/38.6	655.8/6.98	7.4/-.12	92.4/-1.92	35.0/-3.17	24.3/-3.10	40.0/-0.80
K_{YY}/L	.49	.23	.24	.235	.223	.329	.24

Table 3. Analyzed Configuration Characteristics

Configuration / Parameter	1 CTOL CATAMARAN	2 CTOL SINGLE HULL	3 C/STOL DT-NSRDC FULL SCALE	4 VTOL X-WING	5 V/STOL TWIN BOOM	6 V/STOL TWIN BOOM
W or Δ (lbs)	1,244,230	771,343	42,505	24,655	40,728	25,638
L (ft)	120	170	36.87	43.0	39.17	30.83
B (ft)	12	25	8.0	6.25	7.33	6.67
T (ft)	9.75	7.12	4.0	2.5	3.5	3.08
K_{YY} (ft)	66.93	38.82	8.79	10.15	8.74	10.12
X_{CG} (ft)	-2.85	2.67	.5633	.22	-.62	2.57
Z_{CG} (ft)	-20	-7	-1.25	-3.16	-3.33	-3.33
L/B	10	6.8	4.62	6.88	5.34	4.63
$\frac{K_{YY}}{L}$	.557	.23	.238	.236	.222	.328

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5.0 DESIGN PARAMETER VARIATION EFFECT

5.1 Configuration 1, CTOL Catamaran, 1.25M Lb. TOGW

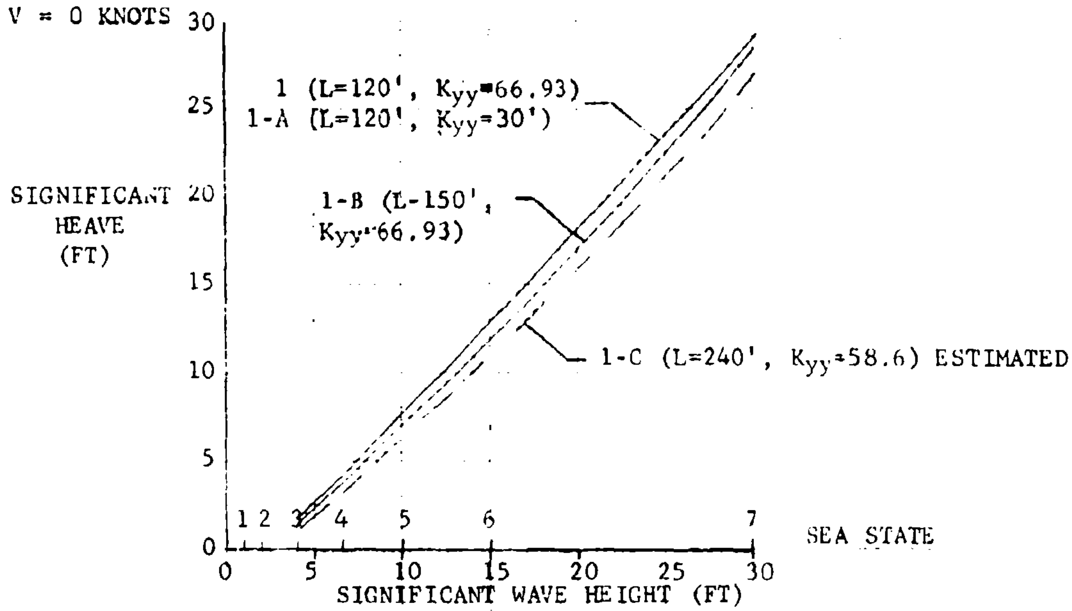
The motions for Configuration 1 were found to be excessive (see Section 4.0). In addition, at zero speed, waves break over the cockpit at a significant wave height of 13 feet, 100 times per hour. Higher wave heights are even worse.

Design modifications were considered to improve longitudinal damping, resultant pitch motion, and acceleration. Alternatives to Configuration 1, 1-A, 1-B, and 1-C, are described in Table 4. Configuration 1-A reduced the radius of gyration by a factor of about 2 and reduced the CG height by a factor of two. Configuration 1-B increased the length from 120 feet to 150 feet. The heave, pitch, and roll of Configurations 1, 1-A and 1-B are shown in Figures 11, 12, and 13. While the pitch motions were improved for Configuration 1-A over Configuration 1, Configuration 1 was still best from an RMS g's standpoint (see Figure 13). This is because of the phasing of pitch and heave. Pitch and heave are higher for Configuration 1 than for 1-A or 1-B but more out of phase (see Appendix 2 for reference to the Response Amplitude Operators, RAO's).

Configuration 1-C, with a doubling of float length and water plane area, is recommended to correct the adverse motions of this catamaran design. If doubling the length by itself does not result in acceptable motion accelerations, increasing float beam and the addition of pitch damping devices (foils fore and aft) may also be required.

Table 4. Configuration 1 Alternatives Analyzed

Parameter \ Alternative		1 CTOL Catamaran	1-A CTOL Catamaran	1-B CTOL Catamaran	1-C CTOL Catamaran
W or Δ	(lbs)	1,244,230	1,244,230	1,244,230	1,244,230
L	(ft)	120	120	150	240
B	(ft)	12	12	12	12
T	(ft)	9.75	9.75	7.8	4.88
K_{yy}	(ft)	66.93	30.	66.93	58.6
X_{cg}	(ft)	-2.85	-2.85	-3.56	
Z_{cg}	(ft)	-20	-10	-20	-20
$\frac{K_{yy}}{L}$		0.557	0.25	0.446	0.244
GM_p	(ft)	121.9	121.9	257.0	1138



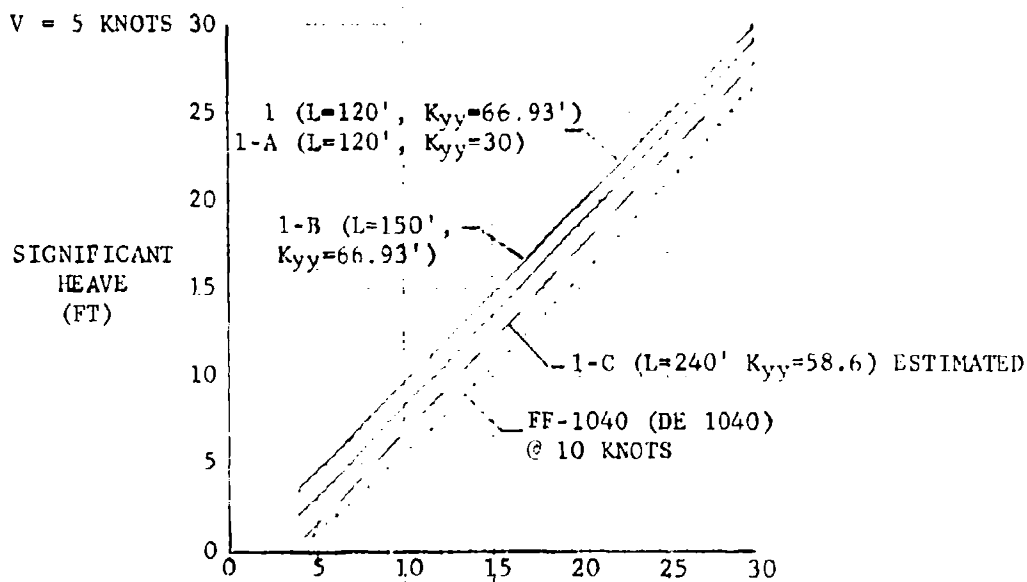


Figure 11. Significant Heavy - Configuration 1 CTOL Catamaran Alternatives

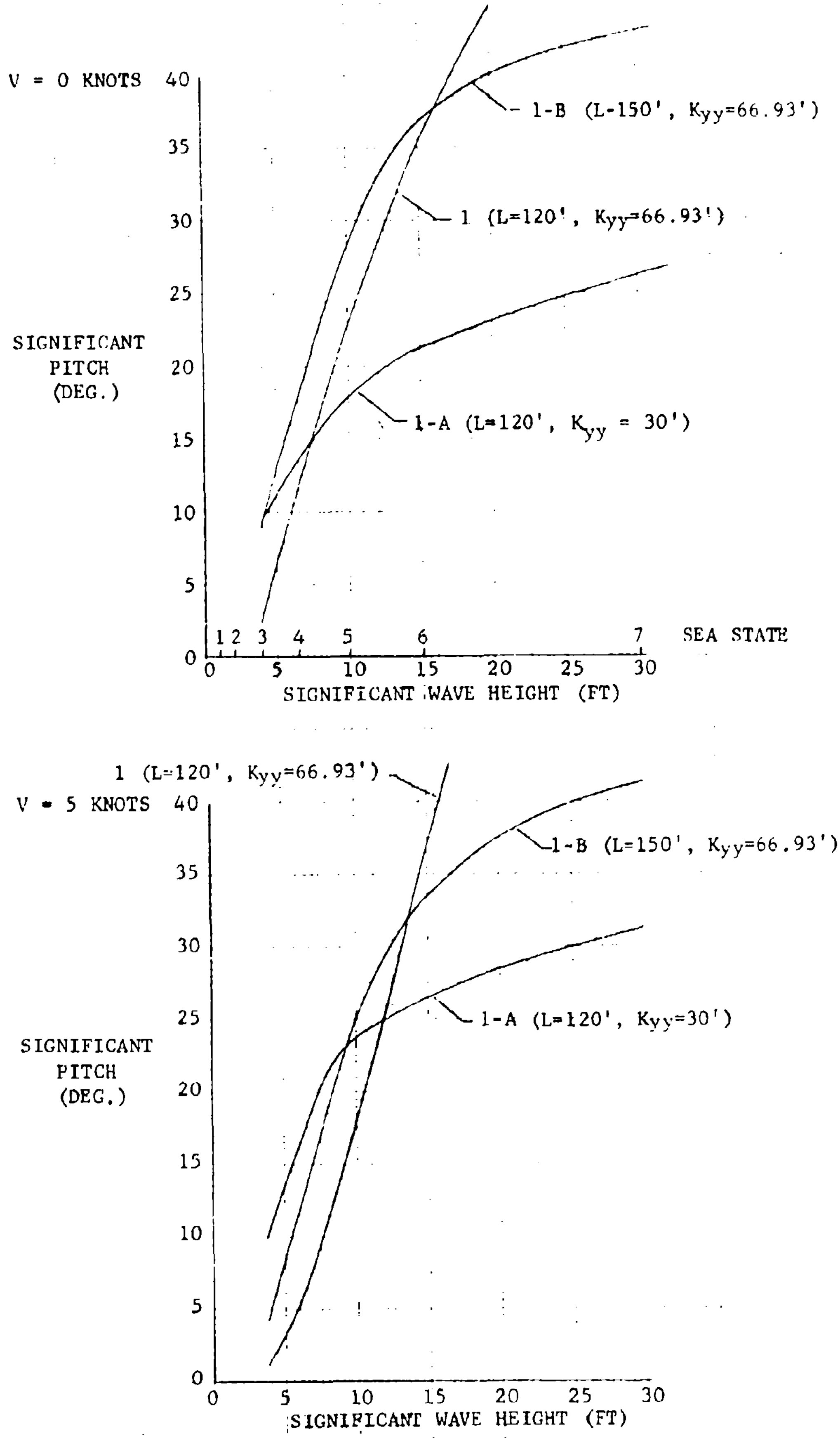


Figure 12 Significant Pitch - Configuration 1, CTOL Catamaran Alternatives

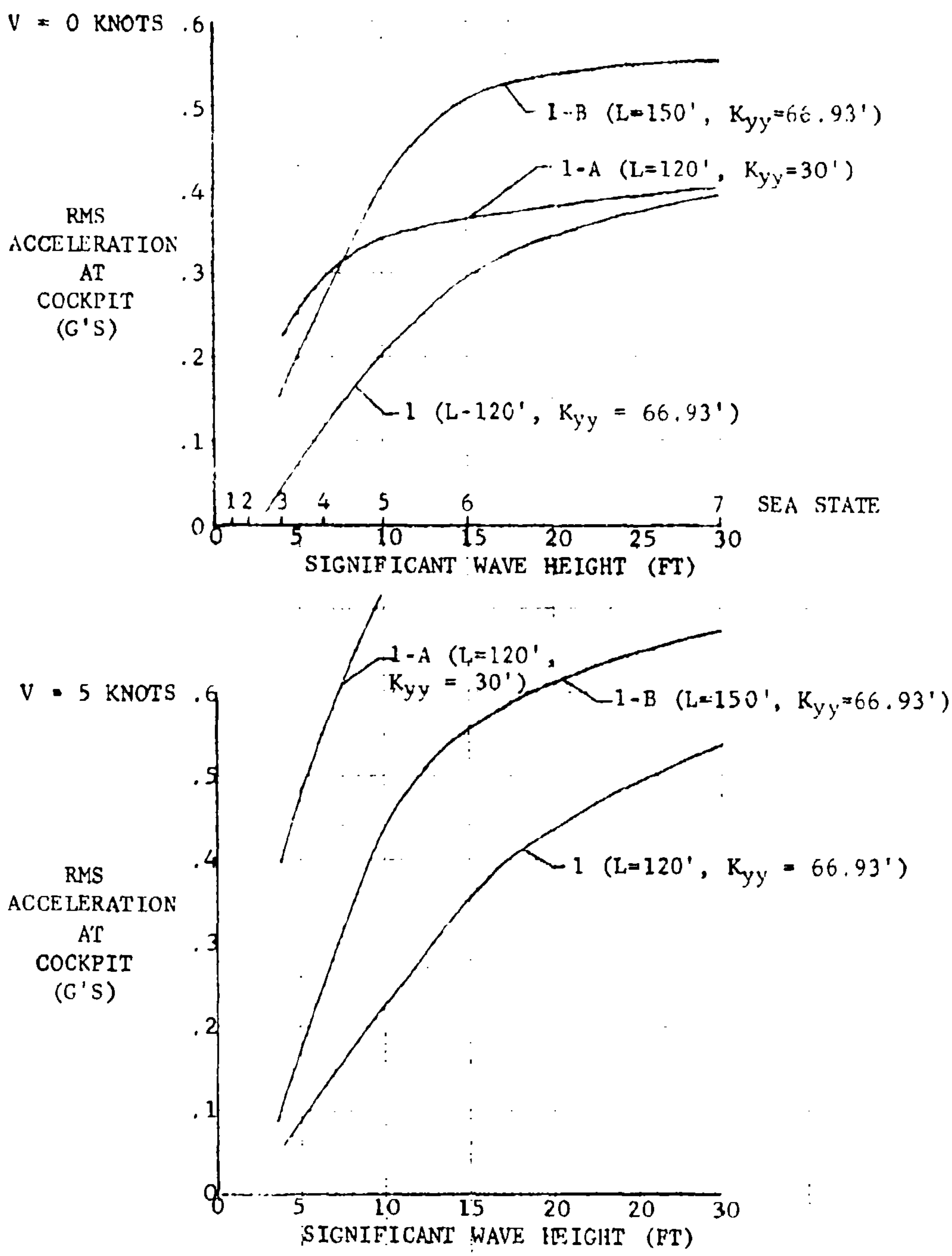


Figure 13. RMS Acceleration at Cockpit - Configuration 1, CTOL Catamaran Alternatives

5.2 Other Sea Based Aircraft Designs

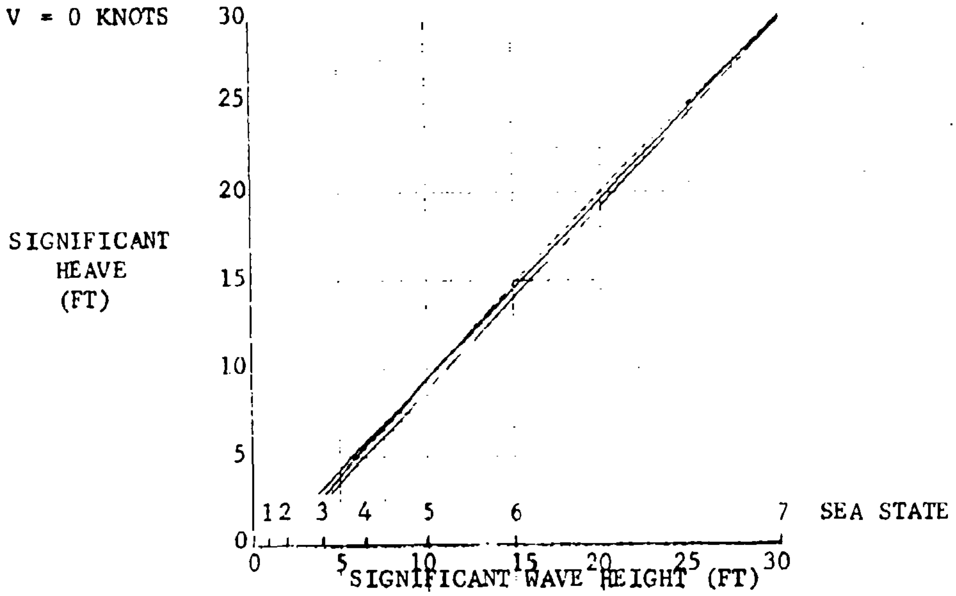
As a part of the Contractor's prior studies, other sea based aircraft designs were analyzed. Because of their significance, they are included here. Two catamaran and three single hull designs were studied (see Table 9 and Figures 14, 15 and 16). This analysis illustrates the same trends found in Section 4.0; particularly Figures 7, 8, and 9, for surface following aircraft in head seas; namely:

1) Heave is directly proportional to (and about equal to) wave height (see Figures 7 and 14). This indicates that the craft are contouring the waves for these sea states.

2) Pitch is proportional to inertia and CG height and inversely proportional to length and depends on shaping (damping). For all configurations with low values of K_{yy}/L ($K_{yy}/L \leq .25$), a limit of about 20 to 30 degrees significant pitch (about 5 to 7.5 degrees RMS pitch) is obtained at zero speed (see Figures 8 and 15). For higher values of K_{yy}/L (.33 to .50), pitch angles can be extreme. This is readily apparent in Figure 8 where Configurations 3, 4, and 5 have a K_{yy}/L of about .24, Configuration 6 has a K_{yy}/L of .33, and Configuration 1 has a K_{yy}/L of .50. This conclusion does not apply to relative large craft or ships. Configuration 2 has the lowest pitch of all aircraft and the FF 1040 (DE 1040) has even less.

3) <u>Low on-water speed and proper craft characteristics can assure a low RMS head seas acceleration, even at the cockpit of the craft. This conclusion is independent of sea state</u>. This can be seen in Figure 9 and Figure 16 for V=0 Knots. Zero speed, head seas acceleration levels of about 0.10 are obtained for the sea based craft of Table 5 and from 0.10 to 0.15 for all of the aircraft investigated in the study (except the 1.25$\overline{M}$ pound catamaran). This appears to be primarily influenced by (a) K_{yy}/L (at all sea states), and (b) length (more so at the lower sea states). As speed increases, these effects become more pronounced. The craft of Table 8 have slightly lower accelerations than those considered in the study. The major differences are because of lower K_{yy}/L (pitch inertia divided by length).

   Figure 17 summarizes this conclusion for three representative craft and shows the effect of variation of K_{YY}/L. All craft have very similar accelerations at zero speed with the .7$\overline{M}$ single hull somewhat better at the low sea states. At 5 knots for the 40,000 pound configuration and at 10 knots for the .7$\overline{M}$ single hull the accelerations are all above .2 g's RMS at significant wave heights above 10 feet. Only at low sea states (below SS 5) does the 170 foot lengths .7$\overline{M}$ S.H. configuration have lower accelerations (i.e. only at low sea states and low speed does length improve the ride).



