

AD-A070 368

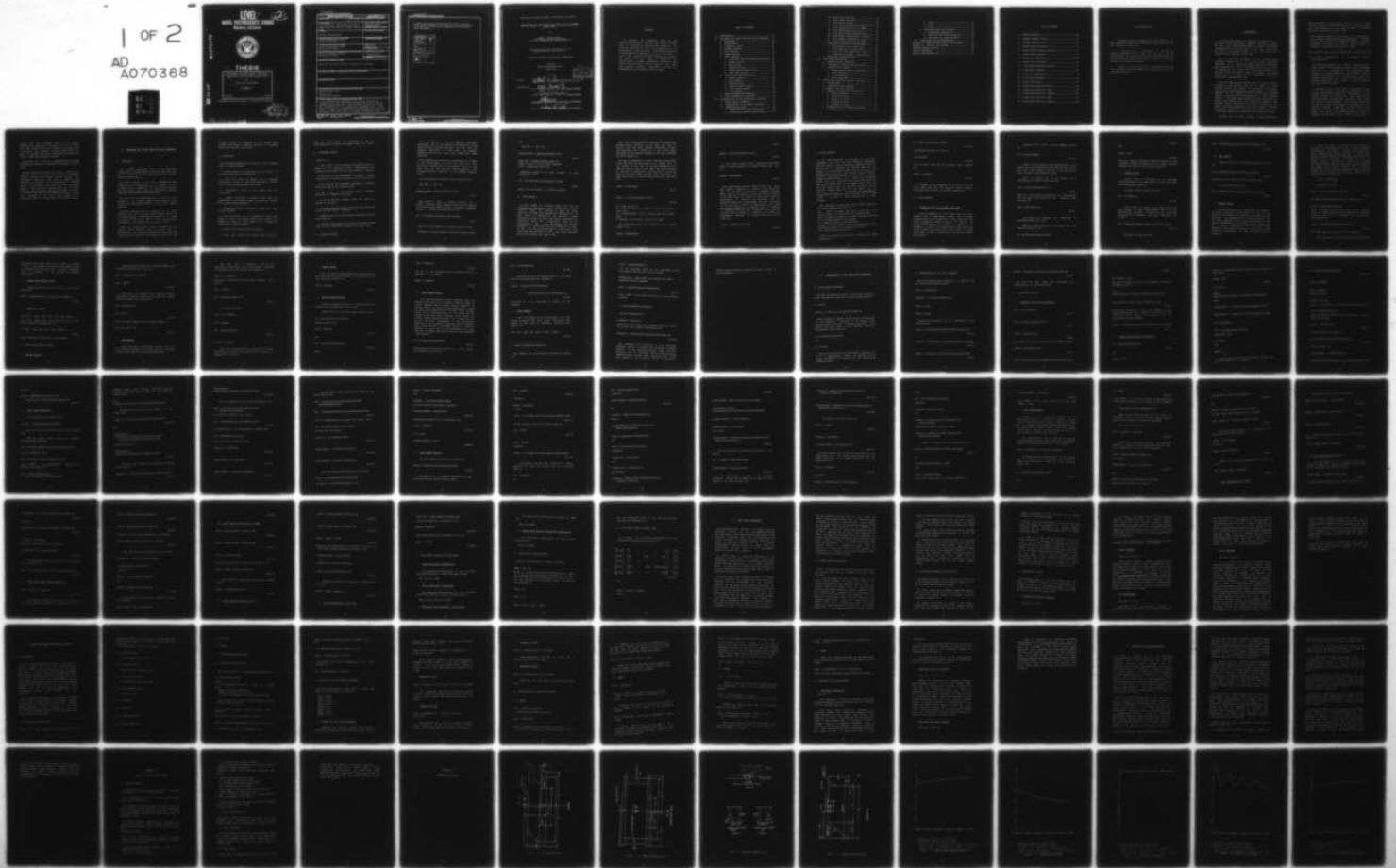
NAVAL POSTGRADUATE SCHOOL MONTEREY CA  
DEVELOPMENT AND TIME DOMAIN VALIDATION OF A LOW-ORDER, CONSTANT--ETC(U)  
MAR 79 L W BARNES

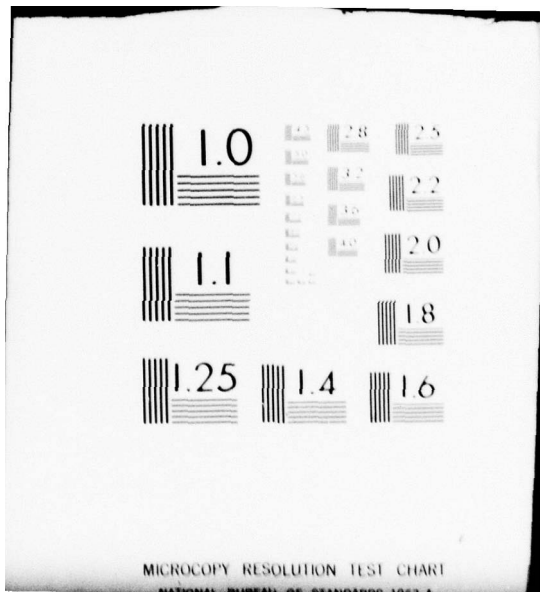
F/G 13/10  
CONSTANT--ETC(U)

UNCLASSIFIED

NL

1 OF 2  
AD  
A070368





MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1010A

LEVEL II

2

NAVAL POSTGRADUATE SCHOOL  
Monterey, California

AD A 070368



6 THESIS

Development and Time Domain Validation  
of a Low-Order, Constant Speed, Pitch-Heave  
Model for the XR-3 Surface Effect Ship

by

10 Leslie William Barnes

11 March 1979

9 Master's Thesis

12 IOP

Advisor:

A. Gerba

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

DDC FILE COPY

DDC  
RECEIVED  
JUN 26 1979  
RECEIVED  
D

257 450

79 06 22 048

505

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Development and Time Domain Validation of a Low-Order, Constant Speed, Pitch- Heave Model for the XR-3 Surface Effect Ship		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; March 1979
7. AUTHOR(s)  Leslie William Barnes		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, CA 93940		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, CA 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Postgraduate School Monterey, CA 93940		12. REPORT DATE March 1979
		13. NUMBER OF PAGES 119
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) surface effect ship XR-3 linear model heave-pitch dynamics		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An improved and simplified model for the Heave-Pitch dynamics of the XR-3 CAB Surface Effect Ship is developed for constant speed operation. The nonlinear equations of motion are linearized about the steady-state operating point. Time-domain validation is accomplished by comparison with the 6 DOF model. A signal flow graph of the craft dynamics is developed and Mason's Gain Rule used to determine the characteristic		



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

↘ S-Domain polynomials describing the craft's vertical plane dynamic behavior, with Bode Plot analysis included. Conclusions are drawn and recommendations for further study are made. ↗

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DDC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/ _____	
Availability Codes	
Dist.	Avail and/or special
A	

Approved for public release; distribution unlimited.

DEVELOPMENT AND TIME DOMAIN VALIDATION OF A LOW-ORDER,  
CONSTANT SPEED, PITCH-HEAVE MODEL FOR THE XR-3 SURFACE  
EFFECT SHIP

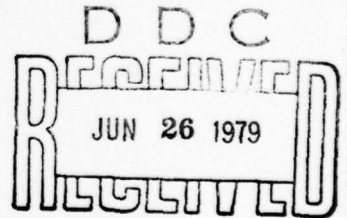
by

Leslie William Barnes  
Lieutenant, United States Navy  
B.S.E.E., University of New Mexico, 1972

Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the  
NAVAL POSTGRADUATE SCHOOL  
March 1979



Author:

*Leslie W. Barnes*  
-----  
D

Approved by:

*Greg Gerba Jr.*  
-----  
THESIS ADVISOR

*Greg Whaley*  
-----  
SECOND READER

*R. K. Kite*  
-----  
CHAIRMAN, DEPARTMENT OF ELECTRICAL ENGINEERING

*William M. Tolles*  
-----  
DEAN OF SCIENCE AND ENGINEERING

## ABSTRACT

An improved and simplified model for the Heave-Pitch dynamics of the XR-3 CAB Surface Effect Ship is developed for constant speed operation. The nonlinear equations of motion are linearized about the steady-state operating point. Time-domain validation is accomplished by comparison with the 6 DOF model. A signal flow graph of the craft dynamics is developed and Mason's Gain Rule used to determine the characteristic S-Domain polynomials describing the craft's vertical plane dynamic behavior, with Bode Plot analysis included. Conclusions are drawn and recommendations for further study are made.

## TABLE OF CONTENTS

I.	INTRODUCTION.....	10
II.	NONLINEAR XR-3 MODEL HEAVE AND PITCH EQUATIONS.	13
	A. BACKGROUND.....	13
	B. ASSUMPTIONS.....	14
	C. COORDINATE SYSTEM.....	15
	D. SIDEWALL MODELING.....	16
	E. SEAL MODELING.....	17
	F. PLENUM MODELING.....	20
	G. CRAFT DYNAMICS.....	21
	1. Plenum Air Mass and Pressure Equations.	21
	2. Buoyant Forces.....	23
	3. Seal Forces.....	24
	4. Planing Forces.....	24
	5. Plenum Gauge Pressure Lift.....	26
	6. Total Lift Forces.....	26
	H. CRAFT PITCH MOMENT EQUATIONS.....	26
	1. Buoyant Moments.....	26
	2. Seal Moments.....	27
	3. Planing Moment.....	29
	4. Plenum Pressure Moment.....	29
	5. Pitch Damping Moment.....	30
	6. Total Moments.....	31
	I. HEAVE ACCELERATION EQUATIONS.....	31
	J. PITCH ACCELERATION EQUATIONS.....	32
III.	LINEARIZATION OF THE HEAVE-PITCH EQUATIONS.....	34
	A. TAYLOR SERIES EXPANSION.....	34
	B. LINEARIZATION OF THE MODEL EQUATIONS.....	35
	C. LINEARIZED EQUATIONS.....	36
	1. Plenum Air Mass Flow Derivatives.....	36
	2. Plenum Gauge Pressure Derivatives.....	37



3.	Heave Force Partial.....	40
4.	Pitch Moment Partial.....	44
5.	Total Differentials.....	50
6.	Total Heave Force Differentials in Z...	51
7.	Total Differentials due to THETA.....	52
8.	Total Differential due to MB.....	53
9.	Total Pitch Moment Differentials in Z..	54
10.	Total Moment Differentials in THETA....	56
11.	Total Moment Differentials in MB.....	56
12.	Total Differentials of Air Mass.....	57
D.	TOTAL MODEL SENSITIVITY COEFFICIENTS.....	58
1.	Heave Sensitivity Coefficients.....	58
2.	Pitch Sensitivity Coefficients.....	58
3.	Plenum Air Mass Sensitivity Coeff.....	58
4.	Plenum Gauge Pressure Coefficients....	59
E.	STATE SPACE REPRESENTATION.....	59
IV.	TIME DOMAIN VALIDATION.....	61
A.	LINEAR PROGRAM DESCRIPTION.....	62
B.	SIX-DEGREE-OF-FREEDOM MODEL SOLUTION.....	63
C.	COMPARISON OF RESULTS.....	64
1.	Plenum Gauge Pressure Transient.....	64
2.	Draft Transient.....	65
3.	C.G. Acceleration.....	65
4.	Pitch Transient.....	66
V.	SIGNAL FLOW GRAPH AND MASON'S GAIN RULE.....	68
A.	INTRODUCTION.....	68
B.	SIGNAL FLOW GRAPH ANALYSIS.....	68
C.	MASON'S GAIN RULE APPLIED.....	70
D.	SOLUTION OF INDIVIDUAL POLYNOMIALS.....	71
1.	Graph Determinant.....	71
2.	Solution of $N_1(S)$ .....	72
3.	Solution of $N_2(S)$ .....	72
4.	Solution of $N_3(S)$ .....	73
5.	Solution of $N_4(S)$ .....	73
E.	SIMPLIFICATION OF TRANSFER FUNCTIONS.....	73
1.	$T_1(S)$ .....	73



2. T2(S) .....	74
3. T3(S) .....	75
4. T4(S) .....	76
F. SIMPLIFIED BODE PLOT ANALYSIS.....	76
1. Simplifying Assumptions.....	76
2. Bode Plots for Pitch Dynamics.....	77
3. Bode Plots for Heave Dynamics.....	77
VI. CONCLUSIONS AND RECOMMENDATIONS.....	79
Appendix A: LINEAR PROGRAM USER'S INSTRUCTIONS.....	83
Appendix B: DRAWINGS AND FIGURES.....	86
COMPUTER PROGRAM LISTING.....	105
LIST OF REFERENCES.....	116
INITIAL DISTRIBUTION LIST .....	118

## LIST OF FIGURES

1.	Assumed Geometry.....	87
2.	Assumed Geometry (cont).....	88
3.	Assumed Geometry (cont).....	89
4.	Plenum Chamber Modeling.....	90
5.	Linear Plenum Pressure Transient.....	91
6.	Linear Draft Transient.....	92
7.	Linear C.G. Transient.....	93
8.	Linear Pitch Transient.....	94
9.	6 DOF Plenum Pressure Transient.....	95
10.	6 DOF Draft Transient.....	96
11.	6 DOF C.G. Acceleration.....	97
12.	6 DOF Pitch Transient.....	98
13.	Signal Flow Graph.....	99
14.	Heave-Pitch Transfer Function.....	100
15.	Linear Pitch Bode Plot (mag).....	101
16.	Linear Pitch Bode Plot (phase).....	102
17.	Linear Heave Bode Plot (mag).....	103
18.	Linear Heave Bode Plot (Phase).....	104

## ACKNOWLEDGEMENTS

The Author wishes to acknowledge his gratitude to the many persons to whom he is indebted for their assistance in the completion of this work.