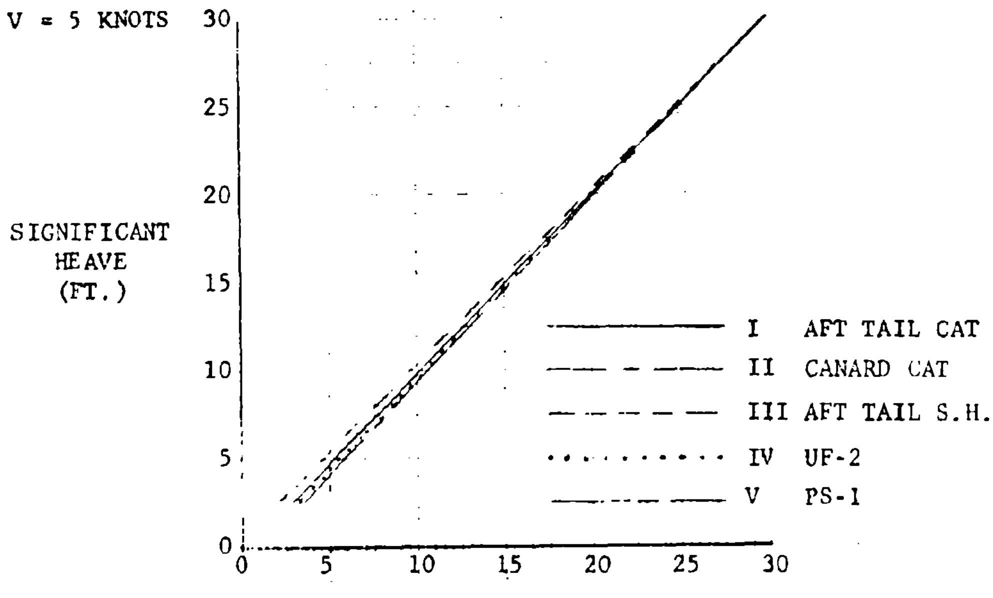


Figure 14. Significant Heave - Other Sea Based Aircraft Designs

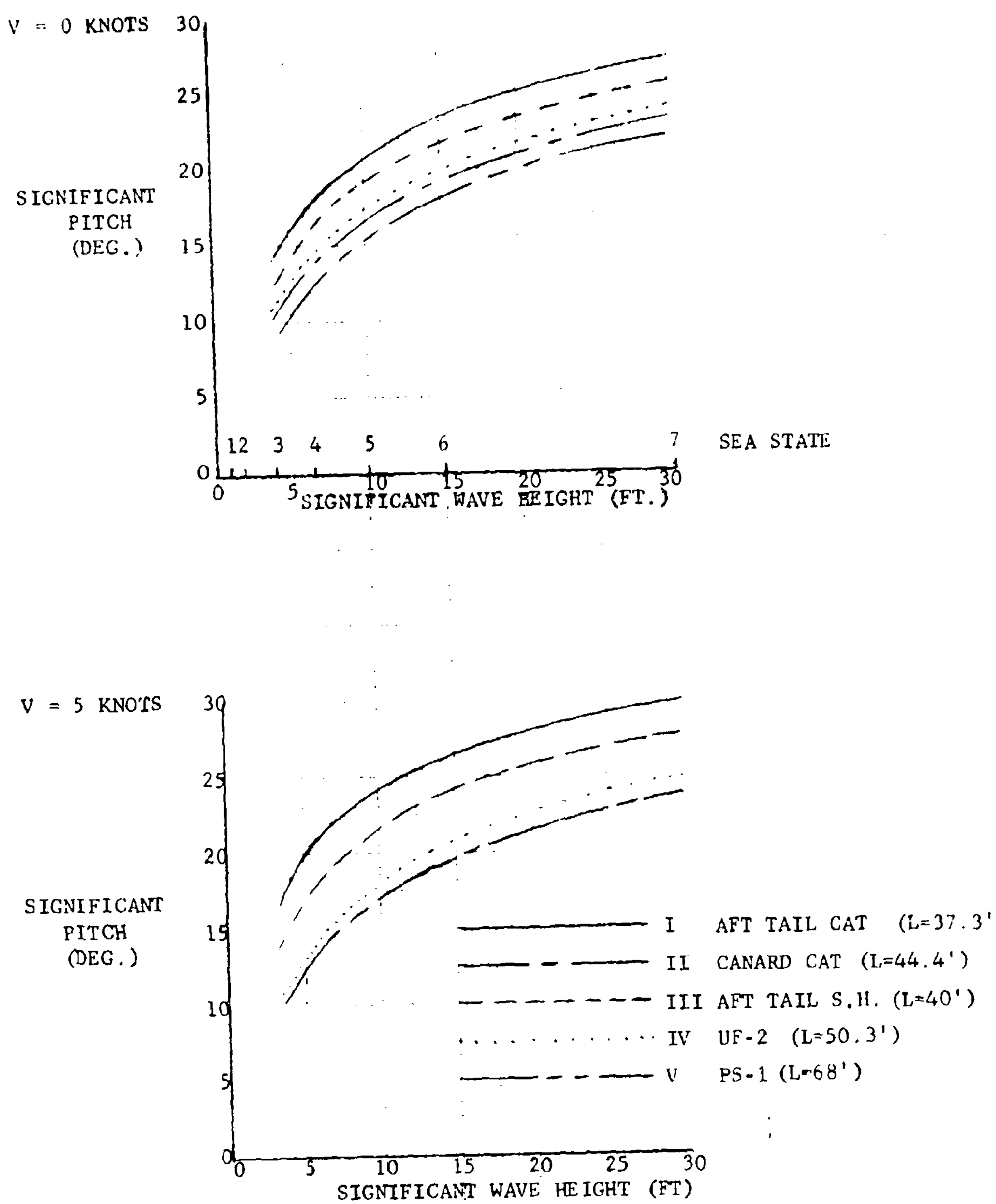
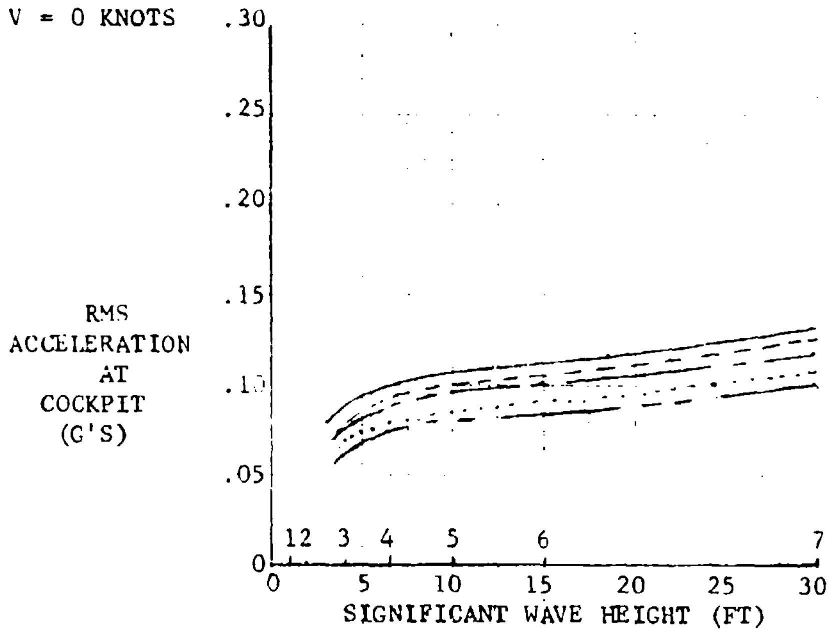


Figure 15. Significant Pitch - Other Sea Based Aircraft Designs



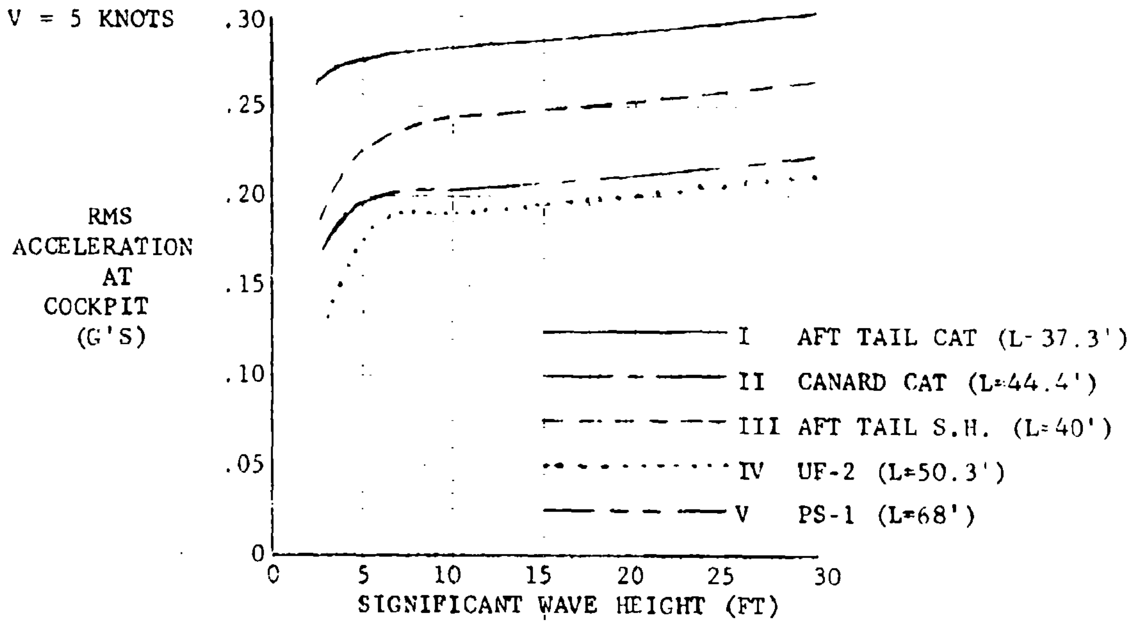


Figure 16. RMS Acceleration - Other Sea Based Aircraft Designs

Table 5. Other Sea Based Aircraft Designs Characteristics

Parameter \ Configuration		I Conventional Aft Tail Catamaran	II Canard Catamaran	III Conventional Aft Tail Single Hull	IV UF-2	V PS-1
W or Δ	(lbs)	40K	40K	40K	80K	86K
L	(ft)	37.34	44.4	40.4	50.34	68.0
B	(ft)	4	4	7		
T	(ft)	3	3	3.75		
K_{yy}	(ft)	5.3	5.33	5.28	6.65	
X_{cg}	(ft)					
Z_{cg}	(ft)	-4.48	-1.066	-3.48	5.64	
$\frac{K_{yy}}{L}$		.142	.12	.132	.132	

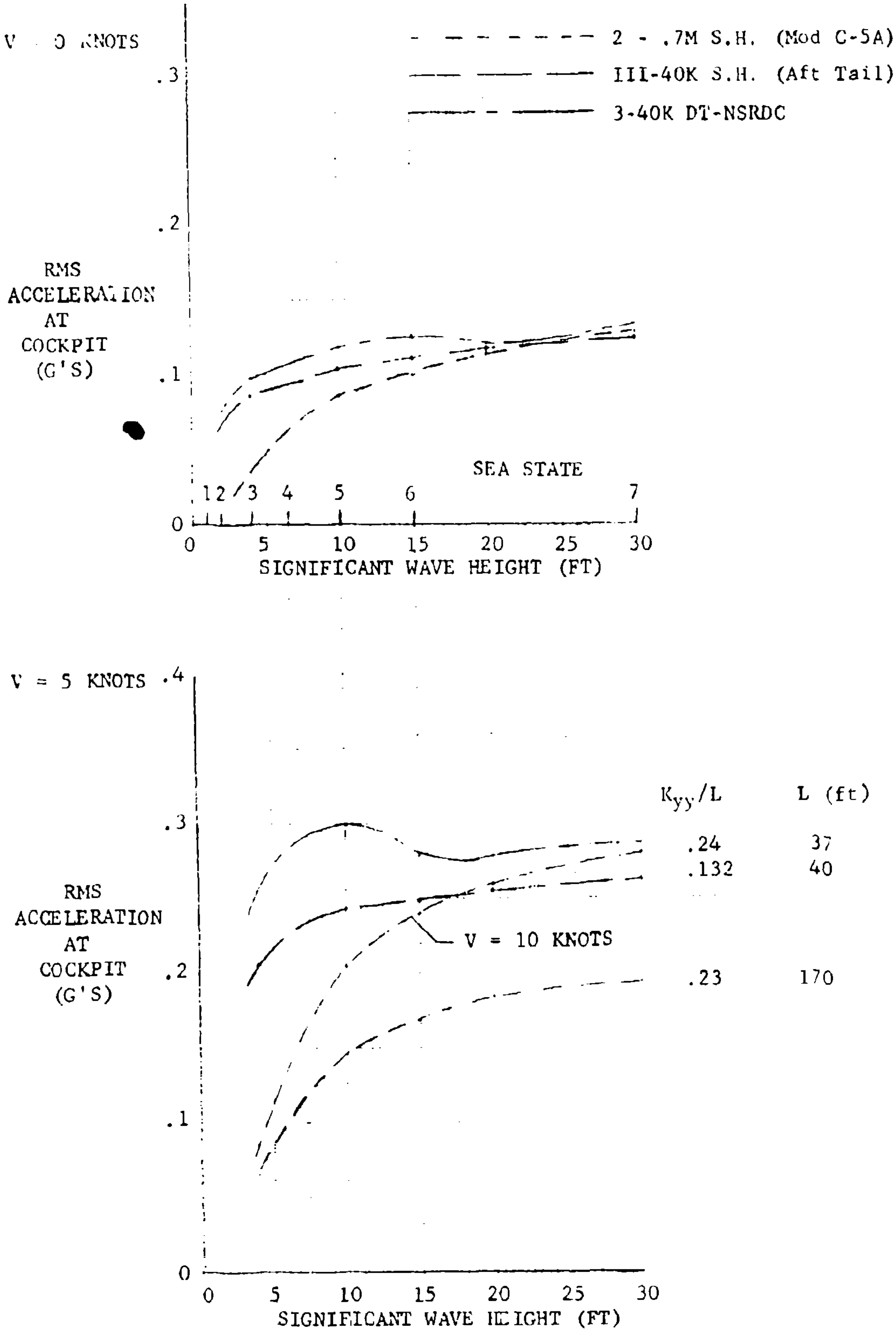


Figure 17. Head Seas - RMS Accelerations at Cockpit of Different Concepts

6.0 MODEL TANK TEST PROGRAM RECOMMENDATIONS

Based on the results of this study, the following recommendations are made for subsequent model tank testing:

1) Extension of analytical study results - This study needs to be extended to precisely define desired configuration characteristics for sea based aircraft design. Variations in K_{yy}/L and L/b at head, beam, and quartering sea conditions establishing the RMS accelerations for representative sea based aircraft (40-50 foot, 40,000 pound and 30-40 foot 25,000 pound TOGW) are indicated. Since the designs considered had normal aerodynamic fineness ratios (length to beam of 4-6) and provided good motions and accelerations on the water at zero speed, high length to beam ratio designs are not required for improved on water motion and normal aerodynamic designs do provide good on water motion characteristics. These conclusions, if verified, place increased emphasis on VTOL technology concepts for sea basing. Extreme hull shaping penalties (high L/B ratios, vertical floats, damping devices) are not required for acceptable on water motion. Since lower L/B hull ratios have higher landing impact g's at the same landing speed, lower landing speeds are indicated to keep landing loads at the same level or lower than flight loads. Pure VTOL technology can provide this capability and also save in configuration weight by avoiding hull weight penalties needed for increased impact landings, dead rise, steps, flares, chines, etc., required for CTOL and STOL water operation. Cruise performance advantages through good clean aerodynamic design configurations are also achieved.

   Analytical studies of beam sea and quartering sea conditions should accompany the model testing.

2) Water takeoff and landing tests need to be performed to establish control limits, design limits and desired configuration features (hull, float shape, engine inlet/exhaust locations) for high sea state operation.

3) Propulsion system/configuration alternatives that provide positive lift in the proximity to the water surface need to be established.

Alternative configurations that feature positive "in surface effect" lift such as RAM wing, underwing/nacelle surfaces or other lifting features should be emphasized.

Propulsion-lift system features that minimize salt water spray injestion must be emphasized. Advanced technology (low Q, high augmentation) systems are indicated. The ability to control the direction of spray may be the best means of avoiding salt spray ingestion. Propulsion-lift systems with this capability should be investigated.

7.0 DEFINITIONS

7.1 WAVE PARAMETERS

ηm	is	wave amplitude	$\eta m = \frac{1}{2} h$ (h = wave height)
β	is	phase angle	
k	is	wave number	$\kappa = \frac{2\pi}{\lambda} = \frac{\omega^2}{g}$
λ	is	wave length	$\lambda = g\frac{T_W^2}{2\pi} = \frac{2\pi c^2}{g} = \frac{2\pi g}{\omega^2}$
ω	is	wave frequency	$\omega = \frac{2\pi}{T_W} = \frac{T_W g}{\lambda}$
g	is	gravitational acceleration	$g = 32.2$ FT/SEC^2
α	is	wave heading	
t	is	time	
T_W	is	wave period	
c	is	wave celerity	$c = \sqrt{\frac{g}{\kappa}} = \frac{\lambda}{T_W} = \frac{gT_W}{2\pi} = \frac{g}{\omega}$
E	is	wave energy intensity	$E = \frac{1}{\lambda}\rho g \int \eta^2(x)dx$ For a full wave length: $E = \frac{1}{2}\rho g \eta_m^2 = \frac{1}{8}\rho g h^2$
h	is	wave height	$h = 2\eta m$

$S\eta(\omega)$ is wave spectral density (FT^2-SEC)

$S\eta(\omega) = \alpha\,\omega^{-5} \exp(-\beta\omega^{-4})$ (ft^2 x sec)

ω = circular frequency (sec^{-1})

$\alpha = \frac{5}{16}\ \omega p^4\ (\bar{H}^{1/3})^2$ (ft^2/sec^4)

$\beta = \frac{5}{4}\ \omega p^4$ (sec^4)

ωp = spectral peak frequency

For fully developed seaways according to Pierson and Moskowitz:

$$\alpha = 0.0081\, g^2 \qquad (ft^2/sec^4) \quad \text{and}$$

$$\beta = 0.0324\, g^2/(H^{1/3})^2 \qquad (sec^4)$$

where

$$\omega_p = 0.4013\, g^{1/2}/(H^{1/3})^{1/2} \qquad (sec^{-1})$$

g = acceleration in ft/sec^2

h_s = significant wave height (ft)

$$h_s = 4.0\left[\int_0^\infty S\eta(\omega)\, d\omega\right]^{1/2}$$

h_s = 4 times the RMS of the spectrum

T_{av} = average period of seaway

For fully developed seaways

$$T_{av} = 1.96\,(H^{-1/3})^{1/2} \qquad (sec)$$

$$\omega_e = \omega - \frac{\omega^2 V \cos\alpha}{g} = \omega\,(1 - \mu)$$

ω_e = apparent wave (exciting) frequency or frequency of wave encounter

V = speed of hull

α = wave heading

$$\mu = \frac{V \cos\alpha}{g}$$

7.2 HULL PARAMETERS

L is length (FT)

B is beam (FT)

T is draft (FT)

∇ is volume (FT^3)

Δ is displacement (weight) (lbs) $\Delta = W = \rho g \nabla$

$\rho g = 64\ LBS/FT^3$

C_b is block coefficient $C_b = \dfrac{\nabla}{LBT}$

C_V is vertical coefficient $C_V = \frac{\nabla}{A_W T} = \frac{\nabla}{C_W LBT}$

A_{WP} is waterplane area

C_W is waterplane coefficient $C_W = \frac{\nabla}{C_V LBT}$

F_N is Froude number $F_N = \frac{V}{\sqrt{gL}}$

V is speed of hull

$\overline{GM}_i$ = metacentric height (ft) in mode i (z_i)
(distance from G to M, metacentric center)

$\overline{GM}_p$ = metacentric height (ft) in pitch (z_ψ)

$\overline{GM}_R$ = metacentric height (ft) in roll (z_θ)

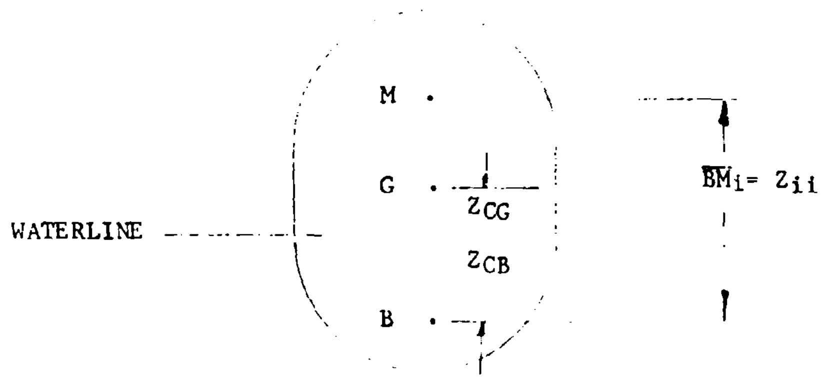
$\overline{GM}_i = \overline{BM}_i - \overline{BG}$

$\overline{BM}_i$ = distance from center of buoyancy to metacentric center (Z_{ii})

$\overline{BG}$ = distance from center of buoyancy to center of gravity G

$\overline{BG} = z_{CB} - z_{CG}$

z_{CG} = distance of CG above water line
(Negative if CG above water line)



Z_{CB} = distance of center of buoyancy below waterline

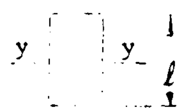
$Z_{CB} \approx H\left(\frac{1}{6} + \frac{C_b}{3C_w}\right)$

$Z_{ii} = \frac{I_{A_{ii}}}{\nabla} = \frac{\text{area moment of inertia}}{\text{displacement volume}}$

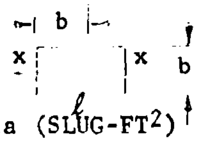
$Z_{yy} = \frac{I_{A_{yy}}}{\nabla}$ = distance $\overline{BM}_i$ in pitch

$Z_{xx} = \frac{I_{A_{xx}}}{\nabla}$ = distance $\overline{BM}_i$ in roll

$I_{A_{yy}} = \iint x^2 \, dx \, dy \; (ft^4)$

for a rectangle  $I_{A_{yy}} = \frac{1}{12} b \ell^3$

$I_{A_{xx}} = \iint y^2(x) \, dy \, dx \; (ft^4)$

for a rectangle  $I_{A_{xx}} = \frac{1}{12} \ell b^3$

$I_{M_{ii}}$ = mass moment of inertia (SLUG-FT^2) $I_{M_{ii}} = K_{ii}^2 m$
K_{ii} = radius

$I_{M_{yy}}$ = mass moment of inertia in pitch

$I_{M_{xx}}$ = mass moment of inertia in roll

K_{ii} = radius of gyration = $\sqrt{\frac{I_{M_{ii}}}{m}} = \sqrt{\frac{I_{M_{ii}}}{W/g}}$

X_{CG} = longitudinal CG location relative to mid ship point (positive if forward of mid ship)

REFERENCE

1. Rockwell International Report, NR76H-113, "Sea Based Aircraft Habitability Criteria," dated 15 October 1976.

2. Massachusetts Institute of Technology Report No. 70-3, Computer Aided Prediction of Sea Keeping Performance in Ship Design, August 1970 by Theodore A. Loukakis.

3. Massachusetts Institute of Technology Report No. 69-2, "A Computerized Procedure for Prediction of Seakeeping Performance," 1969 by Dr. R. F. Beck.

4. U. S. Naval Air Engineering Center Report NAEC-ENG-7782, "Results of Analytical Response Predictions for Two Points on Helicopter Landing Platform of DLG-26 and DE-1040 (FF-1040) Class Destoryers," dated 20 November 1972.

APPENDIX I

SEA STATE RELATIONSHIPS

I. SEA STATE RELATIONSHIPS

1.0 SUMMARY

Significant sea state relationships are summarized in this section for reference during the on-water motion study. More detailed information is provided in the Appendix References (particularly No. 1, 2, and 3). This section is divided into four sections, (1) Sea State Conditions, (2) Sea State Occurrence and (3) Motion Study Results.

1.1 Sea State Conditions

For reference, Table 1 (see Reference 2) and Figure 1 (see Reference 3) are included here. A representative set of sea state data has been taken from Figure 1 using median values and is shown in Table 2. The Pierson-Moskowitz sea spectra were used in the study (see Figure 2). Here

$$S\eta(\omega) = 0.0081\ g^2\ \omega^{-5}\ \exp\left[\frac{-0.0324g^2}{(H^{-1/3})^2}\ \omega^{-4}\right]$$

where $S\eta(\omega)$ is the wave spectra in ft^2-sec for a fully developed sea, g is acceleration in ft/sec^2 and ω is wave circular frequency in 1/seconds.

Figure 3 summarizes some of the basic relationships of waves. As the sea state increases, the wave height and length both increase as shown. Because of energy considerations, the wave slope never exceeds about eight degrees. This is because the accelerations required of the water particles do not exceed the gravity force and the wave crest disintegrates (see Reference 4). Regarding on-water operation of sea based aircraft, this 8° wave slope indicates that roll over conditions are not excessive at zero or low water speed conditions even at high sea states.

For sea based aircraft and long duration operation stability limits may have to be based on wind wave tip over conditions. It should be remembered that open ocean conditions and long duration missions may include the 100 foot breaking wave or freak rogue waves. Obviously, if a sea plane were even tipped over it would not (like a ship) right itself.

Figure 4 is a plot of peak sea state encounter frequency at zero, 5 and 10 knots versus sea state. Thus, increasing forward velocity (by 5 or 10 knots) has a significant effect at frequencies of about 2 radians per second. A 10 knot change at this frequency is equivalent to (almost) doubling the sea state encountered. When going from sea state 2 to 4, the average wave height increases from 1.5 ft. to 3.5 ft. Since the wave energy encountered is proportional to the wave height squared;

$$E = \frac{1}{8}\ \rho g h^2 \qquad \text{(Reference 2)}$$

the relative energy change is five times.

Table 1. Wind and Sea Scale for Fully Arisen Sea

Sea state	Description	Wind: Beaufort wind force	Wind: Description	Wind: Range, knots	Wind: Wind velocity, knots†	Sea: Wave height, ft: Average	Sea: Wave height, ft: Significant	Sea: Wave height, ft: Average 1/10 highest	Sea: Significant range of periods, sec	Sea: T_{max}, period of maximum energy of spectrum	Sea: $\bar{T}$ average period	Sea: $\bar{L}$ average wavelength	Sea: Minimum fetch, nmi	Sea: Minimum duration, hr
0	Sea like a mirror.	0	Calm	Less than 1	0	0	0	0						
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light airs	1-3	2	0.05	0.08	0.10	Up to 1.2 sec	0.7	0.5	10 in.	5	18 min
1	Small wavelets, still short but more pronounced; crests have a glassy appearance, but do not break.	2	Light breeze	4-6	5	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7 ft	8	39 min
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle breeze	7-10	8.5	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	9.8	1.7 hr
					10	0.88	1.4	1.8	1.0-6.0	4	2.9	27	10	2.4
2					12	1.4	2.2	2.8	1.0-7.0	4.8	3.4	40	18	3.8
	Small waves, becoming larger; fairly frequent white horses.	4	Moderate breeze	11-16	13.5	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	24	4.8
3					14	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	28	5.2
					16	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	40	6.6
	Moderate waves, taking a more pronounced long form; many white horses are formed (chance of some spray).	5	Fresh breeze	17-21	18	3.8	6.1	7.8	2.5-10.0	7.2	5.1	90	55	8.3
4					19	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	65	9.2
					20	5.0	8.0	10	3.0-11.1	8.1	5.7	111	75	10
5	Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray).	6	Strong breeze	22-27	22	6.4	10	13	3.4-12.2	8.9	6.3	134	100	12
					24	7.9	12	16	3.7-13.5	9.7	6.8	160	130	14
					24.5	8.2	13	17	3.8-13.6	9.9	7.0	164	140	15
6					26	9.6	15	20	4.0-14.5	10.5	7.4	188	180	17
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind (spindrift begins to be seen).	7	Moderate gale	28-33	28	11	18	23	4.5-15.5	11.3	7.9	212	230	20
					30	14	22	28	4.7-16.7	12.1	8.6	250	280	23
					30.5	14	23	29	4.8-17.0	12.4	8.7	258	290	24
					32	16	26	33	5.0-17.5	12.9	9.1	285	340	27
7	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well-marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh gale	34-40	34	19	30	38	5.5-18.5	13.6	9.7	322	420	30
					36	21	35	44	5.8-19.7	10.3	10.3	364	500	34
					37	23	37	46.7	6-20.5	14.9	10.5	376	530	37
					38	25	40	50	6.2-20.8	15.4	10.7	392	600	38
					40	28	45	58	6.5-21.7	16.1	11.4	444	710	42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong gale	41-47	42	31	50	64	7-23	17.0	12.0	492	830	47
					44	36	58	73	7-24.2	17.7	12.5	534	960	52
					46	40	64	81	7-25	18.6	13.1	590	1110	57
	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole, the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shock-like. Visibility is affected.	10	Whole gale*	48-55	48	44	71	90	7.5-26	19.4	13.8	650	1250	63
					50	49	78	99	7.5-27	20.2	14.3	700	1420	69
					51.5	52	83	106	8-28.2	20.8	14.7	736	1560	73
					52	54	87	110	8-28.5	21.0	14.8	750	1610	75
					54	59	95	121	8-29.5	21.8	15.4	810	1800	81
9	Exceptionally high waves (small and medium-sized ships might for a long time be lost to view behind the waves). The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm*	56-63	56	64	103	130	8.5-31	22.6	16.3	910	2100	88
					59.5	73	116	148	10-32	24	17.0	985	2500	101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane*	64-71	>64	>80‡	>128‡	>164‡	10-(35)	(26)	(18)			

* For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.
† A heavy box around this value means that the values tabulated are at the center of the Beaufort range.
‡ For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.
SOURCE: W. A. McEwen and A. H. Lewis, "Encyclopedia of Nautical Knowledge," p. 483, Cornell Maritime Press, Cambridge, Md., 1953. "Manual of Seamanship," pp. 717-718, vol. II, Admiralty, London, H.M. Stationery Office, 1952. Pierson, Neumann, James, "Practical Methods for Observing and Forecasting Ocean Waves," New York University College of Engineering, 1953.

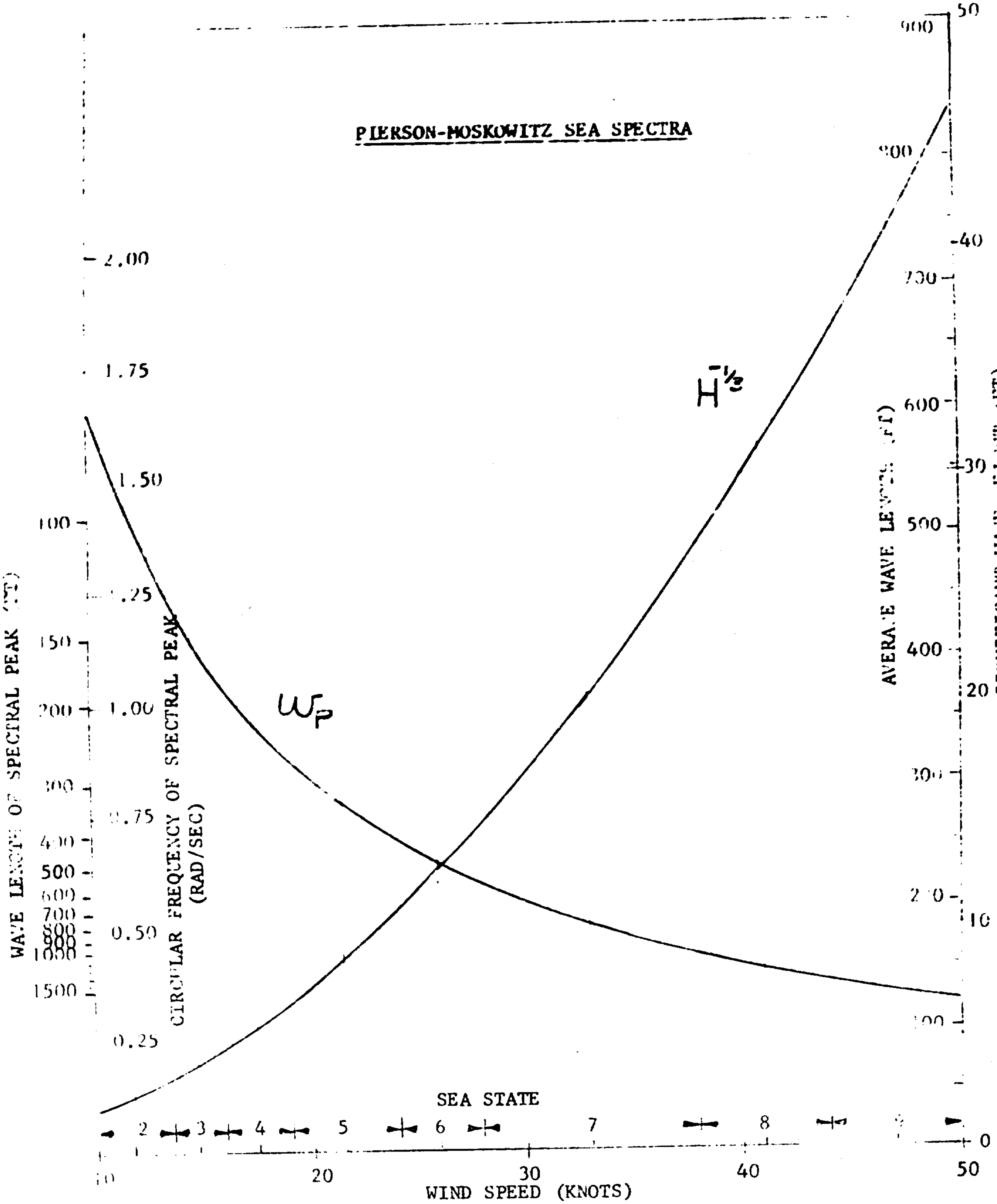


FIGURE 1. PRINCIPAL PARAMETERS FOR FULLY DEVELOPED SEAWAYS

Table 2. Pierson-Moskowitz Median Sea Spectra Values

Sea State	Significant Wave Height $H^{-1/3}$ (ft.)	Average Wave Length λ_{AV} (ft.)	Average Wave Height $\bar{H}_{AV}$ (ft.)	Circular Freq. of Spectral Peak ω_P (RAD/SEC)	Wave Length of Spectral Peak λ_P (ft.)	Average Wind Speed (Knots)
1	1.0	18	.63	3.14	39	5
2	2.4	42	1.5	1.45	95	11.7
3	4.0	72	2.5	1.15	152	14.7
4	5.6	102	3.5	.951	225	17.3
5	8.6	156	5.4	.755	336	21.5
6	12.6	229	7.9	.64	490	26.0
7	20.3	368	12.7	.51	790	33.0
8	31.2	567	19.5	.40	1270	41.0
9	41.0	746	25.7	.35	1570	47.0

$\bar{H}_{AV} = .626\ H^{-1/3}$ $\lambda_P = 39.016\ H^{-1/3}$

$\lambda_{AV} = 18.16\ H^{-1/3}$ $H^{-1/10} = 1.272\ H^{-1/3}$

$\bar{\theta}$ Ave Wave Slope $\approx$ Arc Tan $\bar{H}/\lambda_{AV}/2$; for $H^{-1/3}$. $\bar{\theta} = 6.3°$
for $\bar{H}^{1/10}$. $\bar{\theta} = 8°$

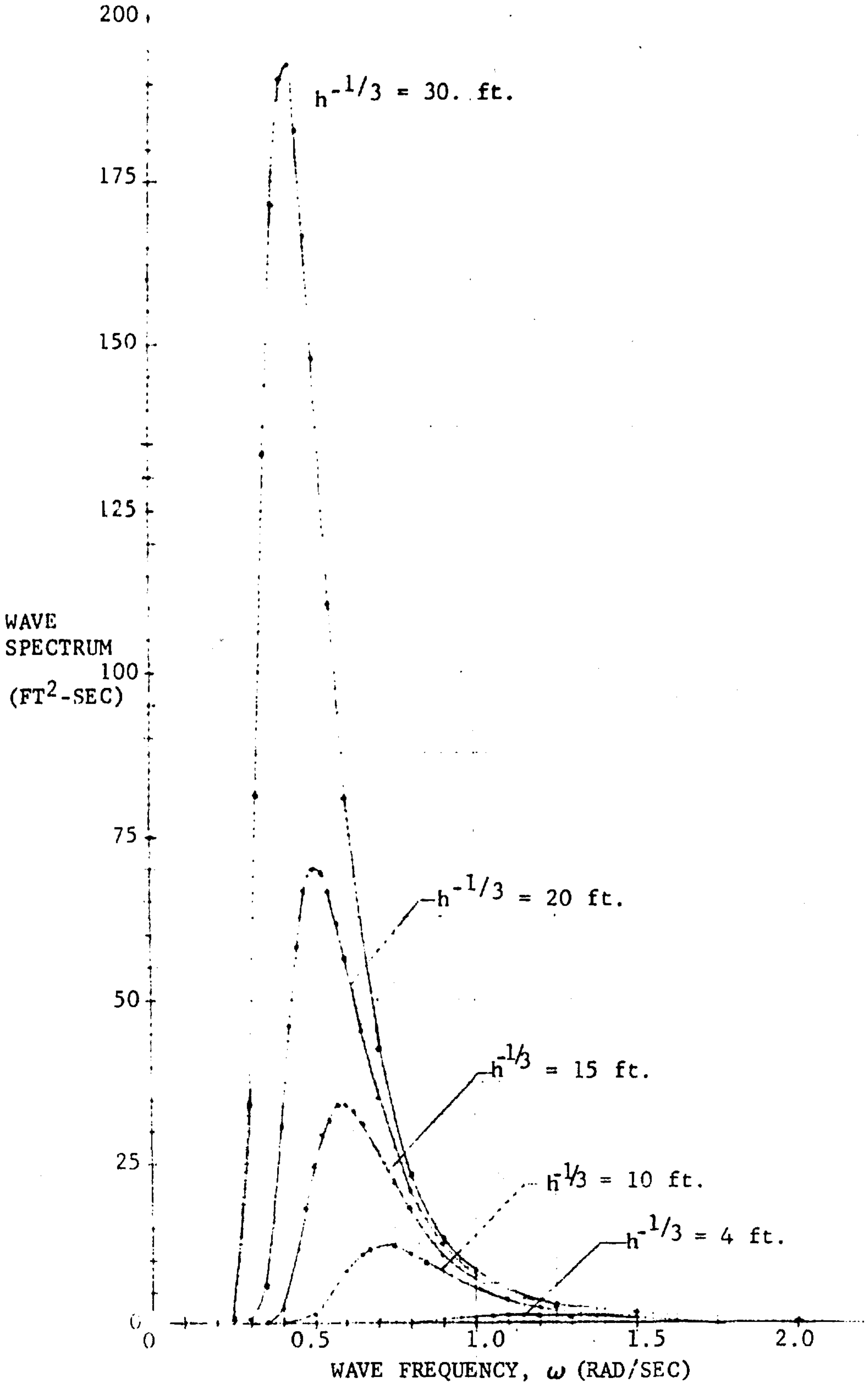


FIGURE 2. WAVE SPECTRUM VS WAVE FREQUENCY

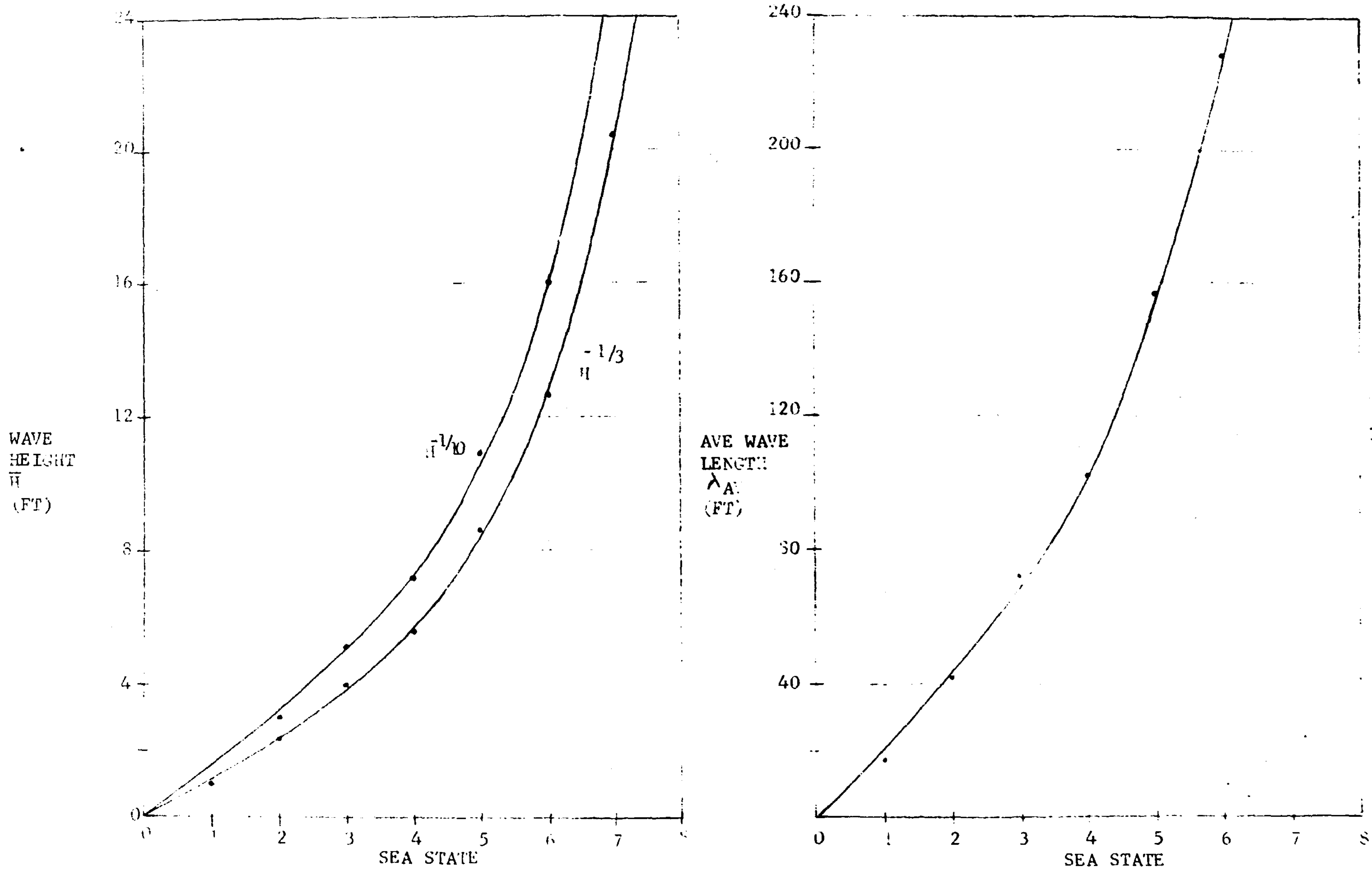


FIGURE 3. WAVE HEIGHT AND AVERAGE WAVE LENGTH VS. SEA STATE (PIERSON-MOSKOWITZ MEDIAN VALUES)