A special note of appreciation is extended to Associate Professor Alex Gerba Jr., not only for his encouragement and assistance, but also for sharing with the author his insight into many areas of control engineering, modeling, and design philosophy.

Finally, to my wife, Marianne, special gratitude for the patience and encouragement she has provided to help me through this period.

## I. INTRODUCTION

In 1973 Leo and Boncal [1] converted the Oceanics Inc. 6 DOF Loads and Motions digital computer simulation program for the 100-B Surface Effect Ship to reflect the physical characteristics of the XR-3 craft. Since that time there has been a continuous effort at the NPS to update and improve on this simulation [2,3,4,5].

One of the major drawbacks of that program which precludes regular use of it for sea state operations simulation is the excessive computational and turn-around times required [6]. As it is presently desired to use the 6 DOF simulation for design and evaluation studies of the proposed 3K Ton SES control System in varying sea state conditions, it is important to significantly reduce the simulation's computational time.

One area where the possibility exists to achieve a major reduction in computational time is the manner in which sidewall forces and moments are calculated. The present form of the 6 DOF program uses a large number of discrete sections (28 per sidewall) with an off-line table look-up scheme to determine the forces generated in each discrete section. The simple model derived by McIntyre [7] uses two sections per sidewall with very simplified geometry that permits on-line computation of the forces and moments. The result of eventual incorporation of this sidewall geometry and forces calculation into the 6 DOF program should be a significant reduction of computation and turn-around time.

Another area of great interest in SES Simulation is



gaining insight into the dynamic behavior of the craft's vertical motion of pitch and heave due to pressure induced lift forces generated in the plenum and seals. As stated in ref [8] as recently as August, 1978,

"The overall precision of the analysis is satisfactory for predicting stability and maneuverability. However, several areas present very complex or difficult physical phenomena to analyze and further effort should be invested to improve understanding of these."

The first area for continuing investigation recommended was;

"A better determination of pitch-heave dynamic characteristics."

An improved knowledge of the dynamic characteristics brought about by the pressure induced forces and moments could lead to a reduction of the computation time required for craft simulation. These pressure effects introduce a stiffening in the integration of sea state induced oscillations and a better understanding of processes could lead to the removal of this stiffness and thus reduced CPU time.

In this work both of these areas are considered. First of all the various craft physical characteristics are modeled, resulting in changes and improvements to the initial efforts by McIntyre [7]. These equations are linearized about a steady-state operating point using the Taylor Series expansion. The linearized equations are cast into a State Space format and simulated on the digital computer. Comparison is made between the time-domain results of the linear model and the 6 DOF model. The State Space representation is used to generate a signal flow graph. Mason's Gain Rule is



applied and the S-domain roots of the craft's characteristic equations are located and it is shown that some simplification and reduction of system order is possible. The resultant S-domain polynomials are used to generate Bode Plots to graphically display the craft's simplified frequency response.

Conclusions are drawn and recommendations are made concerning the validity of the model and areas for future study.

Several procedural notes are in order. Because all equations are to be solved digitally using the FORTRAN computer language and because digital computer text processing facilities were used to generate this document, all formulas will be presented in FORTRAN format. In the thesis body reference to the "nonlinear model", "six degree-of-freedom model" or "6 DOF" model all mean the Loads and Motions program as adapted to the XR-3 test craft at the Naval Postgraduate School [3]. Reference to the linear model refers to the linearized model of the same craft as developed herein.

## II. NONLINEAR XR-3 MODEL HEAVE AND PITCH EQUATIONS

### A. BACKGROUND

The original development work on the simplified two-degree-of-freedom model was done by McIntyre [7]. Several weaknesses in the original model were noted by McIntyre in that work.

The major portion of the work presented here was involved in close examination of all aspects of the original model, comparison of the modeling techniques used therein with other methods and remodeling of several important craft physical characteristics.

One major area of investigation was the lack of pitch damping in the original model, which resulted in the addition of an added-mass effect to the pitch moment equations.

Additional changes involve a revision of the force equations for the rear seal, major changes in the way the plenum chamber is modeled (also added to the loads and motion 6-dof model [2]), and a more rigorous development of the planing force equation of [7].

There are several areas of theory concerning CAB SES modeling where empirical data is lacking due to difficulties with physical measurements. One such area inviting closer inspection was dynamic variation of the

effective center of pressure for the plenum gauge pressure lift effect. A possible approach is suggested herein and included in the model.

## B. ASSUMPTIONS

The following assumptions are made for this constant speed, pitch-heave model:

1. Planing forces are concentrated at the centroid of the keel longitudinal cross section.

2. Total seal force is lumped into a pressure differential acting on the seal face area in contact with the water passing beneath the seal.

3. Aerodynamic forces on the forward seal are disregarded.

4. Dynamic variations in moment lever arms are disregarded for all moments except seals and the moment due to plenum gauge pressure.

5. Dynamic variations in effective plenum roof area will be included.

6. Any lift effects due to aerodynamic forces are lumped in with the planing forces (for reasons to be developed in Chapt IV.) The moments are included in plenum gauge pressure moments .

7. Constant seal leakage area is assumed.

8. Since this model is for constant surge velocity,

drag and thrust forces are considered to be in equilibrium and in balance for moments about the Y axis.

#### C. COORDINATE SYSTEM

(see fig. 1 )

1. The origin of the cartesian coordinate system is located at the calm-water line, longitudinally and transversely coincident with the craft center of gravity.

2. The X axis is the longitudinal coordinate defined as positive as X increases towards the bow of the craft.

2. The Y axis is the transverse coordinate increasing positively towards the starboard side.

4. The Z axis is the vertical axis, increasing positively in a downward direction.

5. ZS is the vertical distance from the center of gravity to the keel.

6. Z is the vertical distance from the calm water line to the vertical center of gravity.

7. THETA is the pitch angle defined as positive as the bow pitches up.

8. Positive pitch moments are defined as moments which tend to cause a positive increase in the angle THETA.

#### D. SIDEWALL MODELING



As it was desired to keep all physical dimensions consistent with the six degree of freedom model, scale model drawings were developed with the data from the sidewall subroutine of that model. All sidewall dimensions used in this model were taken from those drawings.

The sidewalls are modeled in two sections, one forward of the longitudinal C.G. and the other aft. Each sidewall is considered to be of constant width at the water line and the keel, with width increasing in the vertical direction according to an average deadrise angle.

The average forward sidewall area is found to be:

(see fig. 2 and 3b )

$$\text{AVERAGE WIDTH} = \text{LDBAR1} / (2 * \text{TAN}(\text{DR1})) + \text{WS10}$$

(II-1)

where LDBAR1 is draft at forward centroid, DR1 = average deadrise angle forward and WS10 is the average keel width of the forward section. Therefore submerged volume of a forward sidewall is given by:

$$\text{VOL} = \text{L1} * (\text{LDBAR1} / (2 * \text{TAN}(\text{DR1})) + \text{WS10}) * \text{LDBAR1}$$

(II-2)

where L1 is the length of a forward buoyant section.

Following the same procedures the after sidewall width



is:

(see fig. 2 and 3c )

$$\text{AVERAGE WIDTH} = \text{LDBAR2} / (2 * \text{TAN}(\text{DR2})) + \text{WS20}$$

(II-3)

where DR2 = average deadrise angle aft  
LDBAR2 = draft at after buoyant centroid  
WS20 = average keel width aft

Submerged volume of an after sidewall is then determined to be;

$$\text{VOL} = \text{L2} * (\text{WS20} + \text{LDBAR2} / (2 * \text{TAN}(\text{DR2}))) * \text{LDBAR2}$$

(II-4)

where L2 is the length of the after sidewall.

#### E. SEAL MODELING

A major change in McIntyre's model was made by remodeling the stern seal. In the original model a large negative moment was required to place the pitch equations in steady state equilibrium. Investigation of seal forces as presented in [9] revealed a large discrepancy between the after seal forces generated in McIntyre's model and calculations based on the information in [9]. This discrepancy was further supported by actual seal load data presented by Layton in [10]. All seal dimensions used in this model were taken from data presented in [11]. Seal hinge locations were taken from the data used in [5].

Seal lift force forward is generated by plenum gauge pressure acting downward on the seal face area in contact with the water passing underneath the seal. This downward force results in a lift force being generated as the downward movement of the seal displaces the water beneath it.

The seal is considered to have a straight forward face which runs from the hinge point at the plenum roof to the bottom of the keel at an angle determined to be best-fit from the data in ref. [1]. The wetted surface of the seal is considered to lay parallel to and on the water at the point where the seal face intercepts the calm water line. as a result forward seal lift equations are:

$$ASEAL1 = WIDTH * XSEAL1$$

(II-5)

$$XSEAL1 = (LD - L3 * TAN(THETA)) / SIN(31)$$

(II-6)

LD = draft at the C.G

L3 = distance from C.G to point of contact for forward seal face.

LD - L3 \* TAN(THETA) = draft at forward seal face contact point

31 degrees is the interior angle of the seal.

The after seal wetted area is determined in a similar manner to be :

$$ASEAL2 = WIDTH * XSEAL2$$

(II-7)

$$XSEAL2 = (LD+L4*TAN(THETA))/SIN(32)$$

(II-8)

In this model forward seal pressure is considered equal to plenum pressure. As a result forward seal lift is :

$$HSEALF = PBBAR*ASEAL1$$

(II-9)

Since plenum guage pressure tends to force the after seal upward, resulting in venting of the plenum air mass, the rear seal is operated at a pressure slightly above that of the plenum to reduce the venting tendency of the after seal. As a result the after seal requires a modification in modeling. In McIntyre's work the pressure differential (PSEAL-PBBAR) only was considered in the lift force. However, as previously stated, there were large discrepancies in computed loads as compared to measured data from [10]. Therefore in this model, the seal working pressure is considered to be PBBAR plus differential pressure. As a result after seal lift is given by:

$$HSEALA = (PBBAR+PDIFF)*ASEAL2$$

(II-10)

## F. PLENUM MODELING

In the work presented by McIntyre the plenum was considered a box with the only dynamic dimensional variation being in the Z direction. However (as can be seen in fig. 1), although the forward edge can be assumed to be reasonably constant in the Y-Z plane, the forward face of the rear seal slopes rather steeply. Therefore the plenum length (in the X direction) varies rapidly as draft varies. As a result the effective plenum roof area consists of that area from the after edge of the forward seal to the forward hinge point of the rear seal, plus the vertical projection of the unwetted forward face of the rear seal. As an additional consequence it can be seen that the effective plenum center of pressure varies fore and aft as draft varies. In fact as draft increases the C.P. moves forward.

The following variable names will be used to describe the plenum chamber (see fig. 4.)

LPR = length of plenum roof from the rear edge of the forward seal to the hinge point of the after seal.

LPWL = length of plenum at the keel from the after edge of the forward seals to the transom.

LP = length of plenum at the waterline.

BUBHGT = vertical distance from the plenum roof to the bottom of the keel at the center of gravity.

AB = plenum effective roof area.

Using the previous definitions, the plenum roof length and area is:

$$LP = LPWL - (LPWL - LPR) * (LD / SUBHGT)$$

(II-11a)

and effective plenum roof area is

$$AB = WIDTH * LP$$

(II-11b)

with the result that lift due to plenum gauge pressure is:

$$HPRES = -AB * PBBAR$$

(II-11c)

As a comment on the complexity of the lift forces of this model note that for constant plenum pressure increased draft results in decreased plenum lift.

## G. CRAFT DYNAMICS

### 1. Plenum Air Mass and Pressure Equations

For the purposes of this model the rear seal leakage area is considered constant since to assume otherwise would lead to modeling a very difficult and poorly understood dynamic process. In addition the plenum pressure VS air mass process is assumed to be adiabatic in nature. Fan characteristics are those used in the constant air leakage heave only model of Gerba and Thaler in [14]. Air flow into the plenum is taken as positive.



Therefore the airflow into the chamber is given by:

$$Q_{in} = N*(Q_{I0} - K_f * P_{BBAR})$$

(II-12)

Where N is the number of fans supplying air to the plenum,  $Q_{I0}$  is the equilibrium air flow rate for the fan with zero gauge pressure and  $K_f$  is the slope of the fans' airflow VS gauge pressure curve .

$Q_{out}$  is airflow out of the plenum and is determined by the seal leakage equation:

$$Q_{out} = C_n * A_l * (2 * P_{BBAR} / \rho_{HOA})^{**1/2}$$

(II-13)

Where  $C_n$  = seal leakage coefficient,  $A_l$  = seal leakage area, and  $\rho_{HOA}$  = mass density of air. Therefore mass flow rate is:

$$M\dot{B} = \rho_{HOA} * (Q_{in} - Q_{out})$$

(II-14)

The plenum air dynamics are considered in equilibrium when  $Q_{in} = Q_{out}$

Absolute Plenum Pressure is determined from the adiabatic gas law to be:

$$P_b = P_a * (M\dot{B} / (\rho_{HOA} * P_{BBAR}))^{**GAMMA}$$

(II-15)

and,

$$PBBAR = P_b - P_a$$

(II-15a)

Where  $P_a$  = ambient atmospheric pressure (LBF/FT\*\*2)  $\gamma$  = adiabatic process coefficient,  $P_b$  = plenum absolute pressure, and  $PBBAR$  = plenum gauge pressure.

## 2. Buoyant Forces

Buoyant force is calculated by the submerged volume multiplied by the mass density of the fluid times the gravitational constant.

Therefore forward buoyant force is:

$$HBF = -2 * RHO * G * VOL$$

(II-16)

Where volume is given by eqn. II-2,  $RHO$  is the mass density of water (slugs/ft\*\*3) and  $G$  is the gravitational constant. The factor of 2 is introduced to account for 2 sidewalls. The total expression for  $HBF$  is:

$$HBF = -2 * RHO * G * L1 * LDBAR1 * (LDBAR1 / (2 * TAN(DR1)) + WS01)$$

(II-17)

Following the same pattern,

$$HBA = -2 * RHO * G * L2 * LDBAR2 * (LDBAR2 / (2 * TAN(DR2))) = WS10)$$

(II-18)

### 3. Seal Forces

Forward seal force is determined from eqn. II-9 to be:

$$HSF = -PBBAR * WIDTH * (LD - L3 * TAN(THETA)) / SIN(31)$$

(II-19)

where HSF is the heave force due to forward seal.