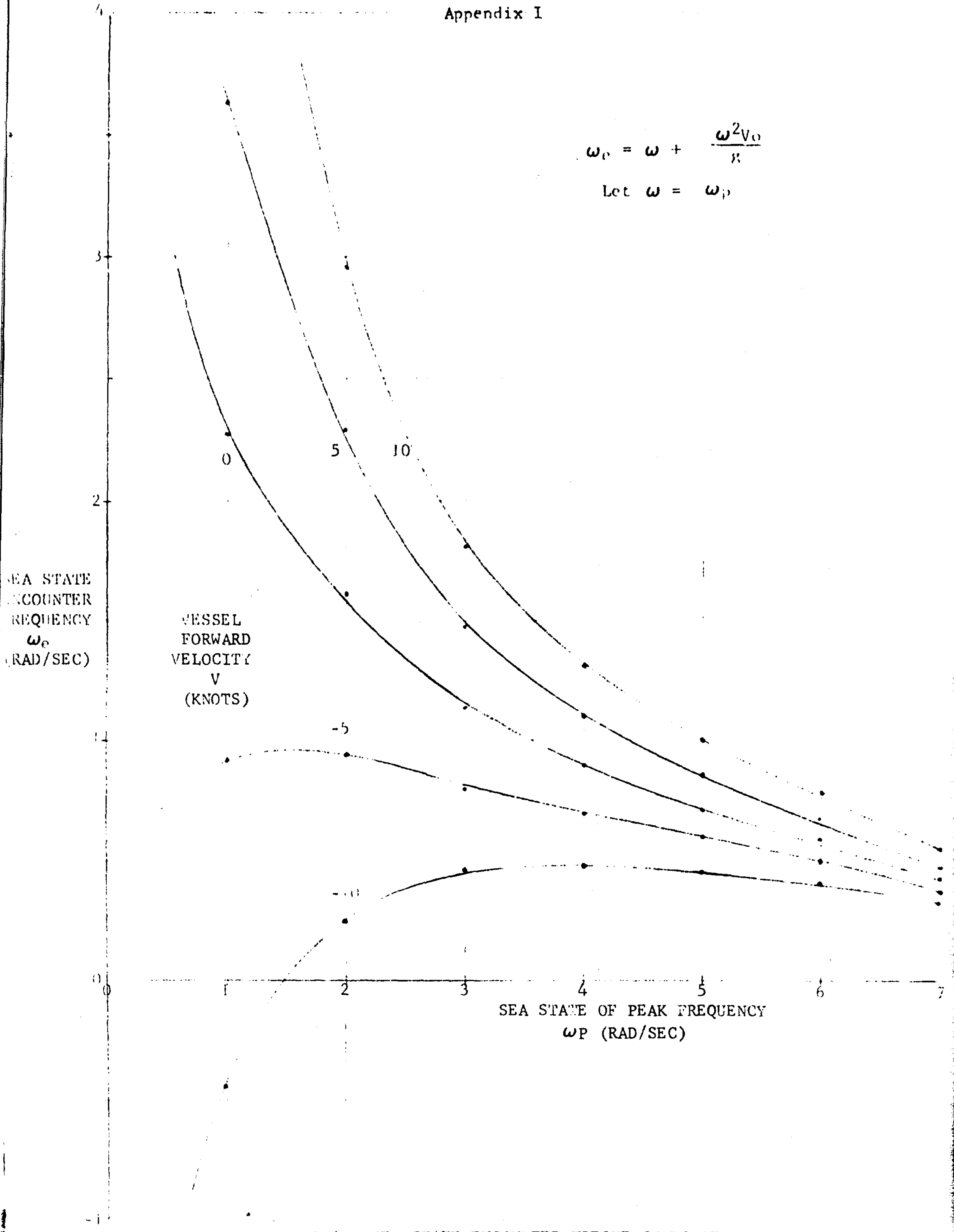


FIGURE 4. SEA STATE ENCOUNTER FREQUENCY VS SEA STATE

1.2 Sea State Occurrence

The occurrence of various sea conditions has been studied in Reference 14, 15, and 16. Figures 5 and 6 are from data taken from Reference 14 and 16 respectively. The operational capability of the PBY and P5M (Figure 6) are shown as circles. For example, the PBY was designed for operation in seas with three foot waves (or about Sea State 2). This constituted about 15 to 18 percent of the time in the Atlantic and Pacific Oceans. The P5M was designed for operation in four foot waves (about Sea State 2 1/2) or about 24 percent of the time. Much greater use of these craft was actually made (see Reference 15) with resultant high loss rates. It should be remembered that the values of Figure 5 are based on average occurrences as observed over the total ocean area and do not reflect the expected occurrence for shipping lanes (which avoid high sea state ocean areas), required ASW areas, etc.

Figure 5 is from Reference 16 that indicates the extreme values of waves (for design of structures to last vs. lifetime). Based on material at hand (Reference 2), the asymptotic wave height for the North Atlantic is 90 feet. The resultant modified Galton distribution (Reference 16) is in Figure 5.

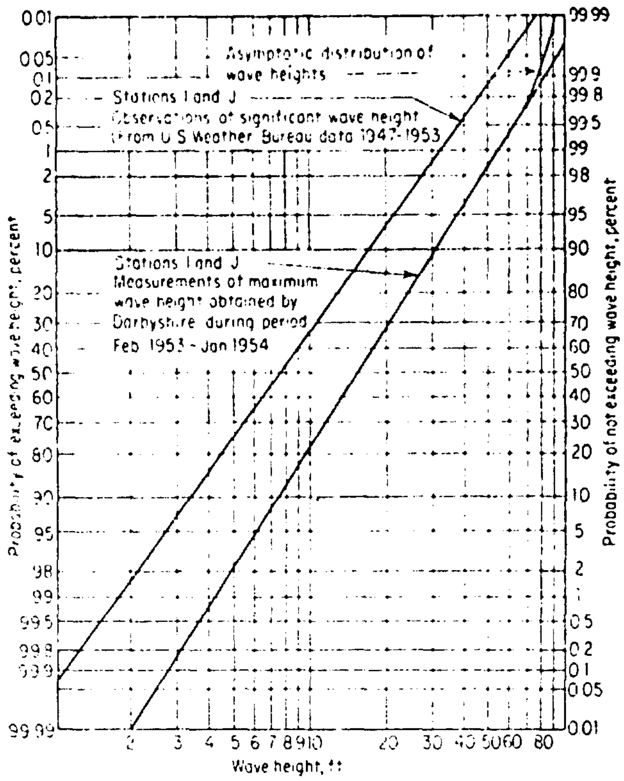


FIGURE 5. WAVE-HEIGHT DATA FOR THE NORTH ATLANTIC

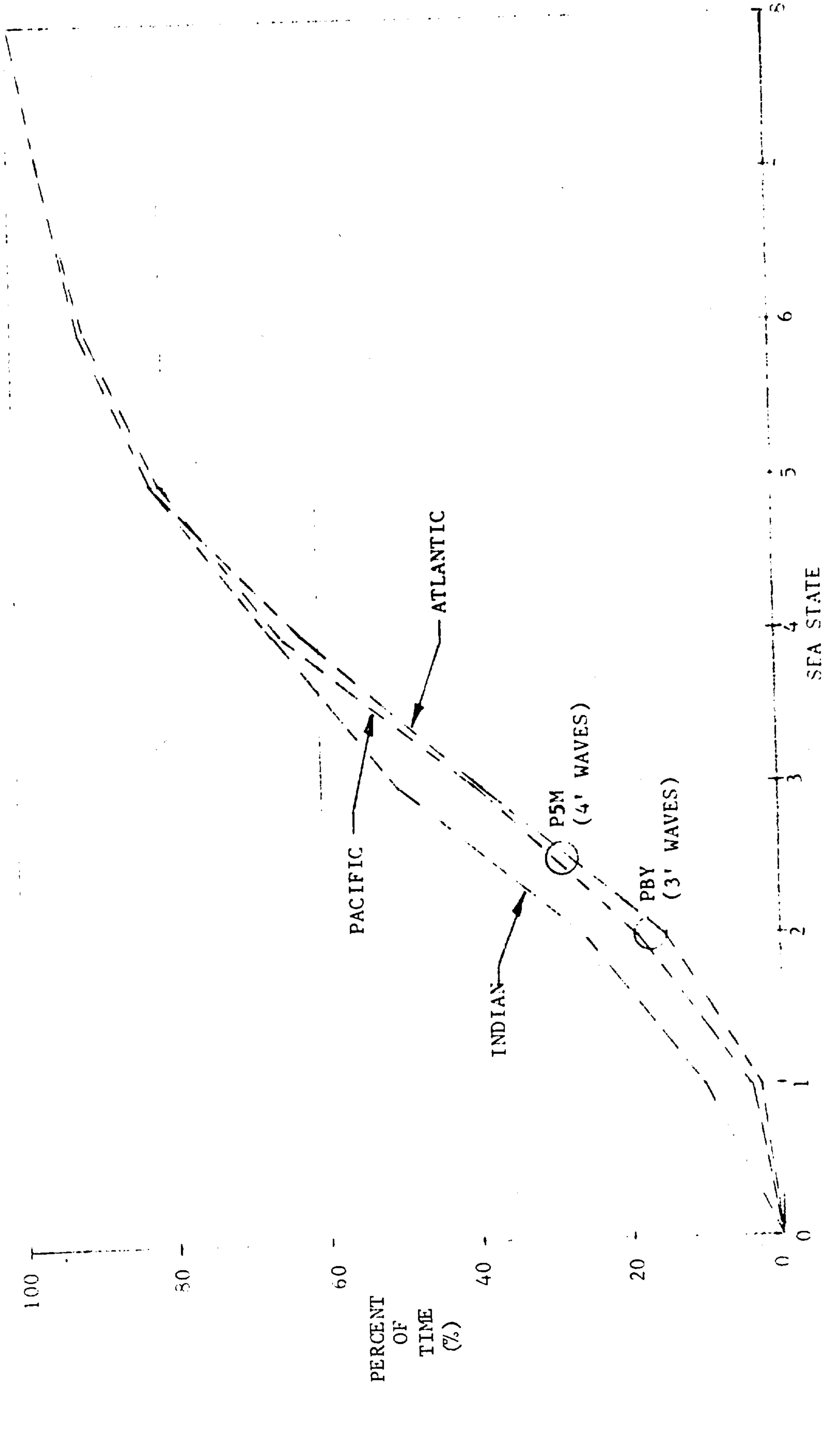


FIGURE 6. FREQUENCY OF DIFFERENT SEA STATES

The estimated operating capability of various aircraft and ships is shown in Table 3.

Table 3. Estimated Operating Capability

SYSTEM	MAXIMUM OPERATING WAVE HEIGHT	AVERAGE SEA STATE FOR INDICATED WAVE HEIGHT	ESTIMATED PERCENT OF TIME SYSTEM CAN OPERATE
PBY	3	2½ - 3	30 - 50% *
P5M	4 - 5	3	40 - 50% *
PS-1	10	4½	72 - 74% *
V/STOL SEA BASED AIRCRAFT	15 - 20	6 - 6½	90 - 93%
CV	20	6½	93% *
AIRFIELD	--	--	98%

* Sea State limited time only

Reference 15 indicates that PBY and P5M craft, when water based, were also limited by weather conditions existing at the forward area sea drome where wind and sea were often worse than provided for in basic flying boat design criteria. Amphibious craft have a higher availability being able to make use of land or water bases. V/STOL aircraft that can operate from ships as well as being amphibious would have the highest possible availability of the craft indicated in Table 3.

As a result, the estimated percent of time indicated for the PBY and P5M are high in that base weather limitations have not been included. The percent of time values for PS-1 and V/STOL sea based aircraft are correspondingly low as their basing flexibility would improve the percent of time they could operate. While the actual operability times are mission dependent, a V/STOL sea based aircraft with both land, ship and high sea state capability should have operability comparable to CV craft and land based airfields.

1.3 On-Water Motion Study

Fundamental relationships regarding vessel motion on the water are summarized in this section. This work is the result of a V/STOL aircraft on-water motion analysis performed by Rockwell International, Columbus Aircraft Division.

1.3.1 Study Summary

On-water motions of stationary catamaran and single hull aircraft were analyzed and compared to other ocean vessels. Forward velocity on the water was not considered in this analysis. Equations of motion and acceleration were developed for heave, roll, pitch, and acceleration. The analysis performed involved uncoupled equations of heave, roll, and pitch. The developed data provided a good insight into the relative motion of the vehicles analyzed. It did not provide absolute values of motion or acceleration. Coupled equations of motion are necessary to provide this information.

As a result of this analysis, however, several significant conclusions regarding sea based aircraft have been determined. These are:

1. Small size amphibian aircraft (under 50 feet in length and under 50,000 pounds) that have low draft so that they "ride with the waves" have acceptable motion and acceleration characteristics for high sea state on-water operation. Aircraft lengths that are a fraction of a wave length at high sea states (so that the aircraft follows the waves) do not have to take severe bending loads, see Figure 7. Important characteristics are hull length and wing span between floats or distance between hulls on a catamaran. Hull lengths and spans of 35 to 50 feet are considered best. This is based on motion and wing/fuselage bending load considerations; the latter being proportional to fuselage length and wing span. These general length and span characteristics are those of Kon Tiki type (surface following) craft which have good open ocean motion and acceleration characteristics.

   For riding on the water at high sea states, important aircraft design limits are length and span. These should be small (preferably about 50 feet) and never more than 100 feet. Load alleviation devices or articulation may be required at these lengths. This is based on Figure 8, which indicates that above an average wave length (λ) of 100 feet, wave heights and consequently roll and pitch motion and bending moments, increase sharply. At λ = 100 feet, the one-tenth highest wave height ($\bar{H}_{1/10}$) is about 13 feet while at λ = 200 feet, $\bar{H}_{1/10}$ = 16 feet .

   Crew comfort is a question of becoming seasick due to adverse motions and accelerations. All of the vehicles considered have relatively low accelerations considering the motions and accelerations of a ship making headway in rough seas. A 500 foot ship at 25 knots in sea state 6 to 7 will have bow accelerations over 1 g. While accelerations in a stationary small craft may be such as to cause seasickness for an operator on his first cruise, the motions are much less severe than those that could be expected by

I MOTION/ACCELERATION

FORCING FUNCTION ∝ TO WATER PLANE AREA (S)

II PITCHING/BENDING MOMENT

$\propto \frac{\text{HULL LENGTH}}{\text{WAVE LENGTH}} \times$ WAVE HEIGHT

(λ)

WATER FORCE = ?? PRESSURE X AREA (S) X WAVE HEIGHT

64,000 LBS = 64 LBS/FT^3 X 1000 FT^2 X 1 FT.

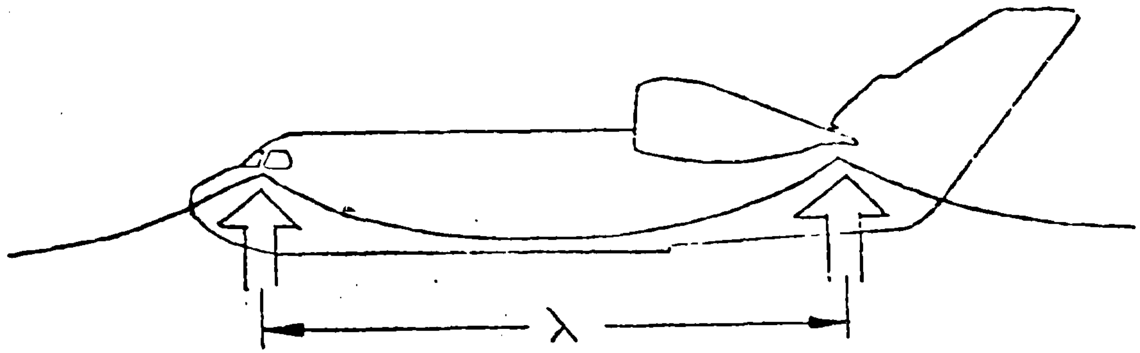


FIGURE 7. SIGNIFICANCE OF AIRCRAFT LENGTH

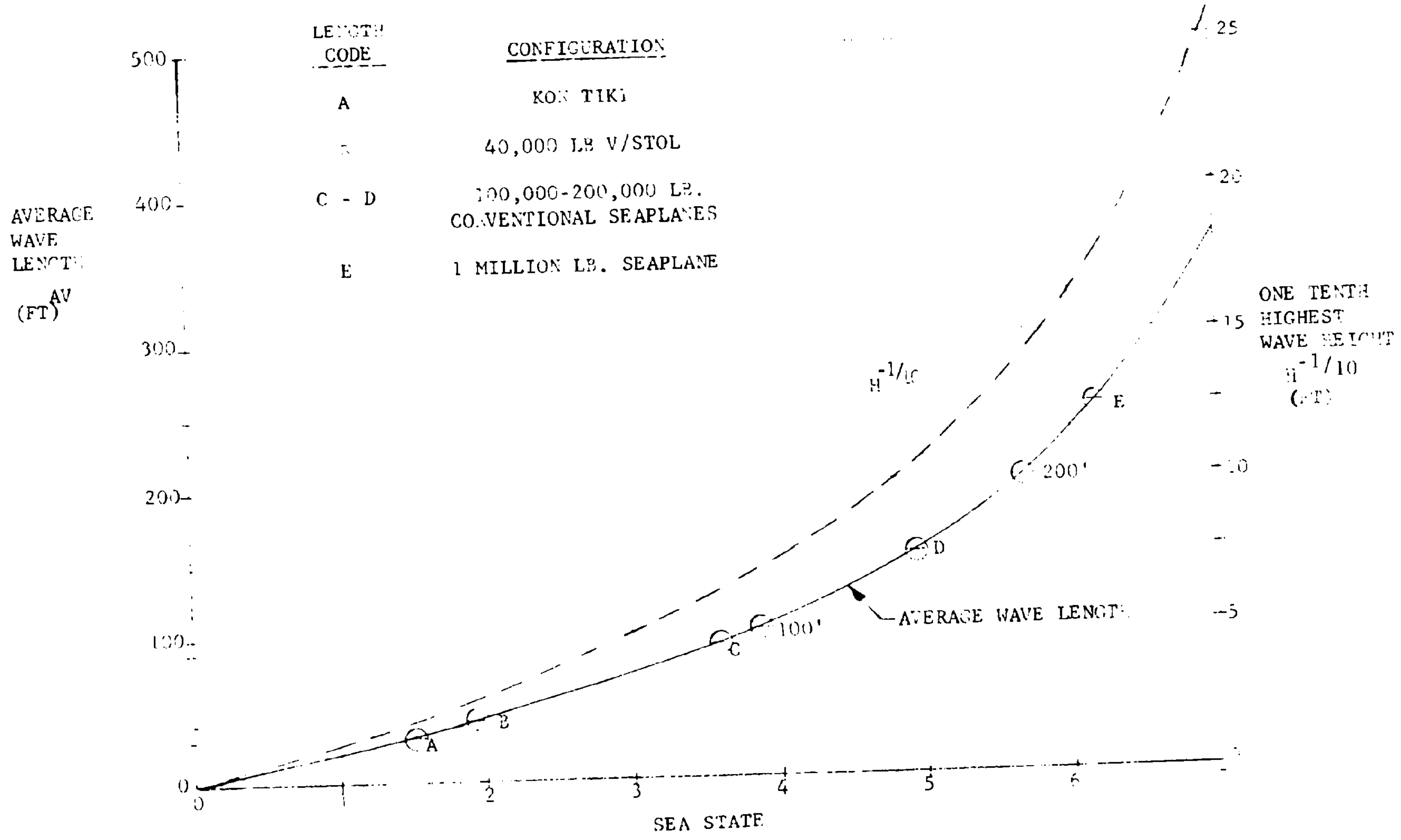


FIGURE 8. SIGNIFICANCE OF AIRCRAFT LENGTH

a crewman aboard a destroyer or cruise at cruise speeds. Except for initial mission seasickness, the motions for either a 50 foot length or 100 foot length sea based aircraft should not adversely affect crew performance.

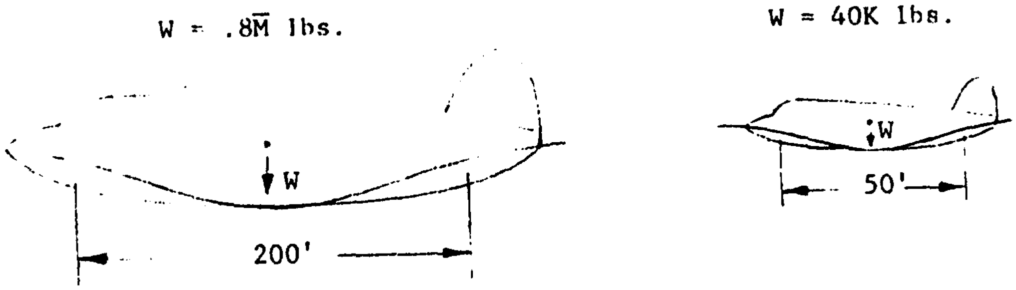
2. Sea based aircraft in the TOGW range of 100,000 pounds to 250,000 pounds should also have acceptable motion characteristics, provided that on the water speeds required are not significant (over 5 to 10 knots). Design conditions that are a function of aircraft size, bending loads, etc., will establish the practicability of these larger aircraft.

3. One overriding point that came out of this analysis is the significance of on water velocity on vessel motion and acceleration. Ships have motion and acceleration problems because they are trying to make headway even in rough seas. Past seaplanes which had to land and takeoff at speeds of 75 to 100 knots over high waves or swells also encountered significant acceleration and loading problems.

4. Beam sea conditions that result in high transverse loads and accelerations should be avoided because of the lower human tolerance to transverse accelerations (about half that of vertical acceleration tolerances). This requires an on-water propulsion device for on-water mobility so that the craft does not have to use in flight engines.

5. Sea based aircraft could be designed to have a deep draft to have little motion on the water. An example of this would be a P5M with verta floats. When this is done however, 1) strength must be added to take the increased bending loads encountered on the floats or hull and 2) height above the water must be provided to clear the maximum wave height expected operationally. Fuselage and wing bending loads are proportional to fuselage/float span length and draft. A sea state of 6 has a wave length of over 200 feet and wave heights (peak-to-trough) of up to 13 to 16 feet. Under this condition, a 800,000 pound plane with a 200 foot length fuselage that is 20 feet in depth would be primarily submerged at the nose and tail (and thus largely supported at the nose and tail). The fuselage bending moment would be about 80 times those for a 50 foot length sea based aircraft (see Figure 9).

   The 4.5g flight loads for a 40K, 50 ft. aircraft are about equivalent to the expected on water bending loads.



$$M_B = \frac{.8\overline{M}}{2} \times \frac{200}{2} = 40\overline{M} \text{ ft-lbs.}$$

$$M_B = \frac{40K}{2} \times \frac{50}{2} = .5\overline{M} \text{ ft-lbs.}$$

FIGURE 9. COMPARISON OF FUSELAGE BENDING LOADS, M_B

For large seaplanes to operate in high sea states, bending loads must be alleviated to avoid excessive loading conditions.

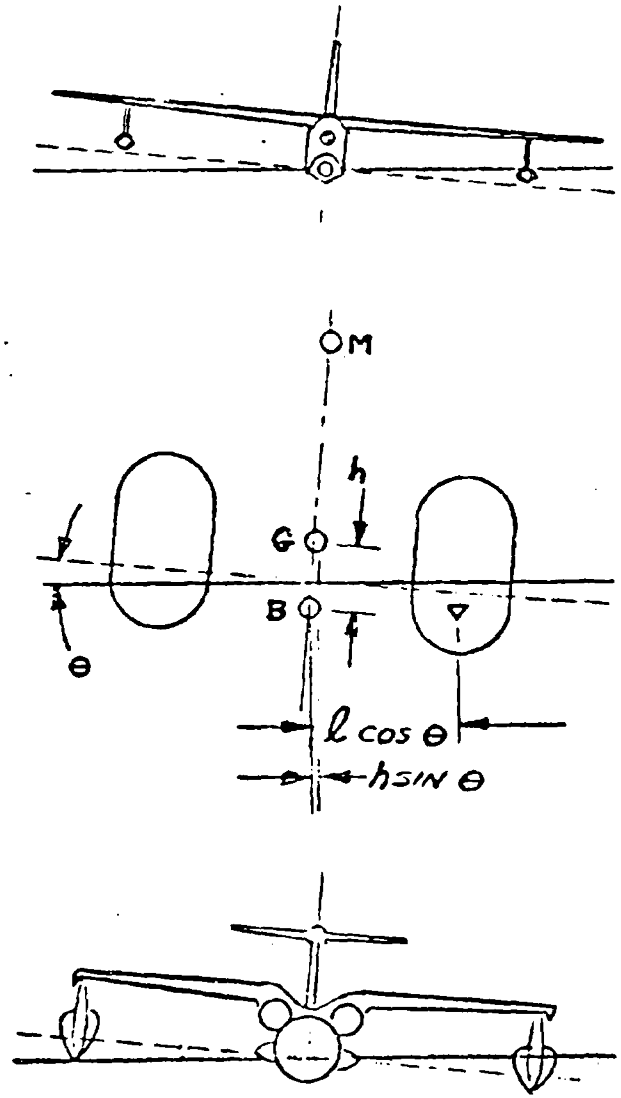
A 50 foot seaplane would not have to span these high waves and would always be on one slope of the wave. The waves it would span would be at sea state 2.4, where the 1/10 highest waves are less than 4 feet high.

A 200 foot seaplane would have to span sea state 5 to 6 waves with the 1/10 highest waves of 12 to 17 feet. The bending loads are much higher here compared to flight bending requirements.

1.3.2 Stability Considerations

Figure 10 compares the static lateral stability of two sea based concepts with seaplanes of the past. Because of the need to keep the wings and engines out of the water, seaplanes had high wing locations with engines mounted on top that resulted in high c.g.'s and large disturbing moments (DM). Compared to the catamaran design presented, the disturbing moments were 2 to 3 times larger. This would also be true of any new large seaplane that was designed to keep the engines out of any conventional water takeoff spray condition.

All three designs meet the stability requirements shown in Figure 11 (14×10^4 lb-ft) at $\theta = 10°$.



45,000 LB. TOGW

	REPRESENT-ATIVE V/STOL CATAMARAN	REPRESENT-ATIVE SEAPLANE	REPRESENT-ATIVE V/STOL SINGLE HULL
h (Ft)	2.7-3.0	7.5-9.0	2.2
DM (Ft.Lbs.) θ = 5°	9400	25,000	9154
ℓ (Ft)	6	35-40	26
Δ (Lb) θ = 5°	12,150	2150	3000
RM (Ft.Lbs.) θ = 5°	73,000	80,000	78,400
θ = 10°	150,000	150,000	150,000
$\frac{RM}{DM}$ (θ = 5°)	7.75	3.2	8.6

FIGURE 10. Stability Comparison

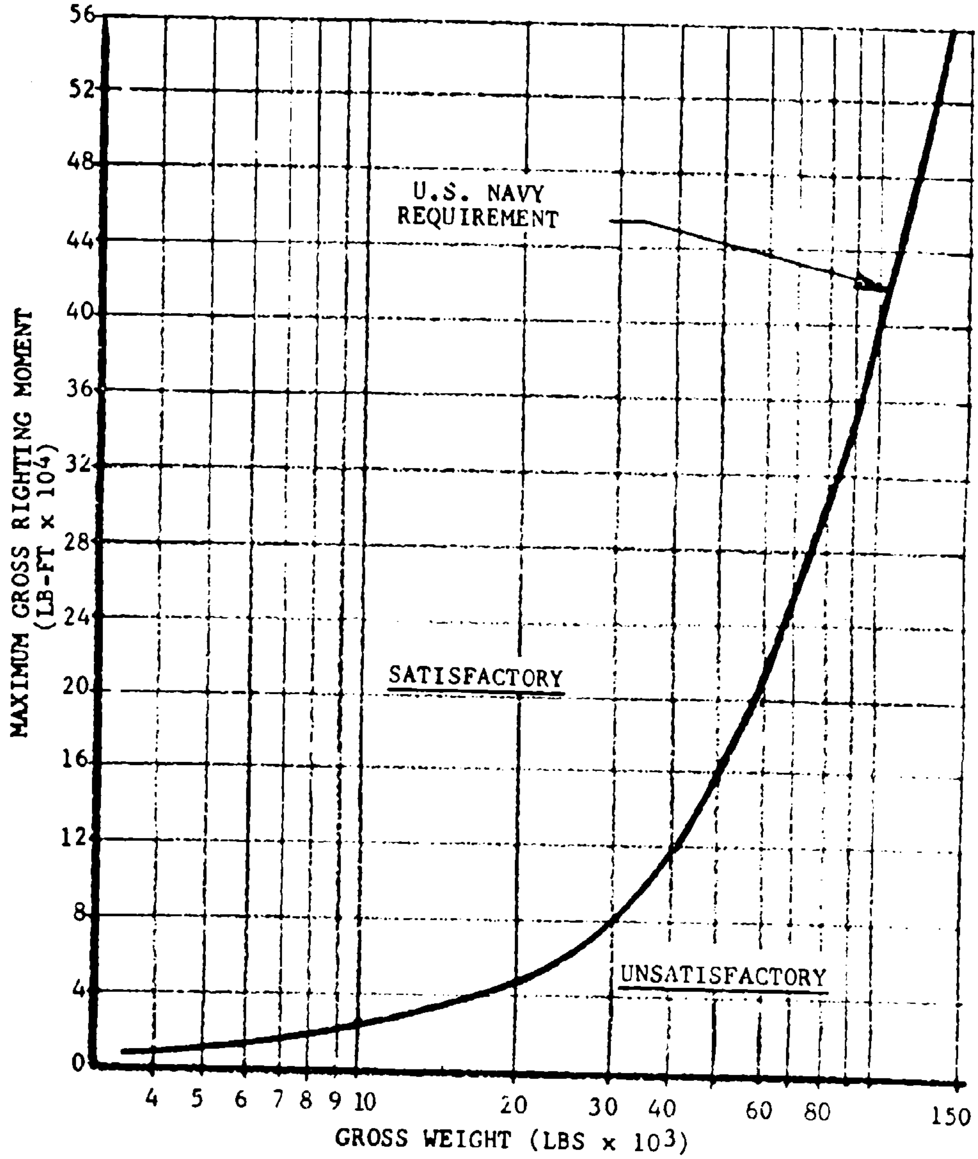


Figure 11 On-Water Stability Requirement

The restoring moments of a single hull seaplane are determined by the outboard float volume and the moment arm length. Once the float is under the water, a maximum restoring moment has been reached. Conventional takeoff seaplanes have in the past, been designed so that there is some float clearance on landing, and thus, when sitting on the water, the seaplane rocks back and forth resting on one float and then the other.

A catamaran always has an increasing righting moment with any magnitude of disturbance, and at a roll angle of five degrees has twice the static stability of past typical seaplanes. In addition, since bending loads are proportional to length, the outboard float seaplane will be subject to significantly higher bending moments than would a catamaran.

REFERENCES

I Sea State Relationships

1. H. O. Publication No. 604, "Practical Methods of Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics," U. S. Navy Hydrographic Office, dated 1955.

2. Handbook of Ocean and Underwater Engineering, Myers, Holm and McAllister, Rockwell Corporation, dated 1969.

3. Massachusetts Institute of Technology Report No. 70-3, Computer Aided Prediction of Sea Keeping Performance in Ship Design, August 1970 by Theodore A. Loukakis.

4. Appendix 2 of Heavy Weather Sailing by K. Adland Coles, Tuckahoe, New York, 1968.

5. Possibilities for Reducing Ship Motions at Sea by Edward V. Lewis, Journal of American Society of Naval Engineers, Nov. 1958.

6. "On the Motion of Floating Bodies" Part II Simple Harmonic Motions, Communications on Committee of Pure Applied Mathematics Volume 3, by Fritz John 1950 (QA1. C734).

7. "Ship Motions Prediction Realistic Short-Crested Seas" by Z. G. Wachnick, and E. E. Zarnick, Society of Naval Architects and Marine Engineers, Nov. 11-12, 1965.

8. Symposium on Ship Operation, Part 1, How They Perform by R. O. Patterson.

9. LPD Motion Study, NSRDC, M. Sekellick, 27 July 1971.

10. Mechanical Vibrations, Den Hartog, McGraw-Hill, 1956.

11. Study of Hydrofoil Seacraft, Grumman Report PB 151475 for the Department of Commerce.

12. Supercritical Planning Hulls by Peter R. Payne, AIAA Paper (CL 26822) No. 74-333 February 1974 (H029279).

13. The Potential of Semi-Submerged Ships in Rough Water Operation, by Philip Mandel, MIT, SNAME, March 1960 (CL 26821).

REFERENCES (Continued)

II Sea State Occurrence

14. Calspan Report No. GM-1968-1 "Open Ocean ASW Air-Sea Craft System Feasibility Study (U)," Volume III Air Sea Craft Operational Sea Environment (AD507576L), dated 1968.

15. U. S. Navy Report Operational History of the Flying Boat Open Sea and Seadrome Aspects - Selected Campaigns of World War II (CL 26405), dated Jan. 1959.

16. Soc. of Naval Arch. Marine Engrs. Tech. Res. Bull. 1-19, Height, Length and Steepness of Seawaves in the North Atlantic and Dimensions of Seawaves as Functions of Wind Forces (trans. by M. St. Denis). Roll, H. V., 1958.

APPENDIX II

RESPONSE AMPLITUDE OPERATORS (RAO'S)

RESPONSE AMPLITUDE OPERATORS (RAO'S)

Based on the theory of linear systems, the spectral density of the response, S (ω) can be found from the relation

$$S_{response}(\omega) = \left| H_j(\omega) \right|^2 \quad S_{wave}(\omega)$$

where:

$H_j(\omega)$ = frequence response operator of the craft (RAO) for craft response j

$S_{wave}(\omega)$ = the spectral density of the seaway (wave spectrum)

$S_{response}(\omega)$ is the mean squared amplitude of the response

Thus, the RAO is the transfer function of the craft and indicates how the craft responds in heave, pitch, etc., per unit of wave spectrum input.

The RAO's are for regular waves and the response is in a seaway (or applys to irregular waves).

Figures 1 through 14 are for configurations 1 through 6. Figure 15 is the wave spectrum plotted to be overlaid on the RAO's. As indicated in Figure 15, the wave energy is found in the frequency range from 0.4 radians/second to 1.5 radians/second at zero speed with the peak frequency decreasing as sea state increases. Thus, most of the high sea state energy is in the frequency band of .75 to .4 radians/second.

Examining the RAO's of Figure 1 through 14 indicates that only configuration 1 has any significant heave, pitch or cockpit vertical acceleration RAO's in this critical frequency band. Also, from Figure 2 and 3, notice the heave and pitch coupling that exists (the bump in the heave RAO at 0.6-0.7 radians/second at the peak pitch amplitude). This expains the high pitch amplitudes and accelerations of Configuration 1, particularly at the higher significant wave heights (or sea states). The high values of pitch and cockpit acceleration RAO's for configurations 3 through 6 are not particularly significant as they occur near or above 2 radians/second. As speed increases, however, these RAO's peaks become more significant.

Figure 16 indicates how the peak frequency changes as on water speed is changed from zero to ± 10 knots. The major effect for an RAO at 2 radians/second is at the sea states of 2 to 4 ($\bar{H}_{1/3}$ = 2.4 to 5.6 feet) when the frequencies of encounter are increased from 1.6 and 0.9 radians/second to 2.95 and 1.3 radians/second. The acceleration RAO peaks for configurations 3, 4, 5 and 6 would explain the generally higher levels of RMS acceleration at zero and 5 knots compared to configuration 2.

Selective hull shaping or slight increases in hull length should be examined to see if configurations 3, 5 and 6 could be improved. Configuration 4 is longer (43 feet) and has a somewhat lower RMS acceleration level. From Figure 15, lengthening to 40 to 45 feet and hull shaping would seem to provide RMS g levels of 0.1 at 0 knots and 0.2 to 0.25 at 5 knots at a significant wave height of 15 feet (sea state 6). Optimizing hull length and selective shaping should provide a 10 to 15 percent improvement in RMS g level reduction.