In a similar manner HSA is:

$$HSA = (PBBAR + PDIFF) * WIDTH * (LD + L4 * TAN(THETA)) / SIN(32)$$

(II-20)

### 4. Planing Forces

McIntyre introduced the planing force phenomena in his model to account for the proven fact that the CAB SES tends to decrease its draft and pitch down as speed increases. His development of the planing equation was not well explained and the basis for selection of the planing coefficient was not clearly stated. Reidel [12] did a special investigation of the planing force phenomena. His results were based on flat plate planing effects to approximate the flat bottom of the craft sidewalls.

Since the water is in contact with the vertical portions of the sidewalls it was felt a more accurate representation was needed. Barnaby [13] states that water contact on the vertical sides of a planing hull rapidly reduces planing lift advantage since one of the advantages of a planing hull is reduced drag due to wetted surface. planing lift results in a speed sensitive tradeoff between static lift (buoyant effects) and dynamic lift (planing effect) that is directly proportional to the angle of attack (for small planing angles) and the square of the velocity. Therefore the planing force is of the form:

$$HPLAN = K*V^{**2}*THETA$$

From Reidel's work,

$$HPLAN = 0.5*AREA*V^{**2}*PI*SIN(THETA)$$

(II-21)

for small angle approximations this simplifies to:

$$HPLAN = RHO*AREA*V^{**2}*PI*THETA$$

Which is the planing force for a flat plate. Barnaby gives no simple formula for the losses due to immersion so we are left with an arbitrary loss coefficient, PLCOEF such that:

$$HPLAN = (PLCOEF)*2*RHO*AREA*V^{**2}*PI*THETA$$

(II-22)

The added factor of 2 accounts for 2 sidewalls.

The planing area is taken from the scale drawings



developed from sidewall data, and the force is assumed to act at the centroid of the flat keel surface, which is consistent with Reidel's work. The loss coefficient will be developed in the section on achieving equilibrium.

#### 5. Plenum Gauge Pressure Lift

Combining equations II-11a , II-11b , and II-11c results in:

$$HPRES = -PBBAR * WIDTH * (LPWL - (LPWL - LPR) * (LD / BUBHGT))$$

(II-23)

#### 6. Total Lift Forces

$$\text{Lift Total} = HPRES + HBF + HBA + HSF + HSA + HPLAN$$

which must exactly equal craft weight (W) for the hull to be in vertical equilibrium, or;

$$W + HPRES + HBF + HBA + HSF + HSA + HPLAN = 0$$

(II-24)

defines equilibrium condition in heave motion.

### H. CRAFT PITCH MOMENT EQUATIONS

#### 1. Buoyant Moments

Forward buoyant moment is the forward buoyant lift times the effective lever arm, or;

$$PBF = -HBF * (\text{Lever arm forward})$$

$$PBF = -HBF * L5$$

(II-25)

Note that the negative sign results from the definition of positive moments and the fact that upward forces are negative by definition.

$$PBA = HBA * \text{LEVER ARM}$$

$$PBA = HBA * L6$$

(II-26)

using the same reasoning, after buoyant moment is:

$$PB \text{ total} = PBF + PBA$$

(II-27)

## 2. Seal Moments

Since the seals are relatively distant from the C.G. dynamic variations in the lever arms are considered in seal moment equations and are developed here.

The seal force is modeled to act at the longitudinal center of the seal wetted length. Therefore the effective lever arm for the seal moment is:

$$PLSF = L3 - XSEAL1/2$$

where PLSF = moment lever arm for seal forward. As a result:

$$PSF = -HSF*PLSF$$

$$PSF = -HSF*(L3 - (XSEAL1/2))$$

(II-28)

In a similar manner

$$PLSA = L4 + XSEAL2/2$$

$$PSA = HSA*PLSA$$

$$PSA = HSA*(L4 + XSEAL2/2)$$

(II-29)

$$PS \text{ TOTAL} = PSF + PSA$$

Note that the dynamic pitch sensitivity to moment arm length is included in the XSEAL terms as defined in equations II-6 and II-8.

### 3. Planing Moment

For the planing force developed in equation II-22 the planing force is concentrated at the centroid of the flat keel which results in:

$$PPLAN = L7 * HPLAN$$

(II-30)

### 4. Plenum Pressure Moment

First the dynamic variation in effective center of pressure will be developed. (see fig.(4))

plenum length is taken from equation II-11a to be

$$LP = LPWL - (LPWL - LPR) * (LD / SUBHGT)$$

Defining LDIFF to be

$$LDIFF = LPWL - LPR$$

(II-31)

and,

$$XCP = XCP0 + (LDIFF * LD / SUBHGT) / 2$$

(II-32)

where



$$XCPO = LPWL/2 - XCG$$

(II-33)

and XCG is the distance from the transom to the C.G. (see fig. 4.) Finally,

$$PPRES = -HPRES * XCP$$

(II-34)

### 5. Pitch Damping Moment

Any frictional damping terms dependent upon the square of pitch rate (i.e. tangential velocity about the Y axis) disappear when the Taylor Series expansion is carried about the zero rate equilibrium point. Since for small signal approximation the model should reflect actual craft characteristics, it was hoped that the changes in seal and plenum modeling would reveal the missing damping characteristics. As it turned out this was not the case. Examination of the hydrodynamic equations in [9] revealed an added mass effect dependant upon a cross velocity term between linear X direction velocity U, pitch rate Q, and added-mass at the stern A33S due to slender body theory applied to the sidewalls. This moment is:

$$FP = -A33S * XLSS ** 2 * U * THETADOT$$

(II-35)

Where XLSS is the distance from the C.G. to the stern, and THETADOT is pitch rate.

$$A33S = YSS^{**2} * RHO * PI / 8$$

(II-36)

where YSS is the cross section width of the side wall at the stern waterline. Therefore,

$$FPDAMP = -2 * XLSS^{**2} * A33S * U * THETADOT$$

$$= -2 * PI * XLSS^{**2} * YLSS^{**2} * RHO * U * THETADOT / 8$$

(II-37)

The factor of 2 is introduced to account for two sidewalls.

#### 6. Total Moments

Since the moments are all referenced to the craft center of gravity, the craft weight contributes zero moment in that frame of reference. Therefore total moments are:

$$PSP + PSA + PBF + PBA + PRES + PPLAN + PDAMP = 0$$

(II-38)

#### I. HEAVE ACCELERATION EQUATIONS.

From Newton's law, acceleration and force are related by:

FORCE = MASS\*ACCELERATION

For the linearized model we are interested in the acceleration on the craft and as a result:

ACCELERATION = FORCE/ MASS and therefore the heave equation of motion becomes:

$$ZDDOT = (HBF+HBA+HSA+HPLAN+HPRES) / MASS$$

(II-39)

where ZDDOT is the second derivative of Z with respect to time.

#### J. PITCH ACCELERATION EQUATIONS

Angular acceleration is:

$$THETADDOT = PTOTAL/IYY$$

Where IYY is the craft inertial moment about the Y axis. As a result total angular acceleration is;

$$THETADDOT = (PBF+PBA+PSF+PSA+PPLAN+PPRES+PDAMP) / IYY$$

(II-40)

This completes the derivation of all nonlinear equations needed to describe the two-degree-of-freedom CAB SES. In the following chapter these nonlinear equations will be linearized using the Taylor Series expansion about a steady state operating point which will result in the equations needed to generate a

dynamic digital-computer simulation of craft motion in  
the time-domain.



### III. LINEARIZATION OF THE HEAVE-PITCH EQUATIONS.

#### A. TAYLOR SERIES EXPANSION

For small perturbations about a steady state operating point the nonlinear function  $Z$  can be approximated by:

$$Z = Z(X, Y)$$

$$Z(0) + dZ = Z(X(0), Y(0)) + (\partial Z / \partial X) * dX + (\partial Z / \partial Y) * dY$$

where  $(\partial Z / \partial X)$  and  $(\partial Z / \partial Y)$  are the partial derivatives of the function  $Z$  evaluated at the steady state operating point  $X(0), Y(0)$ . Cancelling the steady state values from both sides of the equation yields the differential model equations:

$$dZ = (\partial Z / \partial X) * dX + (\partial Z / \partial Y) * dY$$

and

$$Z = Z(0) + dZ$$

where  $dZ, dX,$  and  $dY$  are the differential variables for  $Z, X, Y$  respectively,  $(\partial Z / \partial X)$  and  $(\partial Z / \partial Y)$  are the partial derivatives of  $Z$  evaluated at the steady-state operating point.

## B. LINEARIZATION OF THE MODEL EQUATIONS

There are basically four equations to linearize for the two-degree-of-freedom model:

$$ZDDOT = F(Z, THETA, MB)$$

$$THETADDOT = G(Z, THETA, THETADOT, MB)$$

$$MBDOT = H(Z, MB)$$

$$PBBAR = I(Z, MB)$$

therefore the equations for the differential state variables are:

$$dZDDOT = (dF/dZ) * dZ + (dF/dTHETA) * dTHETA + (dF/dMB) * dMB \quad (III-1)$$

$$dTHETADOT = (dG/dZ) * dZ + (dG/dTHETA) * dTHETA + (dG/dMB) * dMB \quad (III-2)$$

$$dMBDOT = (dH/dZ) * dZ + (dH/dTHETA) * dTHETA + (dH/dMB) * dMB \quad (III-3)$$

$$dPBBAR = (dI/dZ) * dZ + (dI/dTHETA) * dTHETA + (dI/dMB) * dMB$$

(III-4)

Note that the left hand side variables are differentials, not time derivatives.

### C. LINEARIZED EQUATIONS

#### 1. Plenum Air Mass Flow Derivatives

$$Qin = N * (Q10 - Kq * PBBAR)$$

(II-12)

$$Qout = Cn * A1 * (2 * PBBAR / RHOA) ** 1/2$$

(II-13)

$$MBDOT = RHOA * (Qin - Qout)$$

(II-14)

as a result the differential equation for MBDOT becomes:

$$dMBDOT = RHOA * (dQin - dQout)$$

(III-5)

$$dQin = (dQin/dZ) * dZ + (dQin/dPBBAR) * dPBBAR + (dQin/dMB) * dMB$$

(III-6)

$$dQ_{in}/dP_{BBAR} = -N \cdot K_1$$

The partial derivatives of  $Q_{in}$  with respect to all other variables are zero.

$$dQ_{out} =$$

$$(dQ_{out}/dz) \cdot dz + dQ_{out}/dP_{BBAR} \cdot dP_{BBAR} + (dQ_{out}/dMB) \cdot dMB$$

$$dQ_{out}/dP_{BBAR} = C_n \cdot A_1 \cdot ((\rho_{HOA}/2 \cdot P_{BBAR})^{**1/2}) / \rho_{HOA}$$

(III-7)

The partial derivatives of  $Q_{out}$  with respect to all other variables are zero. Inserting equations III-6, and III-7 into II-14 yields the equation for the differential variable  $dMBDOT$ :

$$dMBDOT = (-\rho_{HOA} \cdot N \cdot K_1 - C_n \cdot A_1 \cdot ((\rho_{HOA}/2 \cdot P_{BBAR})^{**1/2})) \cdot dP_{BBAR}$$

(II-15)

## 2. Plenum Gauge Pressure Derivatives.

$$P_b = P_a \cdot (M_b / \rho_{HOA} \cdot V_b)^{**GAMMA}$$

(III-8)

and

$$P_{BBAR} = P_b - P_a$$



Since  $P_a$  is considered constant within the time frame of this model,

$$dP_{\text{BBAR}} = dP_b$$

(III-9)

As a result,

$$dP_{\text{BBAR}} = \text{GAMMA} * P_a * (M_B(0) / \text{RHOA} * V_b(0)) ** (\text{GAMMA} - 1) * d(M_B / \text{RHOA} * V_B)$$

where

$$d(M_B / \text{RHOA} * V_B) = (1 / \text{RHOA} * V_B(0)) * dM_B + (M_B / \text{RHOA}) * d(1 / V_B)$$

$$d(M_B / \text{RHOA} * V_B) = (1 / \text{RHOA} * V_B(0)) * dM_B - (M_B / \text{RHOA} * V_B ** 2) * dV_B$$

$$dV_B = d(V_N - A_B * L_D)$$

$$dV_B = -A_B(0) * dL_D / dZ - L_D(0) * dA_B / dZ$$

remembering that:

$$L_D = Z + Z_S$$

then

$$dL_D / dZ = 1$$

we now need the partial of effective plenum roof area with respect to  $Z$ . Defining

$$AB = ABWL - (ABWL - ABR) * LD / SUBHGT$$

(III-10)

$$ABWL = WIDTH * LPWL$$

$$ABR = WIDTH * LPR$$

further defining

$$ABDIFF = ABWL - ABR$$

which is a constant, the effective plenum roof area is:

$$AB = ABWL - ABDIFF * LD / SUBHGT$$

using the previous definitions the partial of effective roof area becomes:

$$dAB/dZ = -ABDIFF / SUBHGT$$

(III-11)

and the differential volume is:

$$dVb = - (AB(0) - LD(0) * 2 * (ABDIFF / SUBHGT)) * dZ$$

(III-12)

with the result that

$$d(Mb / RHOA * Vb) = (1 / RHOA * Vb(0)) * dZ +$$

$$(Mb(0) / RHOA * Vb(0) ** 2) * (AB(0) - 2 * LD(0) * (ABDIFF / SUBHGT)) * dZ$$

finally,

$$\begin{aligned} dPBBAR = & GAMMA * Pb(0) * ((1/Mb(0)) * dMb + \\ & (1/Vb(0) * (AB(0) - 2 * LD(0) * (ABDIFF/BUBHGT))) * dz \end{aligned} \quad (III-13)$$

### 3. Heave Force Derivatives

The total heave force equation is:

$$H(\text{total}) = HBF + HBA + HSP + HSA + HPLAN + HPRES$$

The total partial derivatives will be done term by term.