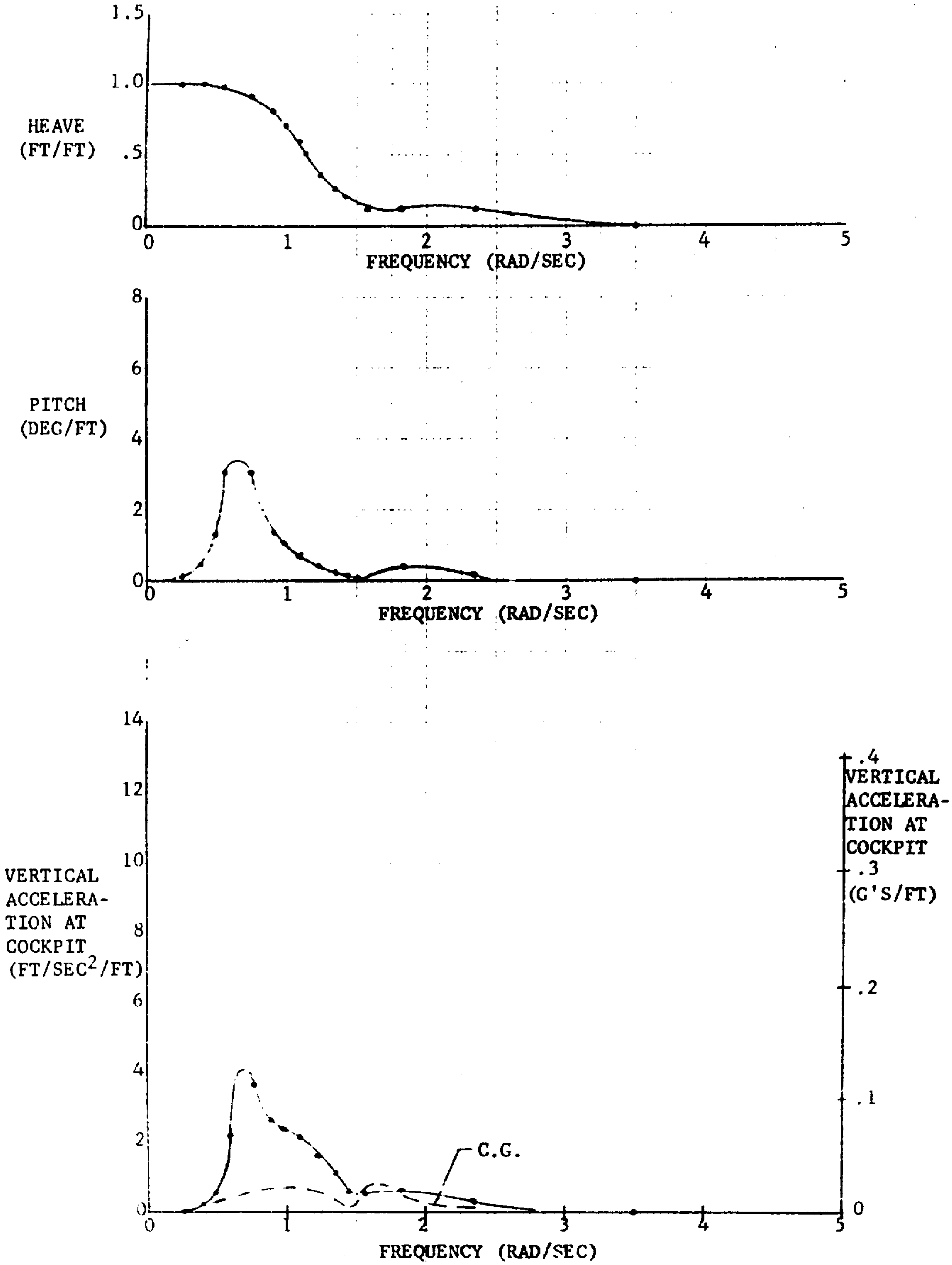


FIGURE 1. RESPONSE AMPLITUDE OPERATORS V = 0 KNOTS
CONFIGURATION 1 CTOL CAT 1.25M

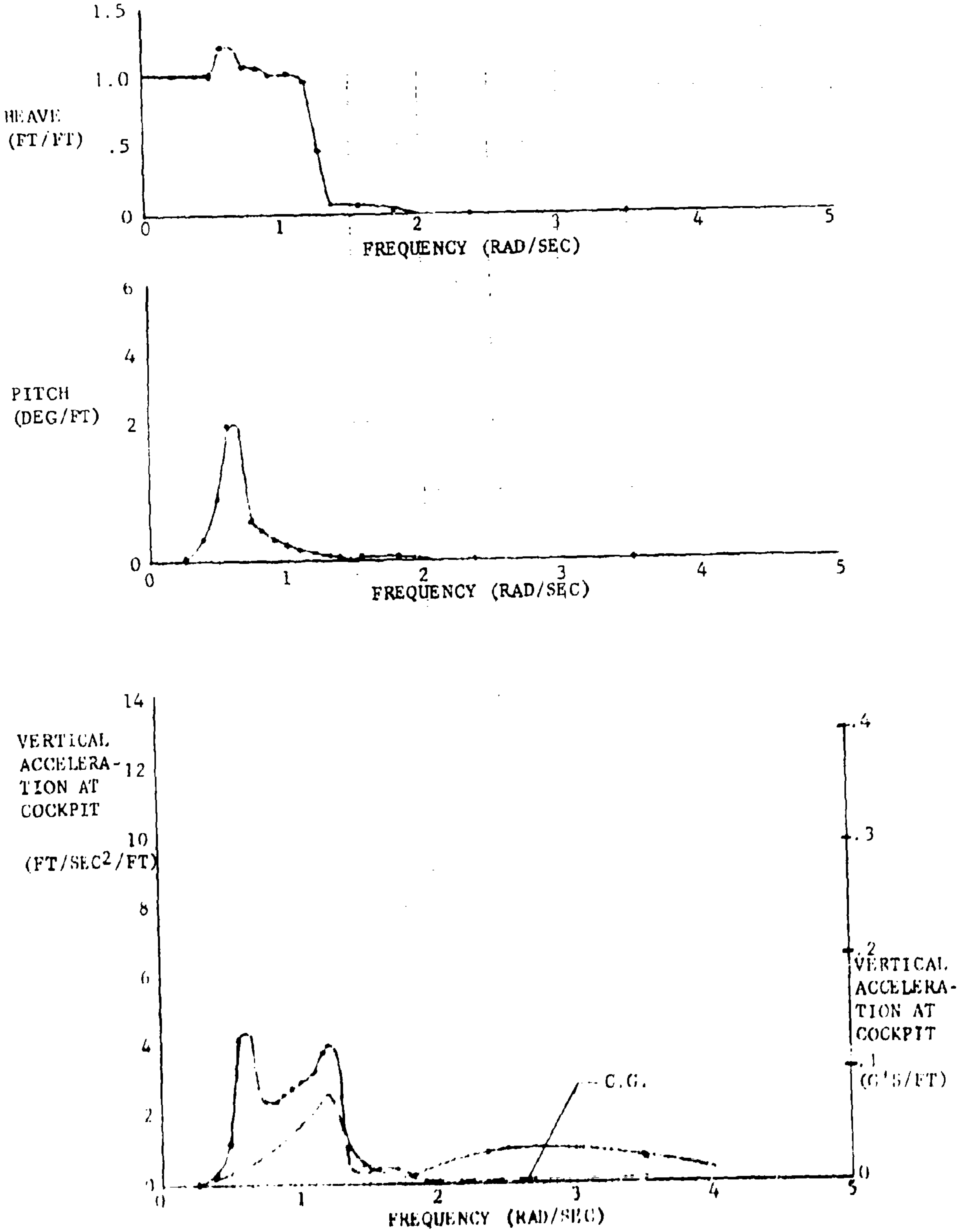


FIGURE 2. RESPONSE AMPLITUDE OPERATORS V = 5 KNOTS
CONFIGURATION 1 CTOL CAT 1.25M

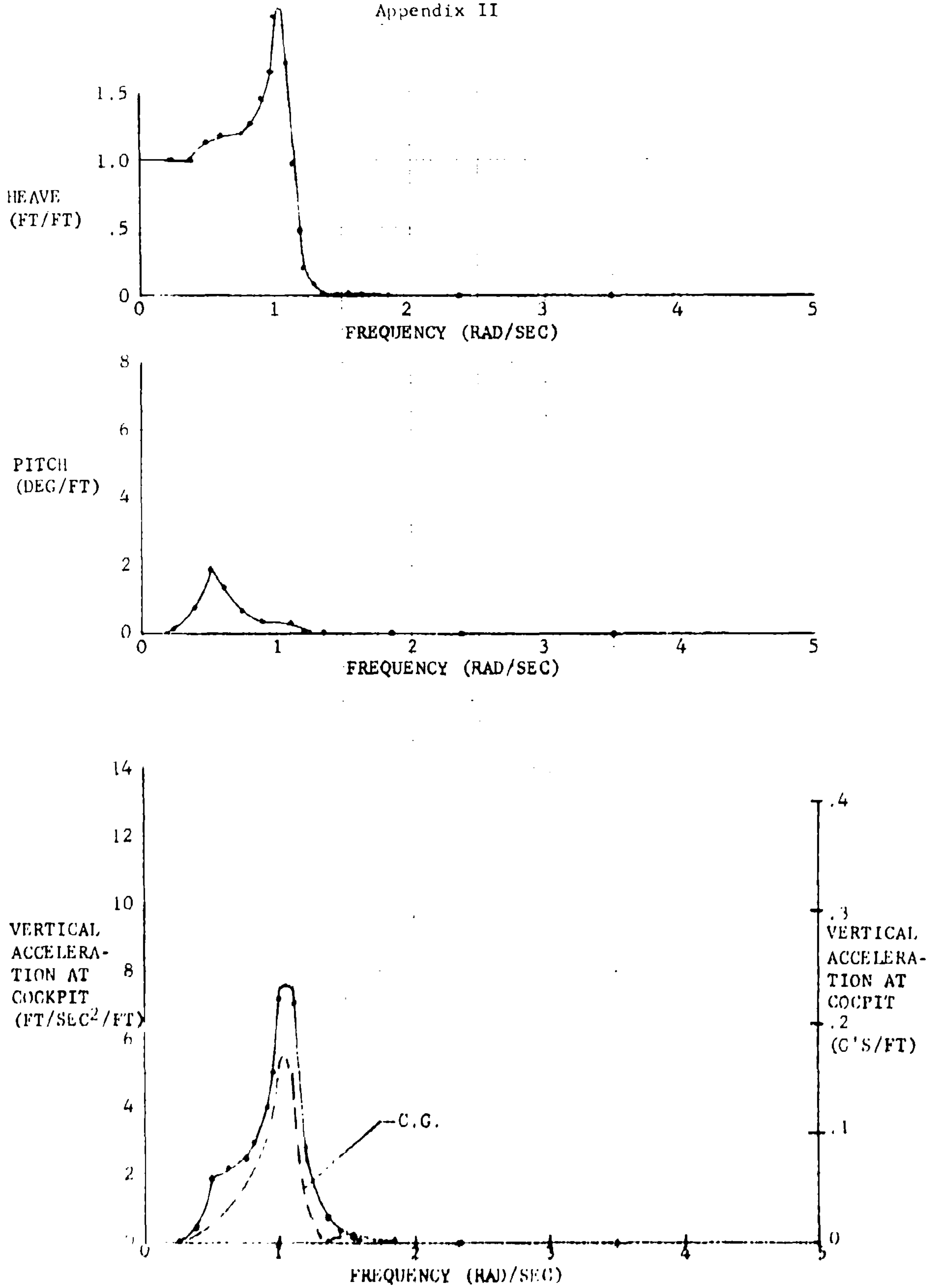


FIGURE 3. RESPONSE AMPLITUDE OPERATORS V = 10 KNOTS
CONFIGURATION I CTOL CAT 1.25M

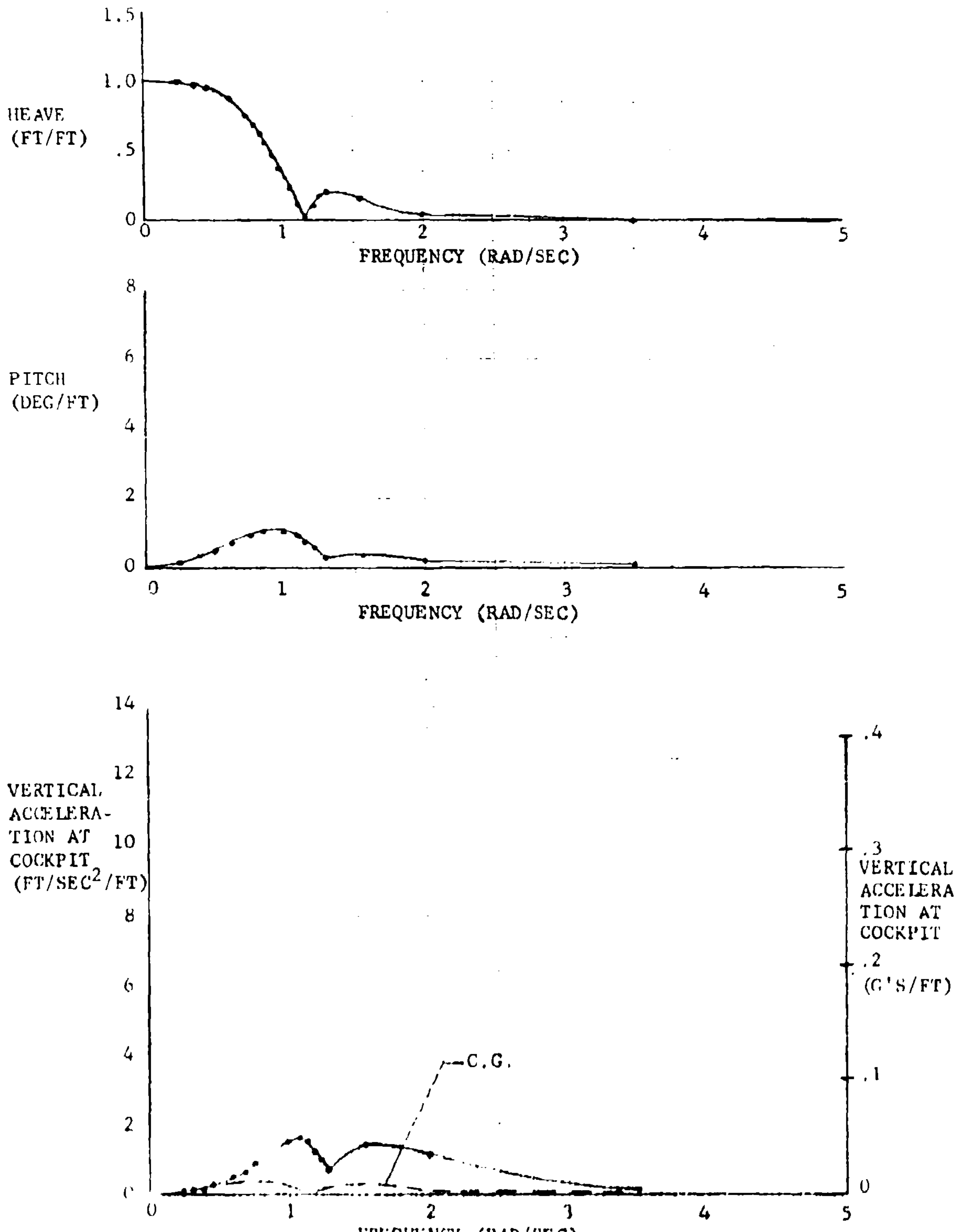


FIGURE 4. RESPONSE AMPLITUDE OPERATORS V = 0 KNOTS
CONFIGURATION 2 CTOL S.H. .769M

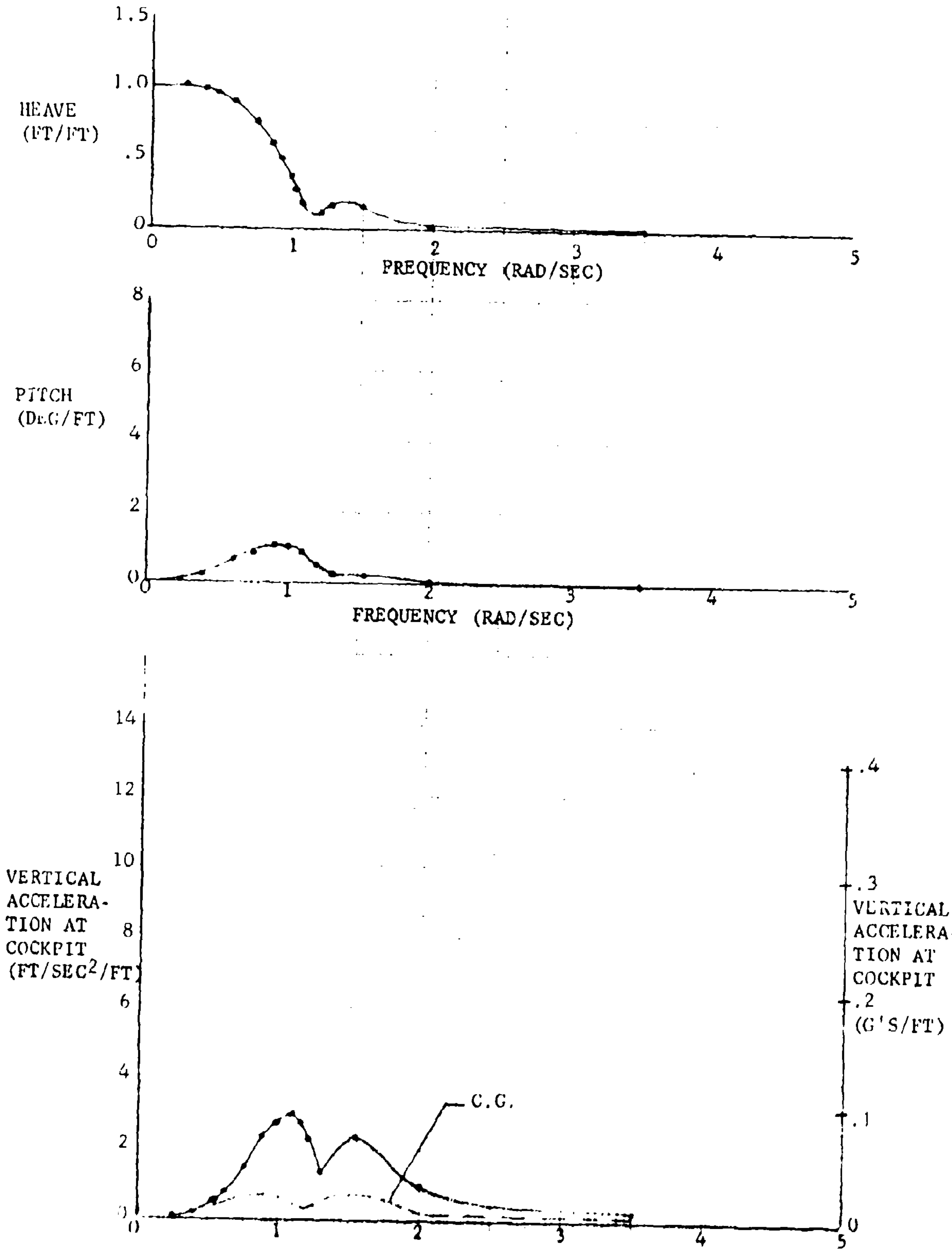


FIGURE 5. RESPONSE AMPLITUDE OPERATORS V = 5 KNOTS
CONFIGURATION 2 CTOL S.T. .769M̄

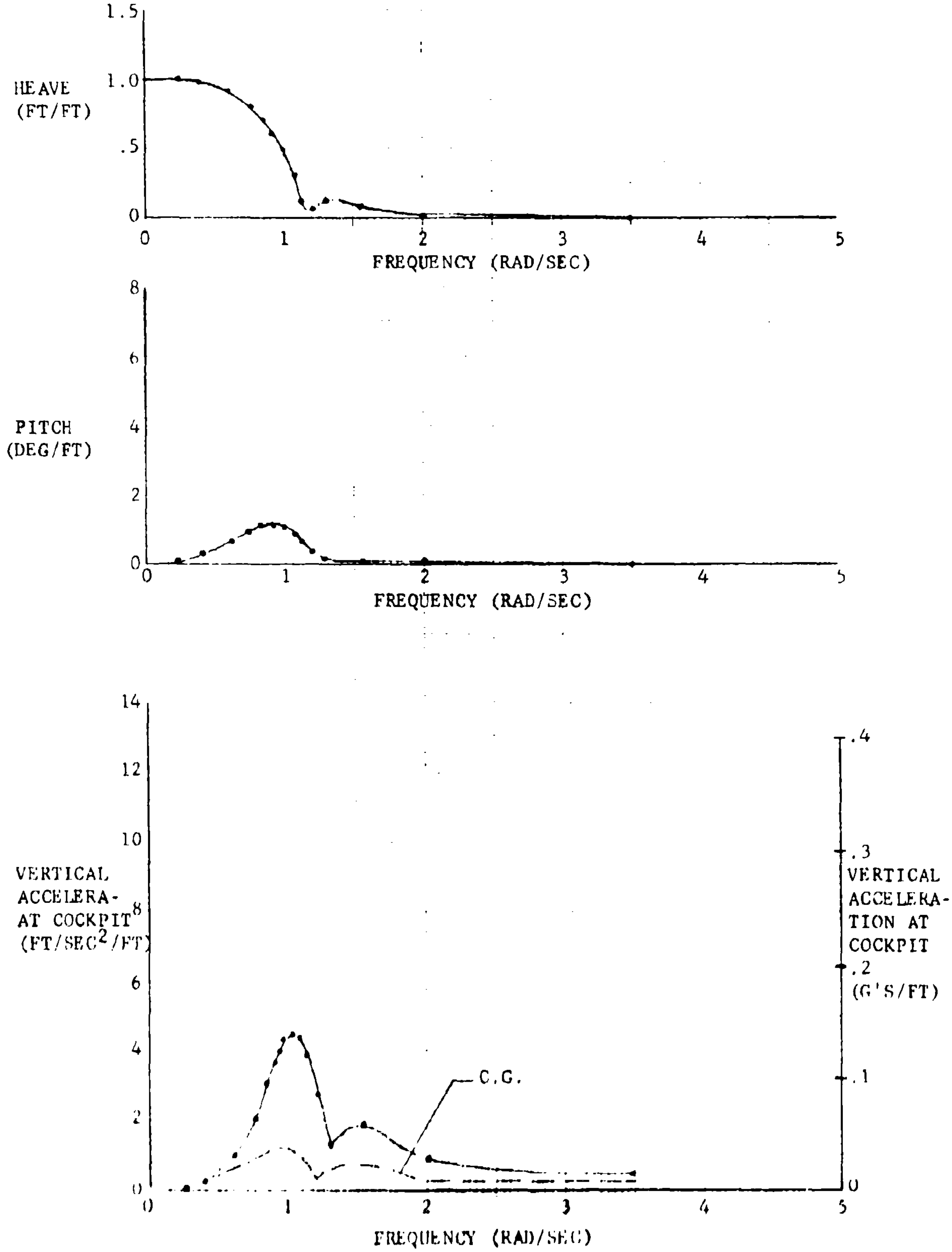