For the forward buoyant force the following simplifications are made:

$$HBF = -2 * RHO * G * L1 * LDBAR1 * (LDBAR1 / (2 * TAN(DR1)) + WS10)$$

let  $K1 = 2 * RHO * G * L1$  then,

$$HBF = -K1 * LDBAR1 * (LDBAR1 / (2 * TAN(DR1)) + WS10)$$

where  $LDBAR1 = (LD - L5 * TAN(THETA))$ . Combining the previous two equations,

$$\begin{aligned} HBF = & -K1 * (LD - L5 * TAN(THETA)) * \\ & ((LD - L5 * TAN(THETA)) / (2 * TAN(DR1)) + WS10) \end{aligned}$$

assuming small pitch angles,  $\text{TAN}(\text{THETA})$  can be approximated by  $\text{THETA}$  which results in the following simplification:

$$\text{HBF} = -K1 * (\text{LD} - L5 * \text{THETA}) * ((\text{LD} - L5 * \text{THETA}) / (2 * \text{TAN}(\text{DR1})) + \text{WS10})$$

Taking the partials of HBF with respect to  $Z$  and  $\text{THETA}$  yields:

$$d(\text{HBF})/dZ = -K1 * ((\text{LD}(0) - L5 * \text{THETA}(0)) / \text{TAN}(\text{DR1}) + \text{WS10}) \quad (\text{III-14})$$

and

$$d(\text{HBF})/d\text{THETA} = K1 * L5 * ((\text{LD}(0) - L5 * \text{THETA}(0)) / (2 * \text{TAN}(\text{DR1})) + \text{WS10}) + K1 * (-L5 / (2 * \text{TAN}(\text{DR1})) * (\text{LD}(0) - L5 * \text{THETA}(0)))$$

which simplifies to :

$$d(\text{HBF})/d\text{THETA} = K1 * L5 * ((\text{LD}(0) - L5 * \text{THETA}(0)) / (\text{TAN}(\text{DR1}) + \text{WS10})) \quad (\text{III-15})$$

Using the same approach, the partials for buoyancy force aft are:

$$d(\text{HBA})/dZ = -K2 * ((\text{LD}(0) + L6 * \text{THETA}(0)) / (\text{TAN}(\text{DR2}) + \text{WS20})) \quad (\text{III-16})$$

$$\begin{aligned} d(\text{HBF})/d\text{THETA} = \\ -L6 * K2 * ((LD(0) + L6 * \text{THETA}(0)) / (\text{TAN}(\text{DR2})) + \text{WS10}) \end{aligned}$$

(III-17)

For the forward seal the total differentials are:

$$\begin{aligned} \text{DHSF} = (d(\text{HSF})/dZ) * dZ + (d(\text{HSF})/d\text{THETA}) * d\text{THETA} \\ + (d(\text{HSF})/d\text{PBBAR}) * d\text{PBBAR} \end{aligned}$$

the following simplification is made;

$$\text{HSF} = -\text{PBBAR} * \text{WIDTH} * (\text{LD} - L3 * \text{TAN}(\text{THETA})) / \text{SIN}(31)$$

(II-19)

let  $\text{WIDTH}/\text{SIN}(31) = K3$  and  $\text{TAN}(\text{THETA}) = \text{THETA}$ , then,

$$\text{HSF} = -K3 * \text{PBBAR} * (\text{LD} - L3 * \text{THETA})$$

with the resultant partials being:

$$d(\text{HSF})/dZ = -K3 * \text{PBBAR}(0)$$

(III-18)

$$d(\text{HSF})/d\text{THETA} = K3 * L3 * \text{PBBAR}(0)$$

(III-19)

$$d(\text{HSF})/d\text{PBBAR} = -K3 * (\text{LD}(0) - L3 * \text{THETA}(0))$$

(III-20)



The partials of after seal force are found in the same manner to be:

$$dHSA = (d(HSA)/dZ) * dZ + (d(HSA)/dTHETA) * dTHETA \\ + (d(HSA)/dPBBAR) * dPBBAR$$

$$HSA = -(PBBAR + PDIFF) * WIDTH * (LD + L4 * TAN(THETA)) / SIN(32) \\ (II-20)$$

let  $K4 = WIDTH / SIN(32)$  and assume small THETA so that:

$$HSA = -K4 * (PBBAR + PDIFF) * (LD + L4 * THETA)$$

the partials then become:

$$d(HSA)/dZ = -K4 * (PBBAR(0) + PDIFF) \\ (III-21)$$

$$d(HSA)/dTHETA = -K4 * (PBBAR(0) + PDIFF) * L4 \\ (III-22)$$

$$d(HSA)/dPBBAR = -K4 * (LD(0) + L4 * THETA(0)) \\ (III-23)$$

Next the planing force partials are derived:

$$HPLAN = -2 * PLCOEFF * RHO * AREA * V ** 2 * PI * THETA$$

let  $KPLAN = (2 * PLCOEFF * RHO * AREA * PI)$  then,

$$HPLAN = -KPLAN * V^{**2} * THETA$$

and,

$$d(HPLAN) = (d(HPLAN)/dTHETA) * dTHETA$$

for this constant speed model, therefore,

$$d(HPLAN)/dTHETA = -KPLAN * V(0)^{**2}$$

(III-24)

Plenum Gauge Pressure lift was defined to be:

$$HPRES = -AB * PBBAR$$

(II-11c)

as a result:

$$d(HPRES)/dPBBAR = -AB(0)$$

(III-25)

#### 4. Pitch Moment Partials

The total moments acting on the craft are:

$$PTOTAL = PBF + PBA + PSF + PSA + PPLAN + PPRES + PDAMP$$

(II-38)

The partials of II-38 will be found term by term, beginning with the forward buoyant moment:

$$PBF = -HBF * L5$$

(II-23)

therefore:

$$d(PBF) = -L5 * d(HBF)$$

so that:

$$d(PBF) = -L5 * (d(HBF) / dZ) * dZ - L5 * ((d(HBF) / dTHETA) * dTHETA)$$

(III-26)

and the partial of the after buoyant moment is:

$$PBA = L6 * HBA$$

(II-26)

$$dPBA = L6 * dHBA$$

therefore,

$$d(PBA) = L6 * (d(HBA) / dZ) * dZ + L6 * (d(HBA) / dTHETA) * dTHETA$$

(III-27)

Seal forces partials must include the dynamic variation in lever arm length, which for the forward seal is:

$$PSF = -HSF * PLSF$$

or,

$$PSF = (PBBAR * ASEAL1) * PLSF$$

therefore,

$$d(PSF)/dPBBAR = ASEAL1(0) * PLSF(0)$$

(III-28)

and

$$d(PSF)/dZ = PBBAR(0) * d(PLSF * ASEAL1)/dZ$$

where

$$d(ASEAL1 * PLSF)/dZ = PLSF(0) * d(ASEAL1)/dZ + ASEAL1(0) * d(PLSF)/dZ$$

$$ASEAL1 = WIDTH * (LD - L3 * THETA) / SIN(31)$$

and

$$PLSF = L3 - (LD - L3 * THETA) / 2 * SIN(31)$$

therefore,

$$d(PLSF)/dZ = -1 / (2 * SIN(31))$$

and

$$d(ASEAL1)/dZ = WIDTH / SIN(31)$$

as a result,

$$d(PSF)/dZ = PBBAR(0) * ((PLSF(0) * WIDTH) / SIN(31) - ASEAL1(0) / (2 * SIN(31)))$$

(III-29)

$$d(\text{psf})/d\text{THETA} = \text{PBAR}(0) * d(\text{PLSF} * \text{ASEAL1})/d\text{THETA}$$

$$d(\text{PLSF} * \text{ASEAL1})/d\text{THETA} = \\ \text{PLSF}(0) * d(\text{ASEAL1})/d\text{THETA} + \text{ASEAL1}(0) * d(\text{PLSF})/d\text{THETA}$$

$$d(\text{ASEAL1})/d\text{THETA} = -L3 * \text{WIDTH} / \text{SIN}(31)$$

$$d(\text{PLSF})/d\text{THETA} = L3 / (2 * \text{SIN}(31))$$

as a result,

$$d(\text{PSF})/d\text{THETA} = -\text{PBBAR}(0) * ((\text{PLSF}(0) * L3 * \text{WIDTH}) / \text{SIN}(31) - \\ \text{ASEAL1}(0) * L3 / (2 * \text{SIN}(31)))$$

(III-30)

For the after seal the derivatives proceed in the manner:

$$\text{PSA} = -(\text{PBBAR} + \text{PDIFF}) * \text{ASEAL2} * \text{PLSA}$$

$$d(\text{PSA})/d\text{PBBAR} = -\text{ASEAL2}(0) * \text{PLSA}(0)$$

(III-31)

In the same manner as shown in the previous paragraph, the partials of moment due to seals aft with respect to the other variables are:



$$d(psa)/dz = -PBBAR(0) * ((PLSA(0) * WIDTH) / SIN(32) + ASEAL2(0) / (2 * SIN(32)))$$

(III-32)

$$d(PSA)/dTHETA = -PBAR(0) * ((PLSA(0) * L4 * WIDTH) / SIN(32) + ASEAL2(0) * L4 / (2 * SIN(32)))$$

(III-33)

The partial of planing moment is:

$$PPLAN = L7 * HPLAN$$

(II-30)

$$d(PPLAN) = L7 * d(HPLAN)$$

$$d(PPLAN)/dTHETA = -L7 * KPLAN * V(0) ** 2$$

(III-34)

For this constant speed model all other partials are identically zero. The Plenum Gauge Pressure also has dynamic variation in the moment lever arm and the derivatives are:

$$PPRES = -XCP * HPRES$$

(II-34)

therefore,

$$dPPRES = -HPRES(0) d(XCP) - XCP(0) * d(HPRES)$$

where

$$XCP = XCP0 + (LDIFF * LD) / (2 * BUBHGT)$$

therefore,

$$d(XCP) / dz = LDIFF / (2 * BUBHGT)$$

and

$$d(PPRES) = -((HPRES(0) * LDIFF) / (2 * BUBHGT)) * dz \\ - XCP(0) * d(HPRES)$$

substituting equation (III-25) yields:

$$d(PPRES) = -((HPRES(0) * LDIFF) / (2 * BUBHGT)) * dz \\ + XCP(0) * AB(0) * dpBBAR$$

Finally, the partial of pitch damping moment is:

$$PDAMP = -2 * PI * XLSS ** 2 * YLSS ** 2 * RHO * u * THETADOT / 8$$

(II-37)

let

$$2 * PI * XLSS ** 2 * YLSS ** 2 * RHO / 8 = KDAMP$$

then

$$PDAMP = -KDAMP * V * THETADOT$$

as a result, since this is a constant speed model,

$$d(PDAMP)/dTHETDT = -KDAMP*V(0)$$

(III-35)

where THETDT is the first derivative of theta with respect to time.

### 5. Total Differentials

Since  $F = M * A$  and the interest is in acceleration terms,  $A = F/M$  and  $dA = d(F)/M$ . the result being that all differentials must be divided by craft mass to achieve the desired linearized heave results. The same general comment holds true for moment differentials, that is; they all must be divided by the craft moment of inertia about the Y-axis.

All differentials must be sorted by the variable of differentiation so that the linearized differential equations of motion may be written. As an example;

$$dZDDOT = ((d(HBF)/dZ) + (d(HBA)/dZ)) / MASS * dZ +$$

The State Variable representation of the system will be presented in a later section of this chapter, however it is convenient to define the State Variables at this time.

$$\underline{X} = (dZ, dZDOT, dTHETA, dTHETDT, dMB)^t$$

(III-36)

and

$$\underline{Y} = dPBBAR$$

(III-37)

since PBBAR is not a state variable the definition for dPBBAR must be substituted for dPBBAR in all equations.

#### 6. Total Heave Force Differentials in Z

Here the total differentials will be found. No explanatory text will be included unless special substitutions requiring an aside are necessary.

The buoyancy terms are:

$$DHBZ = d(HBF)/dZ + d(HBA)/dZ$$

(III-38)

A term must be included which was not previously derived to account for the sensitivity of seal forces due to PBBAR since it is not a State Variable.

$$DHSPZ = (d(HSF)/dPBBAR) * (d(PBBAR)/dZ)$$

as a result,

$$d(HSF)/dPBBAR = -K3*(LD(0) - L3*THETA(0))$$

(III-20)

and

$$DHSFPZ = -K3*(LD(0) - L3*THETA(0)) * d(PBBAR)/dZ$$

similarly for the after seal moment:

$$d(HSA)/dPBBAR = -K4*(LD(O) + L4*THETA(O))$$

(III-23)

and

$$DHSAPZ = -K4*(LD(O) + L4*THETA(O)) * d(PBBAR)/dZ$$

The total seal force differential in Z becomes:

$$DHSZ = d(HSF)/dZ + d(HSA)/dZ + DHSFPZ + DHSAPZ$$

(III-39)

For plenum gauge pressure lift differential the same substitution must be made.

$$dHPRES = -AB(O) * dPBBAR$$

therefore,

$$DHPZ = -AB(O) * d(PBBAR)/dZ$$

(III-40)

Define the sensitivity coefficient of ZDDOT to Z to be:

$$DZZ = (DHBZ + DHSZ + DHPZ)/MASS$$

(III-41)

## 7. Total Differentials in THETA



The following partials are now defined:

$$DHBTB = d(HBF)/dTHETA + d(HBA)/dTHETA \quad (III-42)$$

$$DHSTH = d(HSF)/dTHETA + d(HBA)/dTHETA \quad (III-43)$$

$$DHPTH = d(HPLAN)/dTHETA \quad (III-44)$$

Define the sensitivity coefficient of ZDDOT due to THETA to be:

$$DZTH = (DHBTB + DHSTH + DHPTH)/MASS \quad (III-45)$$

### 3. Total Differentials due to MB

Here since  $dPBBAR$  is not a state variable the partial of  $PBBAR$  with respect to  $MB$  must be substituted in the plenum lift and seals lift terms.

$$d(HSF)/dPBBAR = -K3*(LD(0) - L3*THETA(0)) \quad (III-20)$$

by substituting  $d(PBBAR)/dMB$  for  $dPBBAR$  the result is:

$$d(HSFP)/dMB = -K3*(LD(0) - L3*THETA(0)) * d(PBBAR)/dMB$$

(III-46)

similarly,

$$d(HSAP)/dMB = -K4*(LD(0) + L4*THETA(0)) * d(PBBAR)/dMB$$

(III-47)

$$d(HPRES) = -AB(0) * dPBBAR$$

using the previous substitution yields:

$$d(HPRES)/dMB = -AB(0) * d(PBBAR)/dMB$$

(III-48)

The sensitivity coefficient of heave due to MB can now be defined to be:

$$DZMB = (d(HSFP)/dMB + d(HSAP)/dMB + d(HPRES)/dMB) / MASS$$

(III-49)

### 9. Total Pitch Moment Differentials in Z

$$DPBZ = d(PBF)/dZ + d(PBA)/dZ$$

(III-50)

The dPBBAR substitution yields the partial of seals with respect to pressure with respect to Z.

$$DPSFPZ = ASEAL1(0) * PLSF(0) * d(PBBAR) / dz$$

(III-51)

$$DPSAPZ = -ASEAL2(0) * PLSA(0) * d(PBBAR) / dz$$

(III-52)

therefore the total seal differential in Z becomes:

$$DPSZ = DPSFPZ + DPSAPZ + d(PSF) / dz + d(PSA) / dz$$

(III-53)

Next the Plenum Gauge pressure term is derived:

$$d(PPRES) / dz = -HPRES(0) * LDIFP / (2 * BUBHGT)$$

$$d(PPRES) / dPBBAR = AB(0) * XCP(0)$$

therefore,

$$DPPRESZ = AB(0) * XCP(0) * d(PBBAR) / dz$$

and

$$DPRESZ = d(PPRES) / dz + d(DPPRESZ) / dz$$

(III-54)

The sensitivity coefficient of THETA with respect to Z becomes:

$$DTHZ = (DPSZ + DPSZ + DPPRES) / IYY$$

(III-55)

10. Total Moment Differentials in THETA

$$DPBTH = (d(PBF)/dTHETA + d(PBA)/dTHETA)$$

(III-56)

$$DPSTH = (d(PSF)/dTHETA + d(PSA)/dTHETA)$$

(III-57)

$$DPPLTH = d(PPLAN)/dTHETA$$

(III-58)

define the sensitivity coefficient for THETA to be:

$$DTHTH = (DPBTH + DPSTH + DPPLTH)/IYY$$

(III-59)

Also, define the sensitivity coefficient in THETDT to be:

$$DTHDTH = (d(PDAMP)/dTHDT)/IYY$$

(III-60)

11. Total Moment Differentials in MB

$$dPSAMB = (d(PSA) / dPBBAR) * (d(PBBAR) / dMB)$$

(III-61)

$$dPSFMB = (d(PSF) / dPBBAR) * (d(PBBAR) / dMB)$$

(III-62)

$$DPSMB = DPSAMB + DPSFMB$$

(III-63)

Inserting the dPBBAR substitution yields the partial of plenum gauge pressure moment with respect to MB:

$$d(PPRES) / dPBBAR = -XCP(0) * DHPRES$$

$$d(HPRES) / dMB = -AB(0) * d(PBBAR) / dMB$$

$$DPPMB = XCP(0) * AB(0) * d(PBBAR) / dMB$$

(III-64)

Define the sensitivity coefficient of THETA due to MB to be:

$$DTHMB = (DPSMB + DPPMB) / IYY$$

(III-65)

## 12. Total Differentials of Air Mass



$$d(MB)/dMB = (d(MB)/dPBBAR) * (d(PBBAR)/dMB)$$

define the sensitivity coefficient to be:

$$DMBMB = d(MB)/dMB$$

(III-66)

define the sensitivity coefficient in Z to be:

$$DMBZ = d(MB)/dZ$$

(III-67)

#### D. TOTAL MODEL SENSITIVITY COEFFICIENTS

##### 1. Heave Sensitivity Coefficients

The sensitivity coefficients for the linearized differential equation in heave acceleration are:

DZZ, DZTH, and DZMB.

##### 2. Pitch Sensitivity Coefficients

The sensitivity coefficients for the linearized differential equation in pitch acceleration are:

DTHZ, DTHH, DTHDTH, and DTHMB.

##### 3. Plenum Air Mass Sensitivity Coefficients

The sensitivity coefficients for plenum air mass are:

DMBZ, and DMAMB.

#### 4. Plenum Gauge Pressure Sensitivity Coefficients

The sensitivity coefficients for plenum Gauge Pressure are:

DPBZ, and DPBMB.

#### E. STATE SPACE REPRESENTATION

The state matrix form of a dynamic system is:

$$\dot{X} = AX + BU$$

where  $X$  = a vector of variables representing the states of a set of first order linear differential equations, and  $U$  is the vector of forcing functions, and  $A$  and  $B$  are the matrices of the respective gains. The form of the equations is:

$$\dot{X}_1 = X_2$$

$$\dot{X}_2 = X_3$$

$$\dot{X}_3 = K_1 X_1 + K_2 X_2 + K_3 X_3$$

for the linearized model of the CAB SES the state variables were defined to be :

$$\underline{x} = (dz, dzDOT, dTHETA, dTHETDT, dMB)^t$$

As a result the state matrix representation of the linearized unforced Heave-Pitch model is:

$$\begin{bmatrix} X1DOT \\ X2DOT \\ X3DOT \\ X4DOT \\ X5DOT \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ DZZ & 0 & DZTH & 0 & DZMB \\ 0 & 0 & 0 & 1 & 0 \\ DTHZ & 0 & DTHTH & DTHDTH & DTHMS \\ DMBZ & 0 & 0 & 0 & DMBMS \end{bmatrix} \begin{bmatrix} X1 \\ X2 \\ X3 \\ X4 \\ X5 \end{bmatrix}$$

(III-68)

and

$$dPBBAR = DPBZ * X1 + DPBMB * X5$$

III-69

#### IV. TIME DOMAIN VALIDATION

The linearized model developed in chapter III was validated against the the Six-degree-of-freedom nonlinear model. There were several changes made in the simulation techniques used, and at the same time the changes in center of pressure dynamic variation and planing forces were entered into the 6 DOF model. Establishment of equilibrium for the linear model was accomplished off-line using a TI-59 programmable hand-held calculator with printer.

The first change in simulation technique is the operating point at which the linear sensitivity coefficients were evaluated. In McIntyre's model these coefficients were evaluated at the initial operating point. In this work the coefficients are evaluated at the final steady-state equilibrium point since this is customary in linearization work.

The second major change in simulation was the method used to determine the planing force loss coefficient (PLCOEFF) and the establishment of the arbitrary location of the initial plenum center of pressure. In this model all heave forces are well defined (as modeled here) with the exception of planing force lift. As a result, craft weight and all heave forces except that due to planing lift are summed and the residual assumed to be due to the planing phenomenon. This residual is then used to determine (off-line) the value of PLCOEFF. Note that this method also accounts for any lift due to aerodynamic forces on the bow that were disregarded.

Next all moments are summed about the C.G. except the moment due to plenum pressure lift. The residual moment is assumed to be due to plenum pressure. This residual is used (again off-line) to establish the initial center of pressure. This accounts for any moments not previously accounted for (such as aerodynamic forces on the bow.) McIntyre used the planing lift coefficient to force the model into agreement with the 6 DOF model for natural pitch frequency and used a large, arbitrary, and static moment to force the models into steady state pitch angle agreement. It was felt that using the present method of determination would leave the equations in a form that would be more amenable to extraction of the factors most directly affecting craft characteristics as modeled herein.

#### A. LINEAR PROGRAM DESCRIPTION

User's instructions have been included as appendix A. The program flow can be isolated into four main sections.

1. First the values for craft weight, draft, pitch angle, plenum pressure and speed are entered. To initialize plenum air mass, draft is used to solve for initial plenum air volume, which is then used with initial plenum gauge pressure to solve equation II-15 for plenum air mass. Equation II-12 is then solved for  $Q_{in}$ .  $Q_{out}$  is set equal to  $Q_{in}$  and equation II-13 is solved for seal leakage area. All other heave and pitch nonlinear equations are solved and their values are listed along with residuals of heave and pitch summations. These residuals are added to the initial values of C.G. and angular acceleration and the initial



values are saved for the time domain simulation section.

2. The same operations are carried out for the steady state values of weight, draft, pitch angle, and plenum pressure. The residuals, forces and moments are again listed.

3. These steady state values are used to evaluate the sensitivity coefficients developed in chapter III which are also listed.

4. Finally the state variable solution is simulated using a four-point fixed step Runge-Kutta algorithm and listed for the print interval desired. The option is included to output either printer plot graphical display using the NPS printer plot subroutine PLOTP or the X-Y Versatec plot subroutine DRAWP. The latter should be used for final runs only, with PLOTP used on intermediate runs. Provisions are made for up to 300 discrete output points for the time domain tabular listing.

## B. SIX-DEGREE-OF-FREEDOM MODEL SOLUTION

Two changes were made in the 6 DOF model to account in a more analytic manner for the observed tendency of the XR-3 to pitch down as speed increased.

The first change was to remove an empirical equation used to correct the center of pressure [5] and replace it with the dynamic center of pressure variation developed in chapter II.

The second change was to include in the sidewall subroutine the nonlinear equation for planing forces, with the loss coefficient adjusted to make up (as

closely as possible) for lift loss due to the revised modeling of the plenum chamber.

Finally, the 6 DOF model was run at both 6722 lbs and 6050 lbs weight to establish the initial and final operating points, followed by the weight removal transient run for time domain validation of the linear heave-pitch model.

It should be noted that further study of the 6 DOF model is needed to evaluate the results of the two changes and to more closely establish the arbitrary initial location of the center of pressure. The large amount of CPU and turn-around program times required to run the nonlinear model precluded including that study in this work. Also, for the nonlinear model, X-direction thrust was held constant during the run with the result that speed was 30.33 knots and still increasing at the end of the five second run. This effect will be further discussed in the next section.

### C. COMPARISON OF RESULTS

The graphical output for the five second runs are shown in figures 5 through 8 for the linear model and figures 9 through 12 for the nonlinear model. The fixed integration step size was 0.005 sec for the linear model and 0.001 sec for the nonlinear model.

#### 1. Plenum Gauge Pressure Transient

(see fig. 5 and 9)

In general both models exhibited a rapid initial reduction in pressure followed by a smooth transient back towards the final operating pressure. For the linear model the minimum occurred at 100 milli-seconds, and 110 milli-seconds for the 6 DOF model, with the respective pressures being 21.38 and 21.30. The final values were 24.31 and 24.08 for the linear and nonlinear model respectively.

As can be seen from the graphical data excellent agreement was achieved between the two models.

## 2. Draft Transient

(see fig. 6 and 10)

Both models exhibit a smooth exponential type transient towards the final, lower steady-state draft. The linear model transient settles towards a lower value (6.04 inches as compared to 6.44) which is in part attributed to a difference in modeling of the seal forces. The nonlinear model uses a complex combination of hydrodynamic and hydrostatic lift where the linear model uses a simple pressure differential effect. Also, since the nonlinear model is settling to a significantly lower pitch angle (see para. 4 below), the planing force effect is reduced in that model.

## 3. C.G Acceleration

(see fig. 7 and 11)

Both models show a rapid positive transient in acceleration that closely follows the negative transient

in plenum pressure. Both models reached the initial peak positive C.G. acceleration at approximately 20 milli-seconds after the plenum pressure completed the negative transient. The linear model appears to have greater coupling between pitch and heave looking at the C.G. acceleration, but this is not actually supportable since the linear model has greater pitch amplitude excursions about the exponential pitch transient to the lower steady state value (see fig. 8 and 12.) In general the two models show excellent agreement in transient and damped C.G. acceleration behavior.

#### 4. Pitch Transient

(see fig. 8 and 12)

It is in this area that the two models are in greatest disagreement. Both exhibit a general damped sinusoidal behavior about a center exponential transient to a lower steady state value. In both cases the initial excursion is downward. The natural pitch frequency of linear model is approximately 4.3 radians per second, whereas the nonlinear model exhibits a natural pitch frequency of 6.98 radians per second. There is felt to be one major factor contributing to this large discrepancy, which is the inclusion of the planing force in the nonlinear model. Data presented by Thaler and Gerba [14] showed a natural pitch frequency of 5.8 radians per second and much higher oscillations about the exponential transient. It is felt that the simplified planing forces of the linear model are included in the much more complex hydrodynamic equations of the nonlinear model and are therefore redundant in that model. Due to time constraints, that avenue of investigation is left for future studies. The linear

model is tending towards a steady state value on the order of 0.45 degrees whereas the nonlinear model is tending towards approximately 0.30 degrees. This large discrepancy is partially due to the redundant planing force in the nonlinear model and the fact that speed is also increasing in the nonlinear model which tends to accentuate the planing force and force the craft to pitch down.

In the next chapter a signal flow graph will be developed and Mason's Gain Rule applied to explain the linear model characteristic response in a more analytical fashion.