FIGURE 6. RESPONSE AMPLITUDE OPERATORS V = 10 KNOTS
CONFIGURATION 2 CTOL S.H. .769M

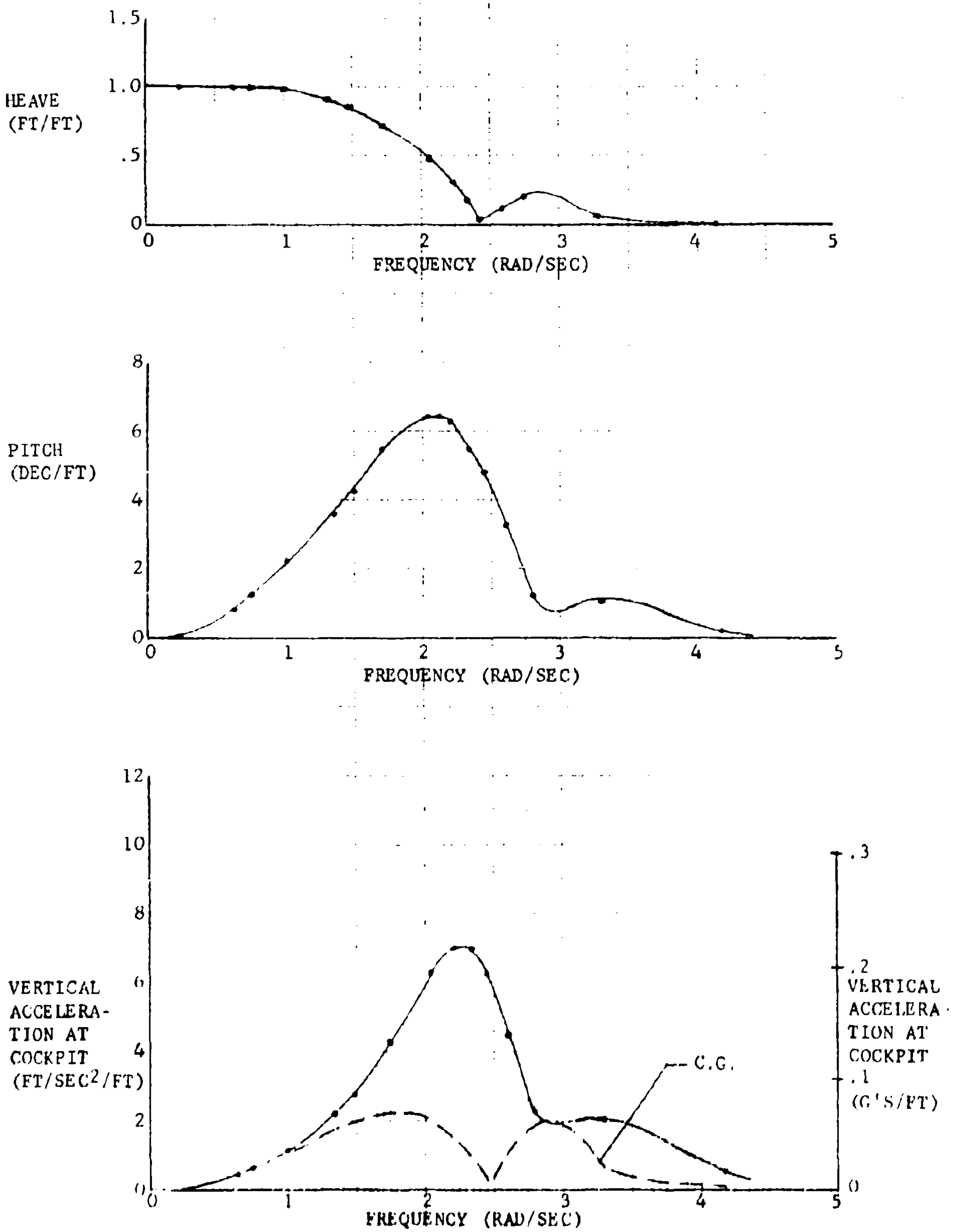


FIGURE 7. RESPONSE AMPLITUDE OPERATORS V= 0 KNOTS
CONFIGURATION 3 DTNSRDC 40K

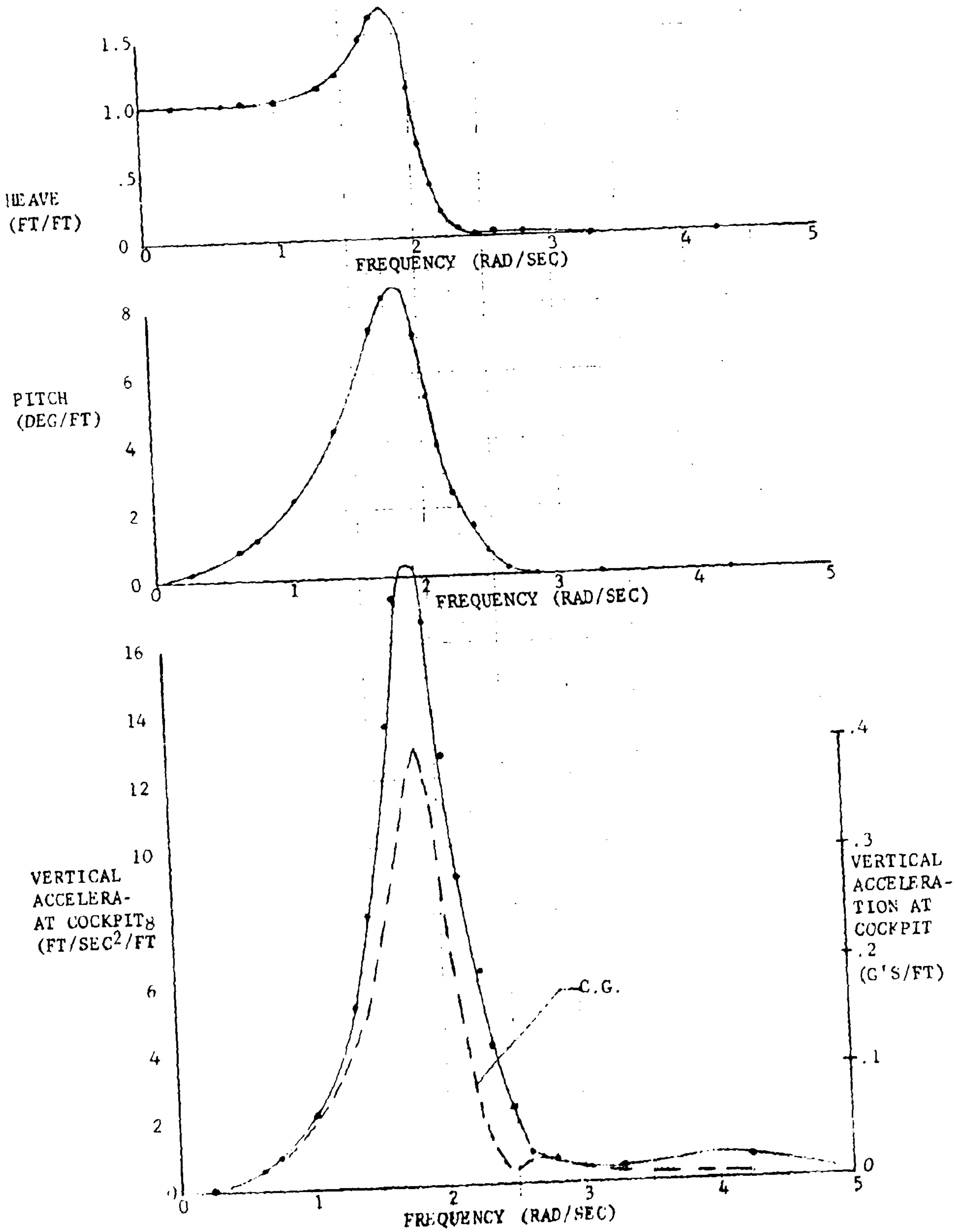


FIGURE 8. RESPONSE AMPLITUDE OPERATORS V- 5 KNOTS
CONFIGURATION 3 DTNSRDC 40K

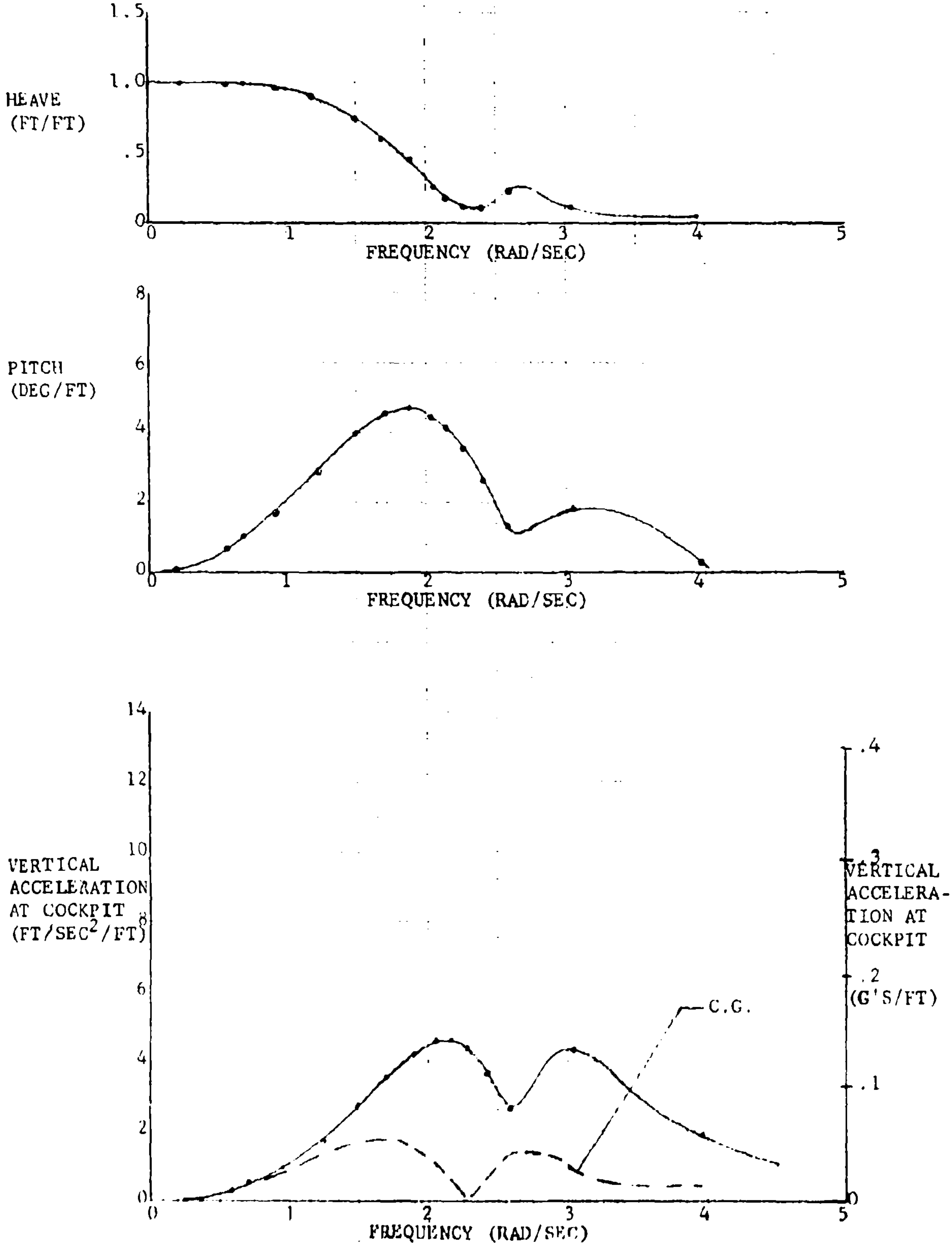


FIGURE 9. RESPONSE AMPLITUDE OPERATORS V = 0 KNOTS
CONFIGURATION 4 X-WING 40K

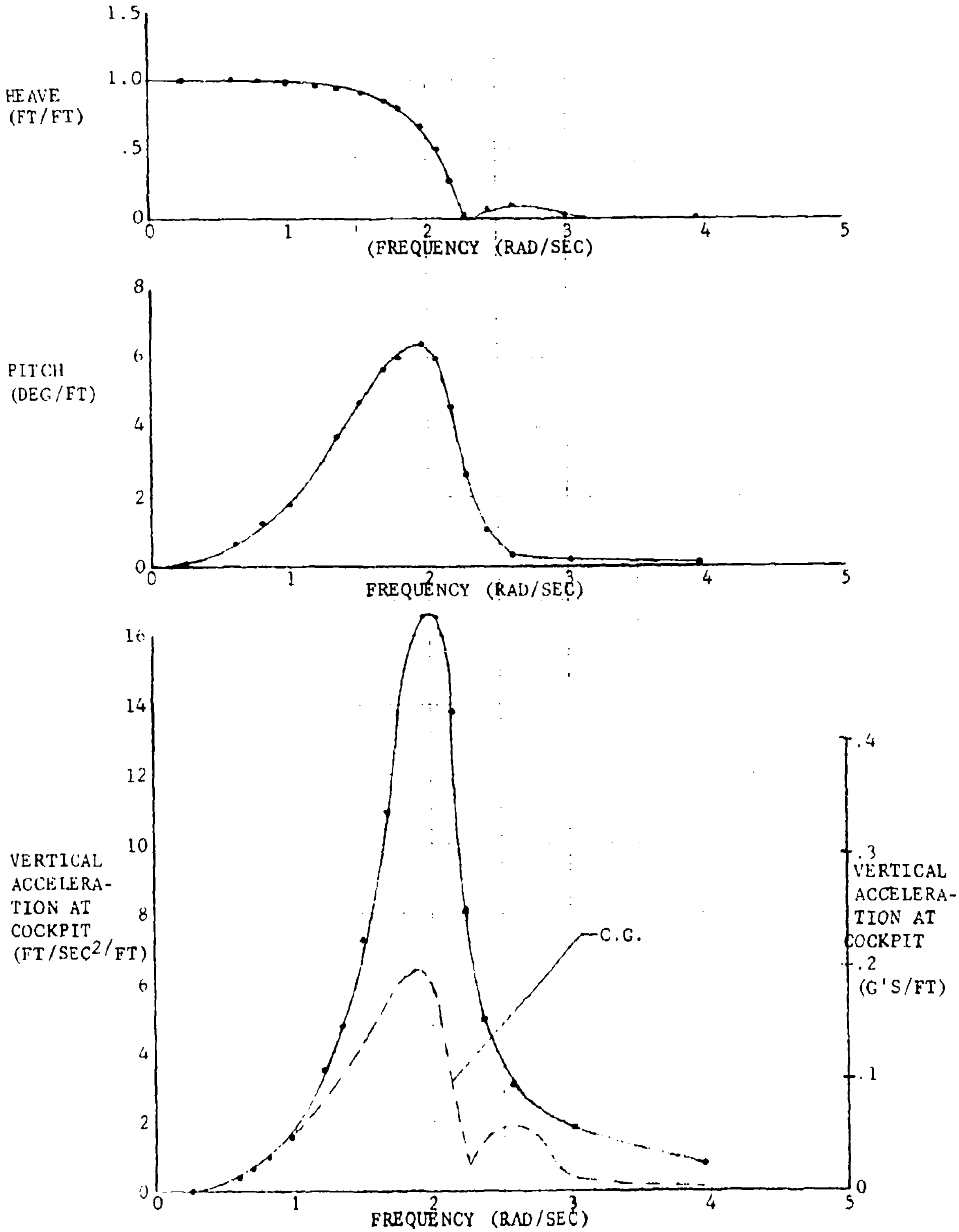


FIGURE 10. RESPONSE AMPLITUDE OPERATORS V = 5 KNOTS
CONFIGURATION 4 X-WING 40K

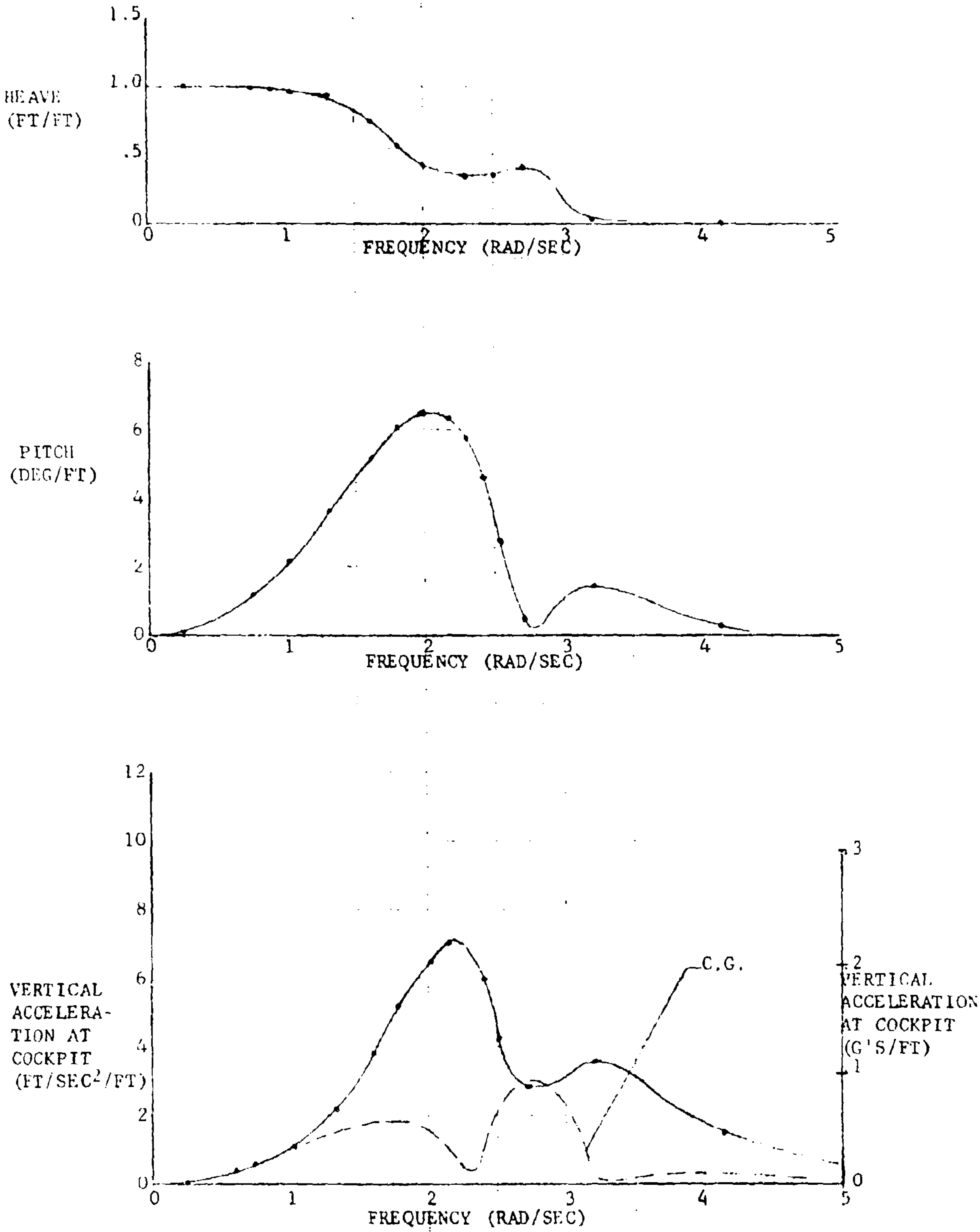


FIGURE 11. RESPONSE AMPLITUDE OPERATORS, V - KNOTS
CONFIGURATION 5 T.B. 40K

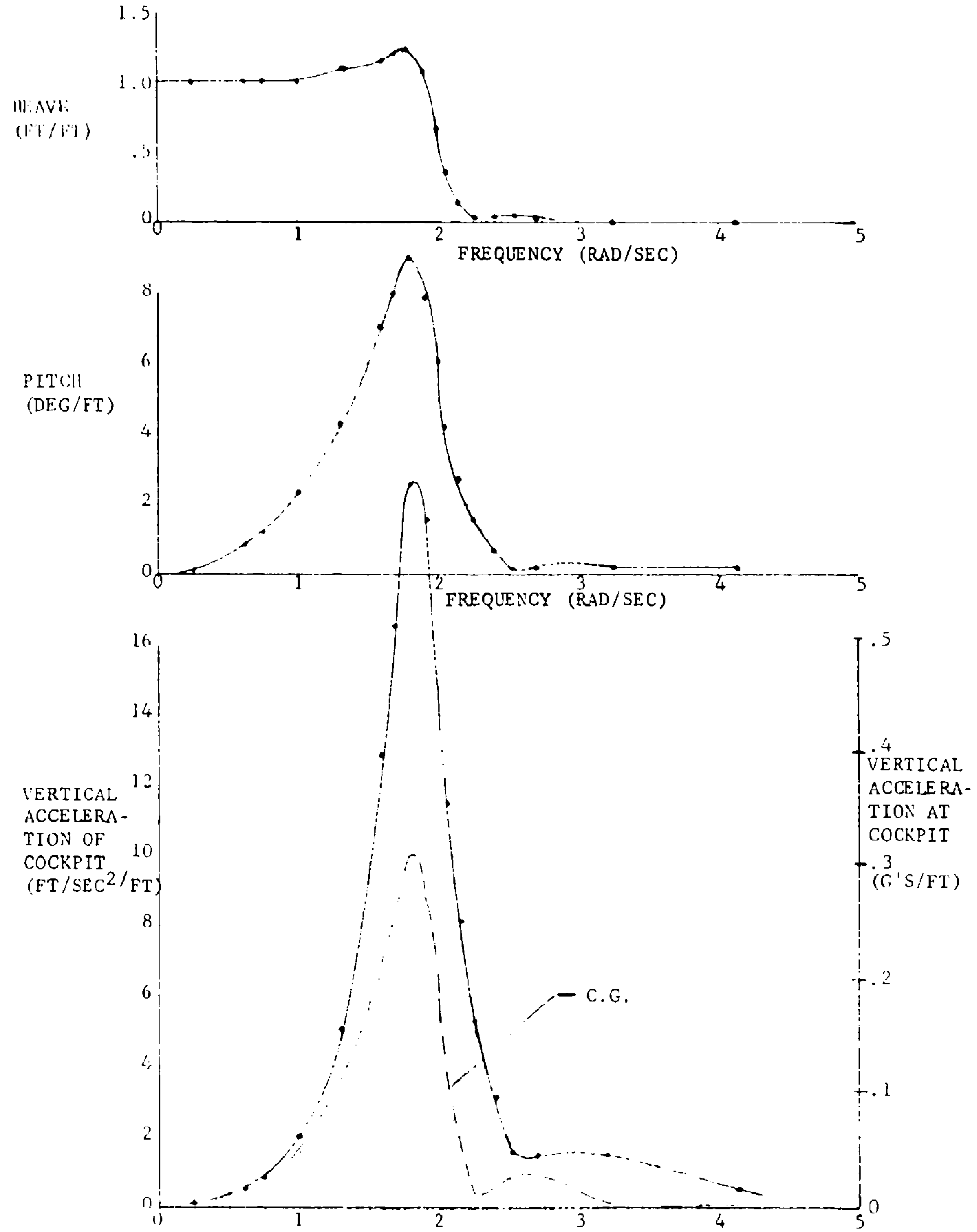


FIGURE 12. RESPONSE AMPLITUDE OPERATORS V = 5 KNOTS
CONFIGURATION 5 T.B. 40K

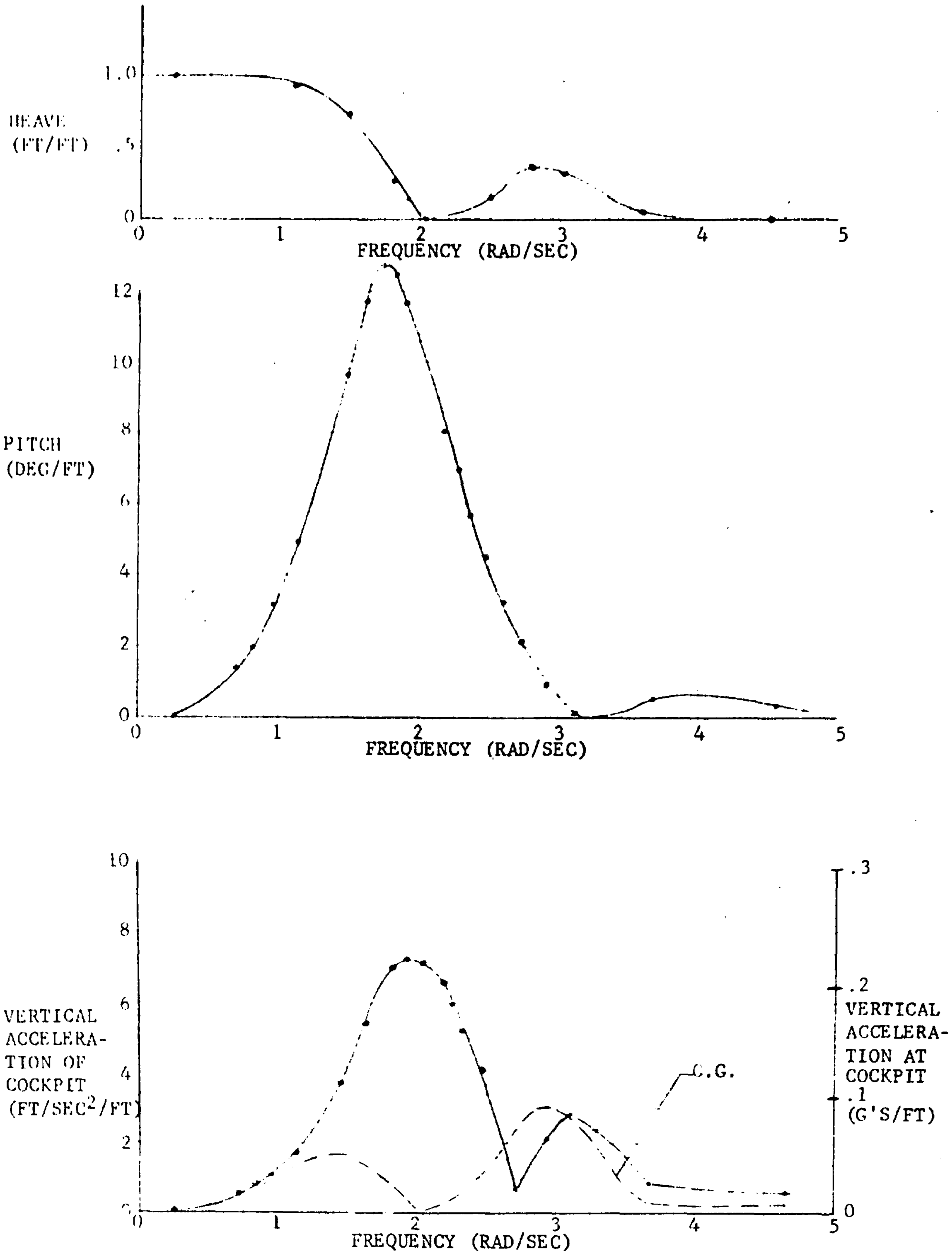


FIGURE 13. RESPONSE AMPLITUDE OPERATORS V - 0 KNOTS
CONFIGURATION 6 T.B. 25K

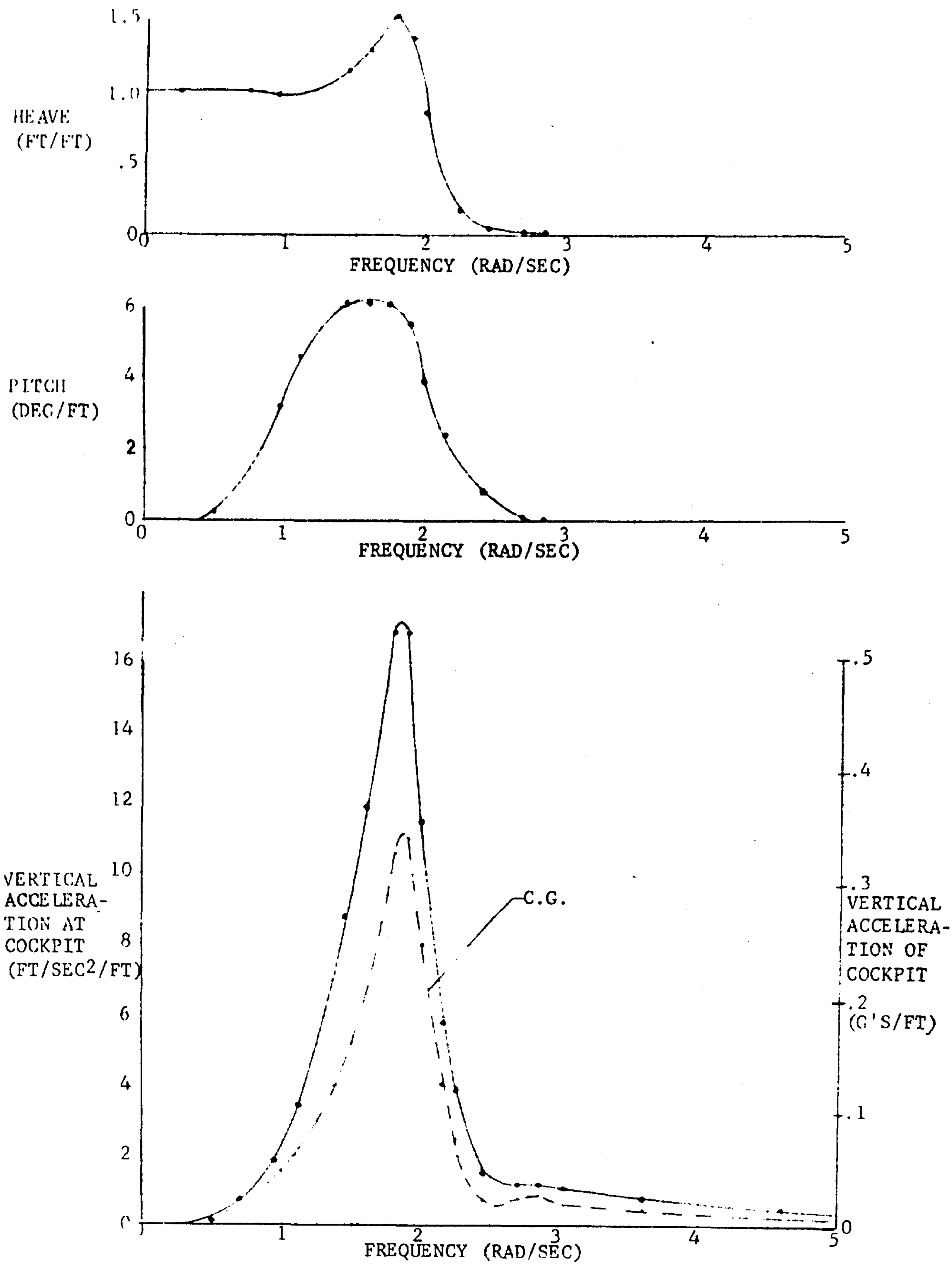
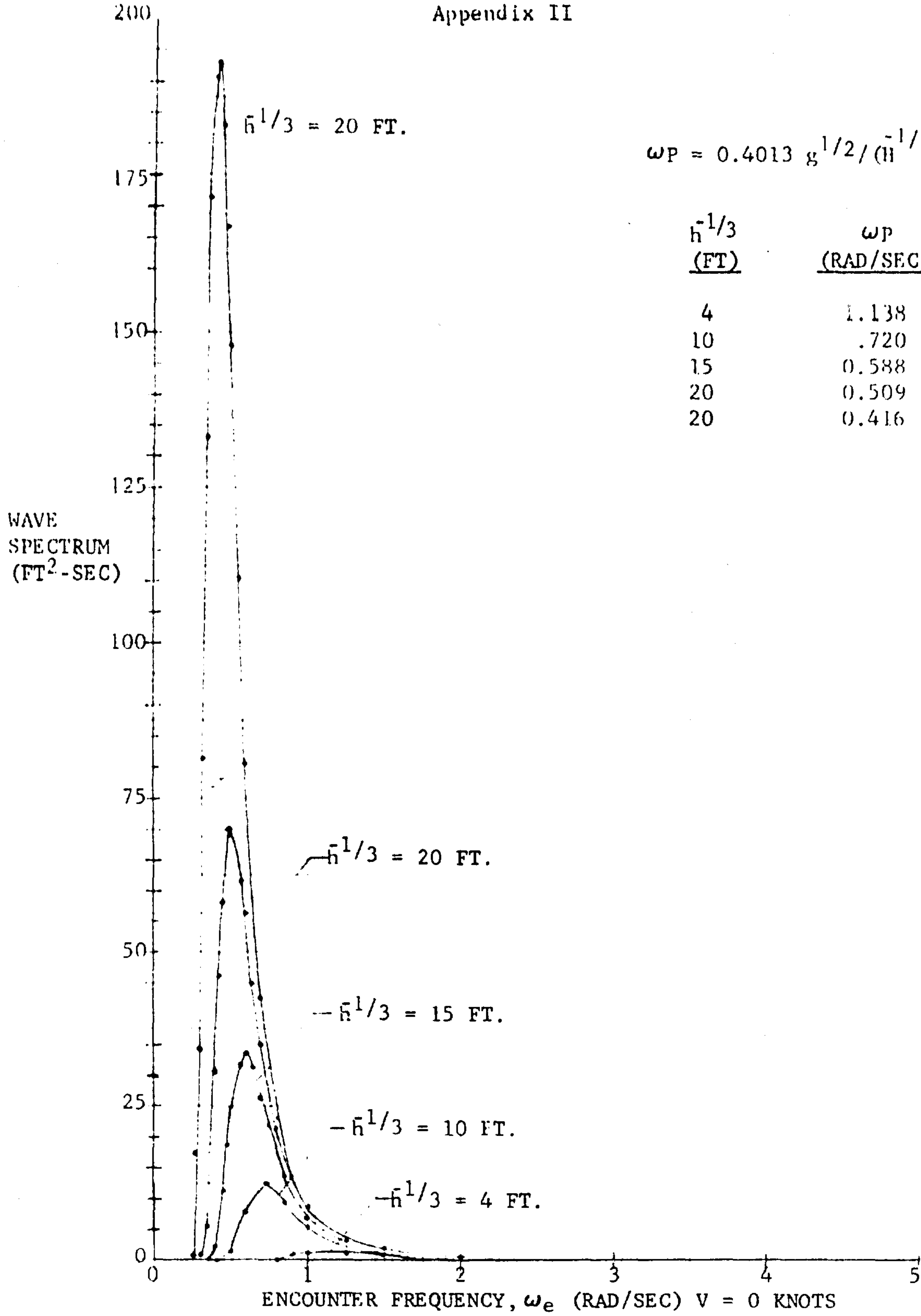


FIGURE 14. RESPONSE AMPLITUDE OPERATORS, V= 5 KNOTS
CONFIGURATION 6 T.B. 25K



$\omega P = 0.4013\ g^{1/2}/(\bar{H}^{1/3})^{1/2}$

$\bar{h}^{1/3}$ (FT)	ωP (RAD/SEC)
4	1.138
10	.720
15	0.588
20	0.509
20	0.416

FIGURE 15. WAVE SPECTRUM VS ENCOUNTER FREQUENCY

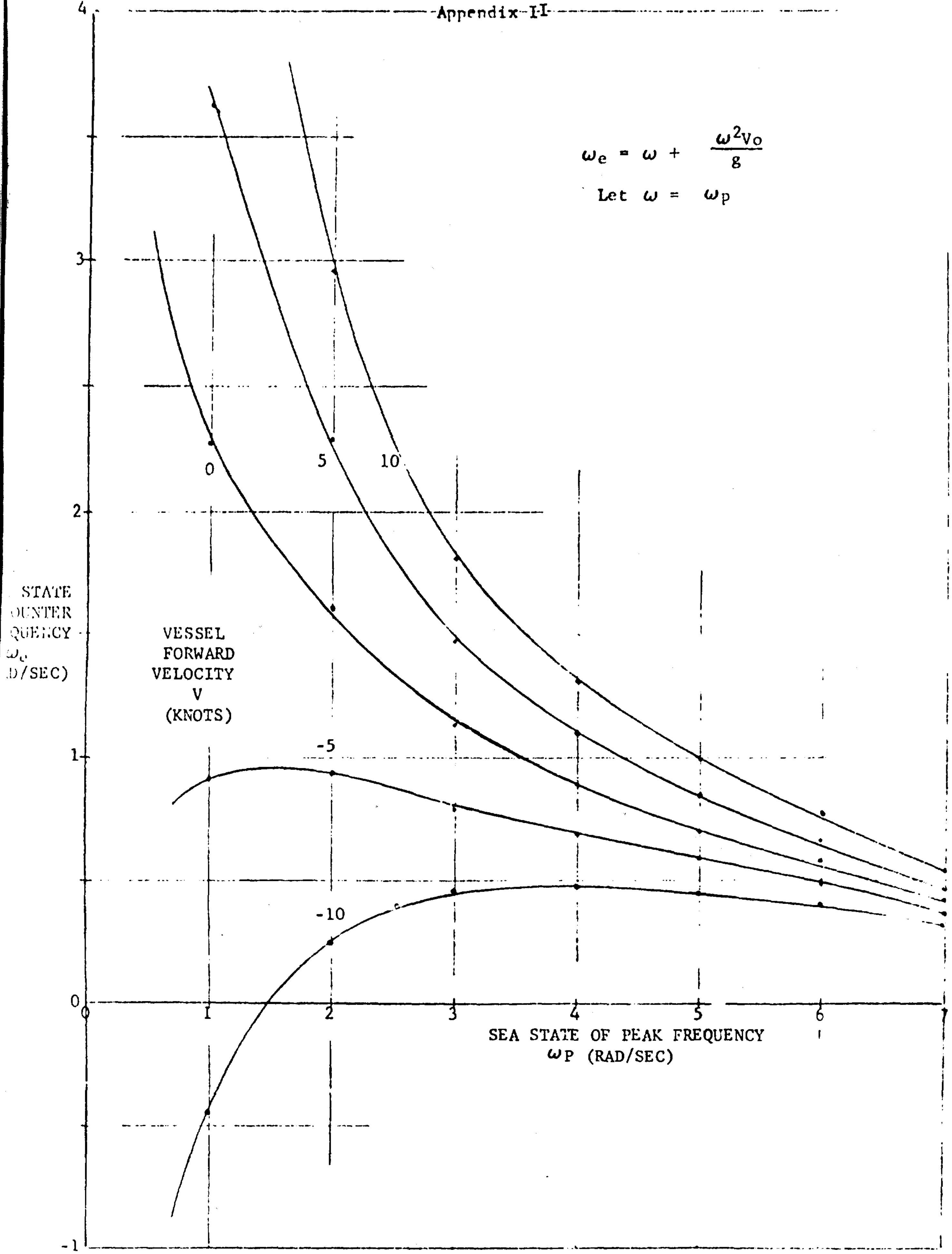


FIGURE 16. SEA STATE ENCOUNTER FREQUENCY VS SEA STATE