## V. SIGNAL FLOW GRAPH AND MASON'S GAIN RULE

### A. INTRODUCTION

The State Variables defined in Chapt II are used to develop a signal flow graph of the craft heave-pitch dynamics. Mason's Gain rule is applied to the signal flow graph to derive analytical S-domain polynomials expressing the transfer functions for pitch moment into pitch angle, heave acceleration into draft and the two cross gains. Using typical gains calculated in the time domain program developed in Chapt III the roots of these polynomials are located and it is shown that pitch dynamics may be very closely approximated by a second-order system. Heave dynamics are also simplified.

Using a simplified approach to the frequency response of the craft to non calm-water conditions, the basics are developed for later sea-state model work. A dynamic system modeling program available at the Naval Postgraduate School is used to generate Bode plots for the craft's frequency response in Heave and Pitch under the simplifying assumptions.

### B. SIGNAL FLOW GRAPH ANALYSIS

Fig 13 was generated using the sensitivity

coefficients defined in Chapter III. From that graph the following feed-forward and feedback loops and paths were identified:

1. Feed Forward, U(THETA) into THETA.

$$P1 = (1/IYY) * (1/S^{**2})$$

2. Feed Forward, U(Z) into Z.

$$P2 = (1/MASS) * (1/S^{**2})$$

3. Feed Forward, U(THETA) into Z.

$$P3 = (1/IYY) * DZTH * (1/S^{**4})$$

4. Feed Forward, U(Z) into THETA.

$$P4 = (1/MASS) * DTHZ * (1/S^{**4})$$

5. Feedback Loops.

$$L1 = DTHTH / S^{**2}$$

$$L2 = DTHDTH / S$$

$$L3 = (DZTH) * (DTHZ) / S^{**4}$$

$$L4 = (DZMB) * (DMBZ) / S^{**3}$$

$$L5 = DZZ/S^{**2}$$

$$L6 = DMBMB/S$$

$$L7 = (DZTH) * (DMBZ) * (DTHMB) / S^{**5}$$

### C. MASON'S GAIN RULE APPLIED

Mason's gain rule for a closed multi-loop system is:

$$T = \text{SUM}(Pk * DELTAK) / \text{DELTA}$$

where,

T = transmission gain from an input to an output node.

DELTA = the graph determinant

DELTAK = cofactor of the kth path

Pk = gain of the direct path from input to output

Using Mason's gain rule the graph determinant (DELTA) is found to be of the form:

$$D(s) = (B5 * S^{**5} + B4 * s^{**4} + B3 * s^{**3} + B2 * s^{**2} + B1 * s + B0) / S^{**5}$$

The forward direct path U (THETA) to THETA is:

$$N1(s) = (1/IYY) * (1/S^{**5}) * (A3 * s^{**3} + A2 * s^{**2} + A1 * s + A0)$$

The forward path U (Z) to Z was found to be:

$$N2(s) = (1/MASS) * (1/S^{**5}) * (A3*s^{**3} + A2*s^{**2} + A1*s + A0)$$

The forward direct path U(THETA) to Z is:

$$N3(s) = (1/IYY) * DZTH * (s + A0) / s^{**4}$$

The forward path for draft coupling into pitch (U(Z) to THETA is:

$$N4 = (1/MASS) * DTHZ * (s + A0) / s^{**4}$$

#### D. SOLUTION OF THE INDIVIDUAL POLYNOMIALS

The gains used below were taken from a typical time domain run as developed in chapter IV.

DZZ = -2178.0  
 DZTH = -121.3  
 DZMB = -5499.0  
 DTHZ = 28.78  
 DTHTH = -22.31  
 DTHMB = 72.1  
 DMBZ = -28.79  
 DMBMB = -73.11

##### 1. Solution of the Graph Determinant

Inserting the numerical values for the typical sensitivity coefficients listed above and using only the

dominant terms where possible, the roots of the graph determinant were found to be:

$$\text{DELTA} = (S^{**2} + 71.8*S + 2066)*(S + 0.5086)*(S^{**2} + 0.72*S + 22.74)/S^{**5}$$

These factors represent a pair of complex poles located at  $-35.71 \pm j27.84$ , a real pole located at  $-0.5085$ , a pair of complex conjugate roots located at  $-0.360 \pm j 4.755$ , and a fifth order zero located at the origin.

## 2. Solution of N1(S)

$$N1(S) = (1/IYY)*(S + 0.427)*(S^{**2} + 72.68*S + 2146)/S^{**5}$$

This polynomial factors into a real zero located at  $-0.427$ , a pair of complex conjugate zeros located at  $-36.34 \pm j 28.74$ , and a fifth order pole located at the origin.

## 3. Solution of N2(S)

$$N2(S) = (1/MASS)*(S^{**2} + 0.7721*S + 22.35)*(S + 72.38)/S^{**5}$$

Which factors into a pair of complex conjugate zeros located at  $-0.3856 \pm j 4.712$ , a real zero at  $-72.38$ , and a fifth order pole located at the origin.



4. Solution of N3(S)

$$N3(S) = (1/IYY) * DZTH * (S + 73.11) / S^{**4}$$

Which represents a real zero at -73.11, and a fourth order pole at the origin.

5. Solution of N4(S)

$$N4(S) = (1/MASS) * DTHZ * (S + 73.11) / S^{**4}$$

Which has the same pole and zero locations as N3(S).

E. SIMPLIFICATION OF TRANSFER FUNCTIONS

1. T1(S)

$$T1(S) = THETA(S) / U(THETA, S)$$

Therefore from Mason's Gain Rule:

$$T1(S) = N1(S) / DELTA$$

$$T1(S) = (1/IYY) * (S + 35.34 \pm 428.7) * (S + 0.427) / \\ (S + 35.1 \pm j 27.84) * (S + 0.508) * (S + 0.36 \pm j 4.755)$$

To simplify let the complex conjugate zeros at  $-36.34 \pm j28.7$  cancel the poles at  $-35.9 \pm j27.84$ , and the real zero at  $-0.427$  cancel the pole at  $-0.508$ . The result is the simplified second order system:

$$T1(S) = (1/IYY)/(S^{**2} + 0.72*s + 22.74)$$

Inspection of the time domain pitch response with respect to natural frequency and damping confirms this basic underdamped second order response.

## 2. T2(S)

$$T2(S) = Z(S)/U(Z,S)$$

$$T2(S) = (1/MASS)*(S + 0.3856 \pm j4.712)*(S + 72.38) / (S^{**2} + 35.1 \pm j 27.84)*(s + 0.5085)*((S + 0.35 \pm j4.755)$$

Canceling the pole at  $-0.36 \pm j 4.755$  with the zero at  $-0.3856 \pm j4.712$  results in the simplified response:

$$T2(S) = (1/MASS)*(S + 72.33)/(S + 0.508)*(S^{**2} + 71.8*S + 2066)$$

Further simplification can be made if  $(S + 72.33)/(S + 0.508)$  is approximated by  $72.33/(S + 0.508)$  (which is valid for longer time period considerations.) As a result  $T2(S)$  becomes:

$$T2(S) = (72.33/MASS)/(S+0.508)*(S**2 + 71.8*S + 2066)$$

which has poles located at -0.508, and  $-35.9 \pm j27.83$ . This is in quite close agreement with the results obtained by Thaler and Gerba 14 for the same airflow condition ( $Kq = 1.0$ ) for their heave-only linearized model. Their results were a real pole at -0.33 and a complex pair at  $-35.1 \pm j34.4$ . This is of the form:

$$T(S) = K/(S + 0.38)*(S**2 + 70.2*S + 2415)$$

### 3. T3(S)

$$T3(S) = Z(S)/U(THETA)$$

Here it is noted that there are no pole zero pairs that conveniently cancel so that the transfer function becomes:

$$T3(S) = (1/IYY)*DZTH*S*(S + 72.33) / (S + 35.1 \pm j 27.84)*(S + 0.5085)*(S + 0.36 \pm j4.775)$$

Making the simplification used in the previous section, the result is:

$$T3(S) = (72.33/IYY)*DZTH*S/(S**2 + 71.8*S + 2055)*(S + 0.508)*(S**2 + 0.72*S + 22.74)$$

Which can be further simplified by looking at the long term response vice initial few milli-seconds to  $(S/(S + 0.508)) = 2$  so that:

$$T3(S) = (142/IYY) * DZTH / (s^{**2} + 71.8*s + 2066) * (s^{**2} + 0.72*s + 22.74)$$

#### 4. T4(S)

Since the transfer functions are the same except for the gains the solutions are the same except for the gains:

$$T4(S) = (1/MASS) * DIHZ * S * (S + 72.33) / DELTA$$

where the same simplifying assumptions may be applied.

## F. SIMPLIFIED BODE PLOT ANALYSIS

### 1. Simplifying Assumption

(see fig. 12)

The assumption is made that the craft linearized frequency response transfer functions can be separated into two transfer functions.

The first block  $G1(W, U, \dots)$  expresses the disturbing moments and accelerations generated by the craft interacting with the waves. This function was developed by Thaler and Gerba [14] for the heave-only model. In that simpler model the function  $G1$  was a complex function of encounter frequency, angle of incidence, craft length compared to encounter wavelength etc.. This portion of the overall frequency response of this model is left for future work due to time

constraints.

The second block G2 (We) represents the heave-pitch dynamics of the model as developed in chapters II, III, and IV, which respond to the disturbing moments and accelerations from block G1.

The Transfer functions T1 and T2 (unsimplified) were simulated using the IBM-360 simulation language DSL with  $S = j\omega$  with the following results.

## 2. Bode Plots for Pitch Dynamics

(see figs. 15 and 16 )

Figure 15 represents the normalized (numerator gain constants set to 1) gain in dB's versus  $\Omega$ . Note that the abscissa scale is  $\Omega$  in powers of 10 since this is a convenient means to achieve a logarithmic scale on the X-Y plotter output. As can be seen the response strongly supports the simplification to second-order system. These plots represent the full transfer function T1(j $\omega$ ) vice the simplified system. Figure 16 further supports the simplification as the phase plot starts at zero degrees and shows only a very slight positive increase prior to the rapid change toward -180 characteristic of an underdamped system. Also note that above the damped natural frequency the magnitude plot falls at -12 dB per octave.

## 3. Bode Plots for Heave Dynamics

(see figs. 17 and 18)



Figure 17 represents the normalized magnitude versus  $\Omega$  for the heave dynamics. The system is characteristic of an overdamped third order system with small gain increases at the craft's natural pitch frequency, which represents the pitch dynamics feeding back into heave dynamics. However the gain magnitude curve has already fallen 20 dB below its lower frequency response gain before the pitch coupling begins to manifest itself. As can be seen in fig. 18 the phase plot shows the same third order pole response with slight second order zero influence at the natural pitch frequency.

## VI. CONCLUSIONS AND RECOMMENDATIONS

As shown in Chapters IV and V the simplified Pitch-Heave model developed herein is a very reasonable simulation of the XR-3 test craft for the given operating conditions. Heave, Pressure, and C.G. Acceleration were in very close agreement. Pitch on the other hand showed some difference in natural frequency and damping factor. It is felt that this difference is primarily attributable to the inclusion of a redundant planing force calculation in the 6 DOF model. Historically the results of the 6 DOF computations<sup>14</sup> for pitch response have been very similar to the results for the linear model, in both natural frequency and damping characteristics. This can be attributed to the fact that the additional planing force did not exist in the original 6 DOF program.

Since one of the major concerns with the 6 DOF model is the excessive computational times involved in sea-state simulations the conclusion may be drawn that eventual substitution of the sidewall and seal force linear model equation in the 6 DOF program will substantially reduce CPU time, with some resultant loss in computational accuracy. By way of comparison, disregarding compiling time and output time, the linear model required approximately 9 seconds of CPU time for the 5 second simulation while the 6 DOF model required 9 minutes of CPU for the 5 second run. This is a computation time improvement on the order of 60 times.

From the time-domain plenum gauge pressure data it can

be seen that the dynamic variation in effective plenum roof area has a noticeable effect on the plenum pressure transient behavior as compared to previous results 14 . The initial pressure down transient was faster, dropped to a lower value , and began it's recovery more quickly. Therefore the plenum roof dynamic variations strongly affects the C.G. acceleration characteristics of the craft and therefore it's transient behavior.

The dynamic center of pressure variation developed herein proved to be a very draft sensitive phenomenon. Although the length of the other lever arms as modeled herein change by a similar amount, percentage of variation is radically different. For the seals the variation is on the order of inches in 10 feet, where the variation in lever arm for plenum pressure lift is on the order of inches in a single foot (or less.) This implies that dynamic C.P. variation is the dominant factor in steady state pitch angle versus steady state draft.

Planing forces as included in this model are now in a form where the basic factors as far as craft construction characteristics are readily recognized. This force provides part of the answer to craft pitch-down characteristics as initially investigated by Reidel [9], with the remainder of the moment being developed by the C.P. variation for pressure. The planing force provides a clue as to how, during construction, the craft's pitch amplitude excursion characteristics may be controlled.

Several areas for future investigation have become apparent in this work.

1. Verification of the effect of dynamic center of

pressure variation and planing forces as incorporated in the 6 DOF model over the entire speed operating range.

2. Incorporate the simple modeling for sidewalls and seals into the 6 DOF model and investigate the trade-off between CPU time and computational accuracy.

3. A closer look at the seal forces used herein. It is possible that a simple gain factor needs to be included in these equations in order to optimize the steady-state seal forces with respect to actual load data as measured during experimental test runs of the craft 10 .

4. Incorporate sea state forces and moments into the simplified model by simulation of the forces and moments that are generated by craft interaction with the sea. Evaluate the accuracy of the method used by comparison with data generated by the simple model and the 6 DOF model in sea-state conditions.

5. Analytical investigation of the craft physical characteristics that have predominant influence on the natural pitch frequency and damping by using the gain terms from the results of the signal flow graph analysis done in Chapter V.

6. Use the simplified model to develop a ride-comfort control system. Test the resulting design on the 6 DOF model, and compare the results obtained with those suggested by ROHR [7]. It has been known empirically for some time that the craft exhibited simple second order behavior in the pitch mode. Now that this fact has been analytically verified the implications for an automatic control system for pitch response are powerful. A simple control system can be visualized

that does not involve either complex optimal control system design work or hardware. A simple acceleration and rate feedback control system is implied, with the possibility of adding a speed input to the system to compensate for the localized linearity of the craft characteristics.



## APPENDIX A

### LINEAR SES MODEL USER'S GUIDE

#### A. General Comments

The program as listed following Appendix B is intended for useage via the hot card reader at NPS.

It is intended to run in Fortran G with Plotting option (PROC = FORTCLGP.)

The program is structured on the assumption that the initial and final state variables are in equilibrium prior to data entry, but will run regardless. The force and moment residual listings will indicate the value of imbalance, if any.

The craft physical dimensions are alterable by changing the cards in the craft dimension section of the main program, which are keyed to the craft geometry herein.

#### B. Data Deck Setup.

The /\* and //GO.SYSIN DD \* cards are inserted following the end card in Subroutine VERSAP, followed by the data deck as described

1. Plot option card (IPLOT), format II. IPLOT = 1 =  
VERSATEC X-Y plotter output.

IPLOT = 0 = PRT PLOT output

2. List option card (ILIST), Format I1

ILIST = 1 = Forces and moments, with residuals and all sensitivity coefficients listed.

ILIST = 0 = Input craft operating conditions only listed.

3. Time and Integration variables.

TI, TF, NPTS, NSTEP Format (2F10.4, 2I10)

Ti = problem start time (normally 0.0)

TF = Problem stop time (seconds)

NPTS = number of tabular output points desired.

NSTEP = number of integration steps.

note: it is best to make NSTEP an integer multiple of NPTS, and never less than NPTS.

4. Planing coefficient and arbitrary center of pressure input, i.e. READ( ) AKP, PLCOEFF

Format = 2F10.4

5. Initial Conditions card.

The initial craft conditions are read in in the following order: weight (Lbs.), Draft (in), Pitch angle (Deg.), PBBAR (psf), and speed (fps.) Format is 5F10.4

6. Final Conditions.

The final conditions are read in the following order and format: weight (Lbs), Draft (in), Pitch angle (Deg), and PBBAR (psf), Format 4F10.4. Since this is a constant speed model, initial and final speed are assumed equal.

7. Label Cards.

Label cards for VERSATEC output are the last 10 cards.

There are five graphs in this mode. Draft(in), C.G. Acceleration (G's), Pitch Angle (Deg.), Pitch Acceleration (Deg/SEC\*\*2), and PBBAR (Each graph requires two label cards, Format (6A8), which print on two lines below the graph. The graphs are output in the order listed above.

APPENDIX B

DRAWINGS AND FIGURES

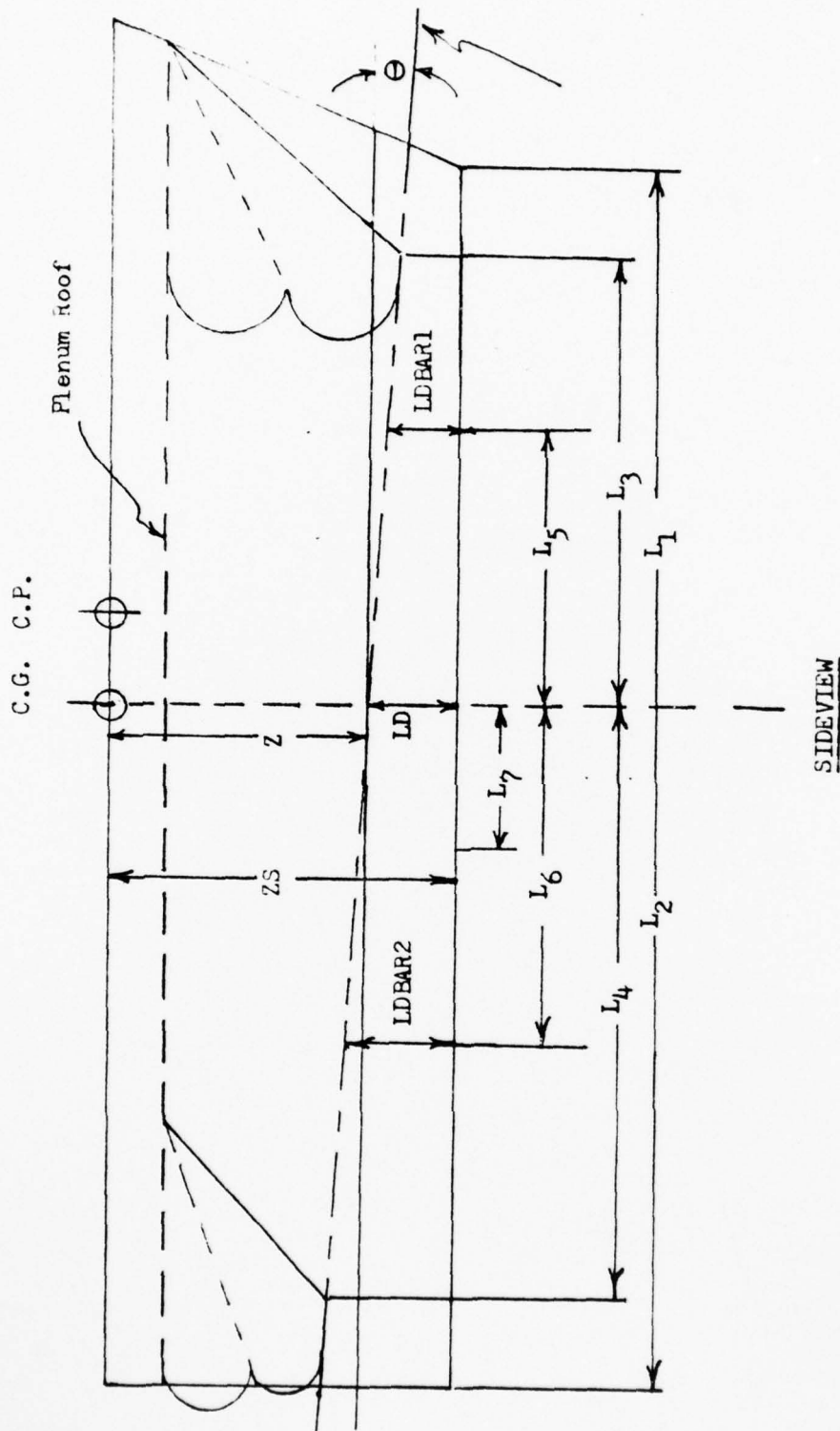


Figure 1 - ASSUMED GEOMETRY



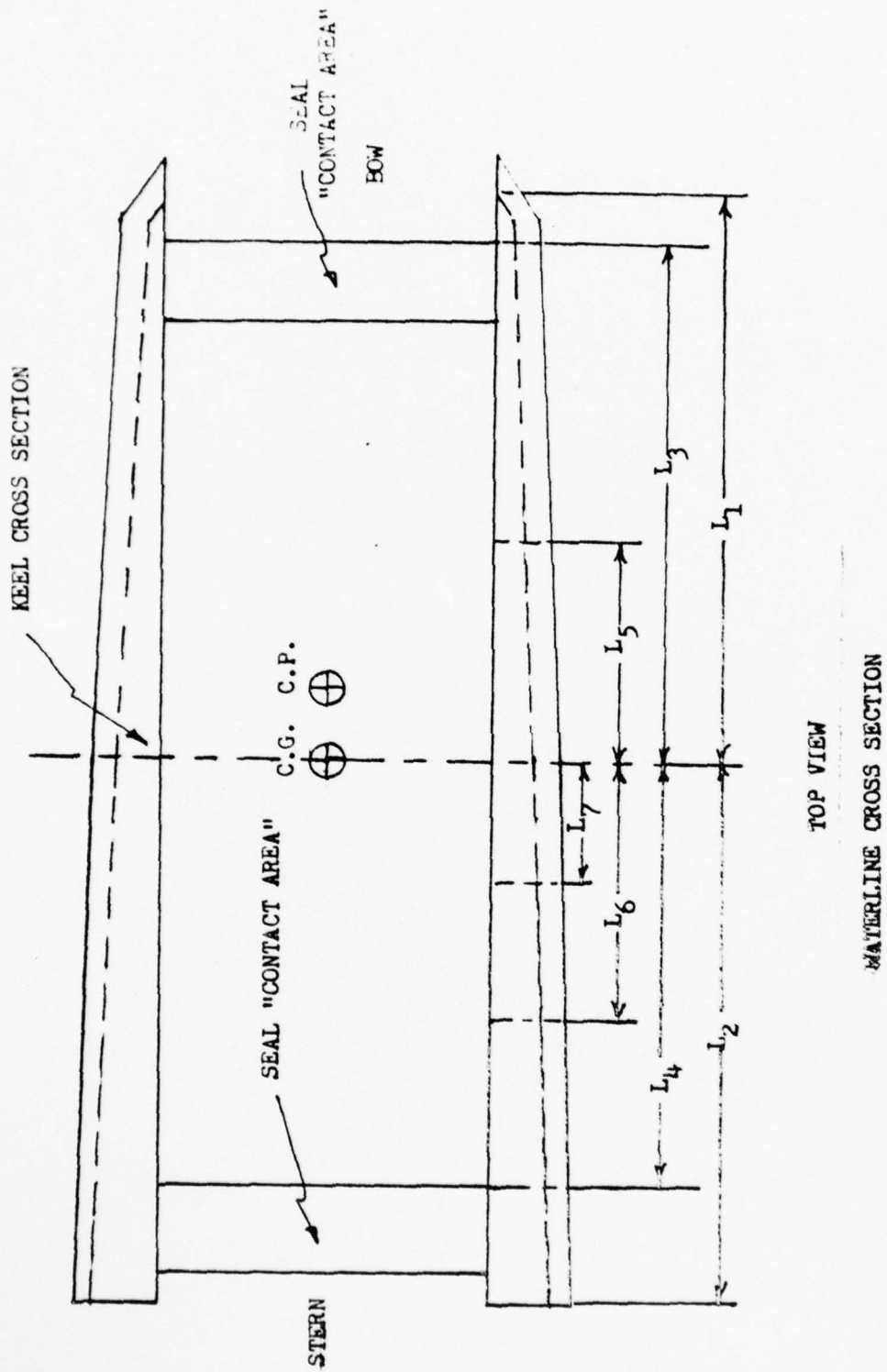
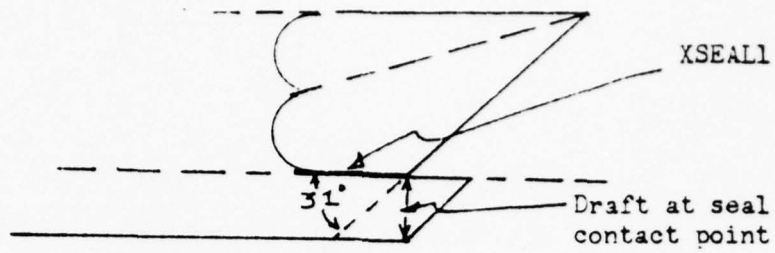
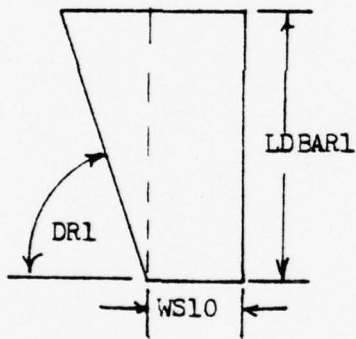


Figure 2 - ASSUMED GEOMETRY (CONT)



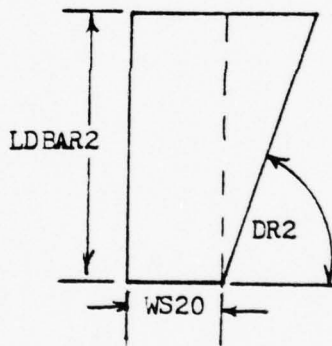
BOW SEAL  
 (Details of Stern Seal the same)

FIGURE 3A



VERTICAL CROSS SECTION  
 FORWARD

FIGURE 3B



VERTICAL CROSS SECTION  
 AFT

FIGURE 3C

Figure 3 - ASSUMED GEOMETRY (CONT)

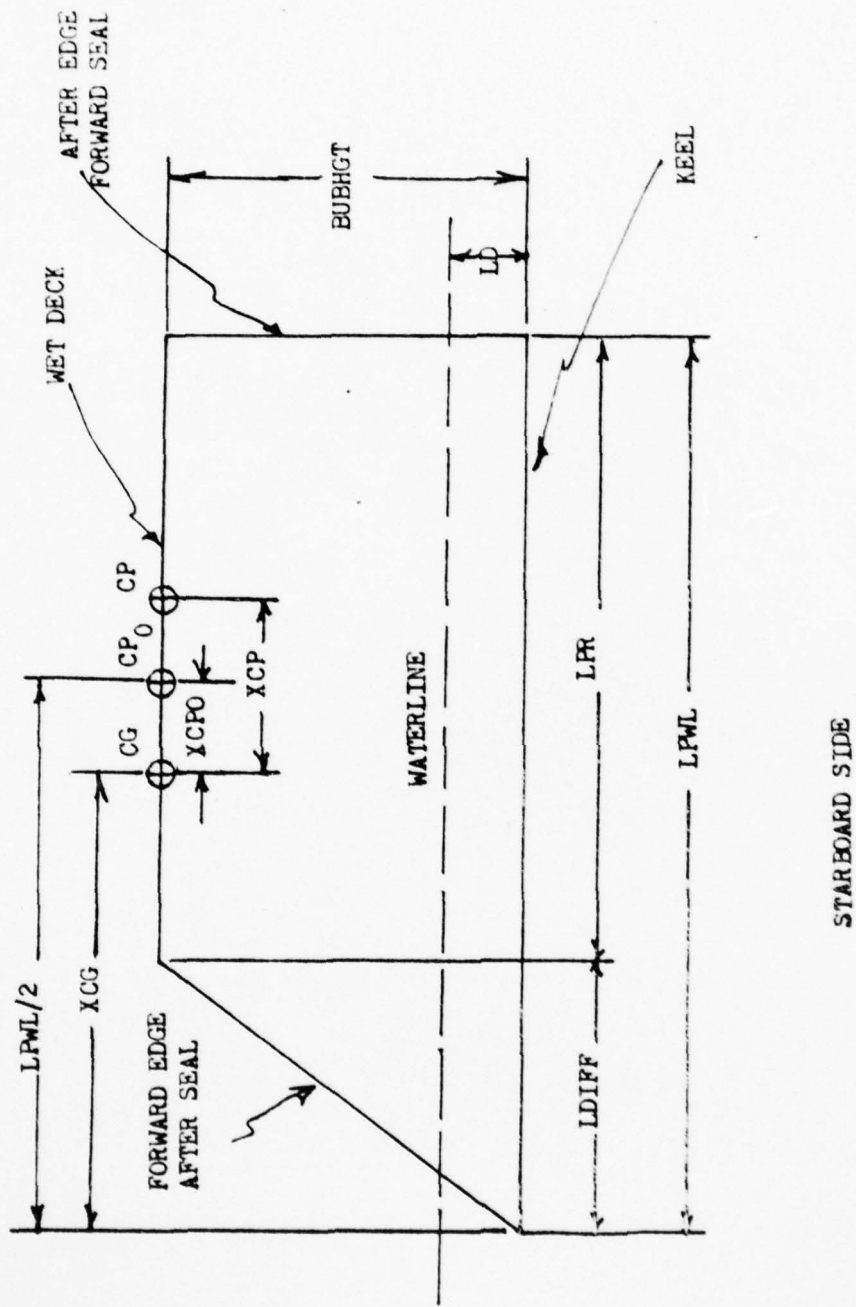
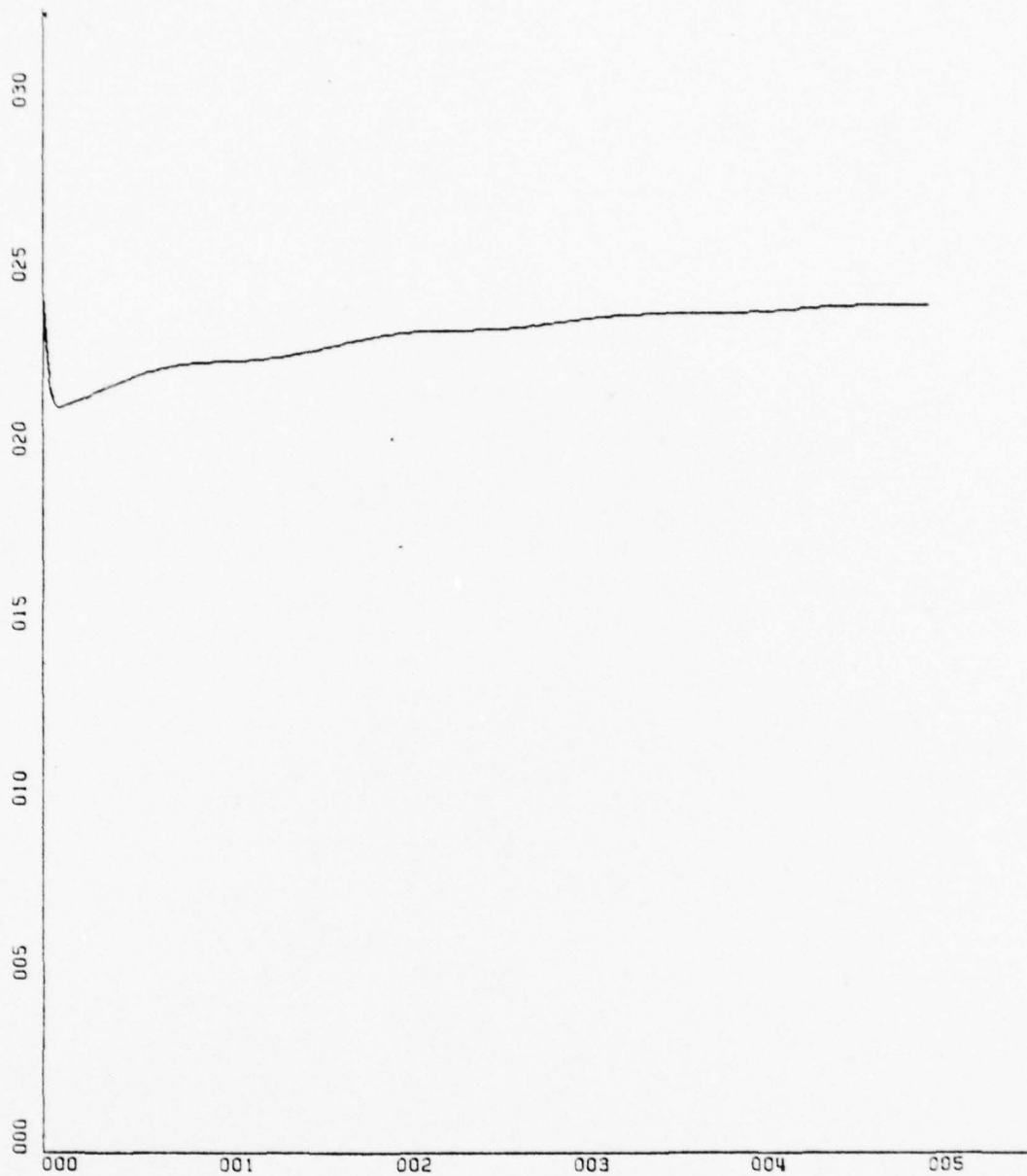


Figure 4 - PLENUM CHAMBER MODELING

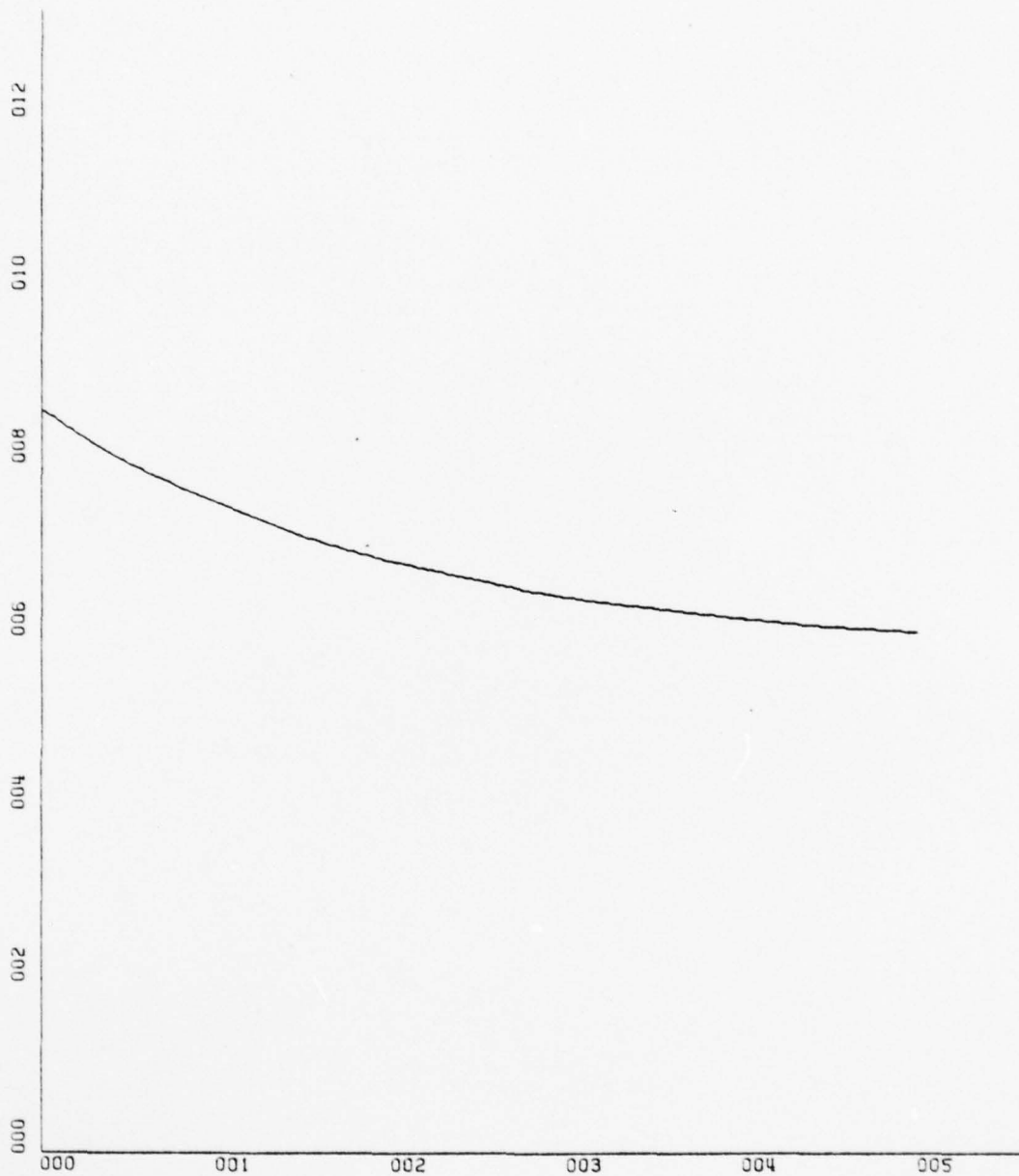


X-SCALE=1.00E+00 UNITS INCH.

Y-SCALE=5.00E+00 UNITS INCH.

PLOT IS PLENUM GAUGE PRESS  
CAB SES LINEAR 2 DOF MODEL

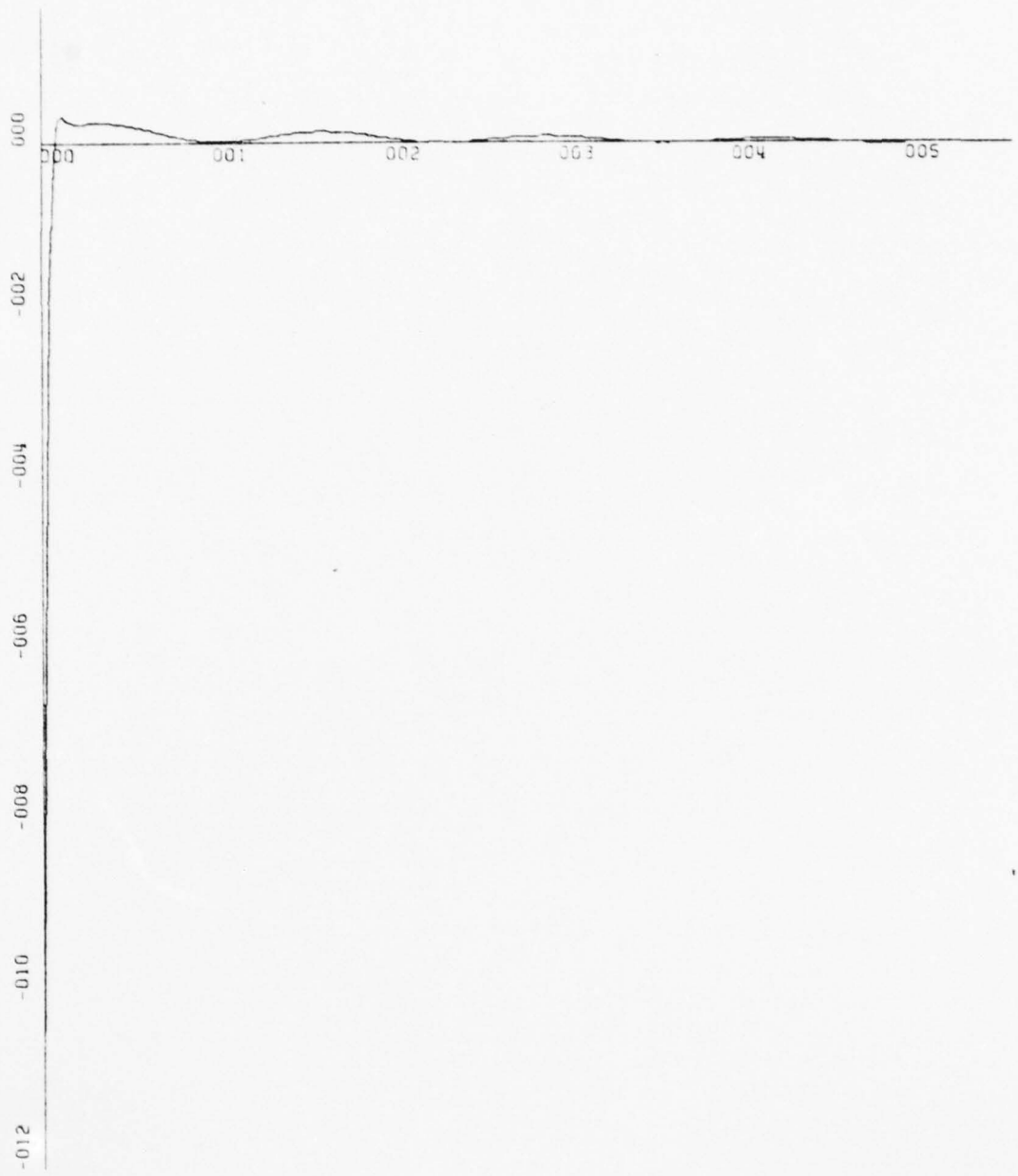
Figure 5 - LINEAR PLENUM PRESSURE TRANSIENT



X-SCALE=1.00E+00 UNITS INCH.  
Y-SCALE=2.00E+00 UNITS INCH.  
PLOT IS DRAFT (INCHES)  
CAB SES LINEAR 2 DOF MODEL

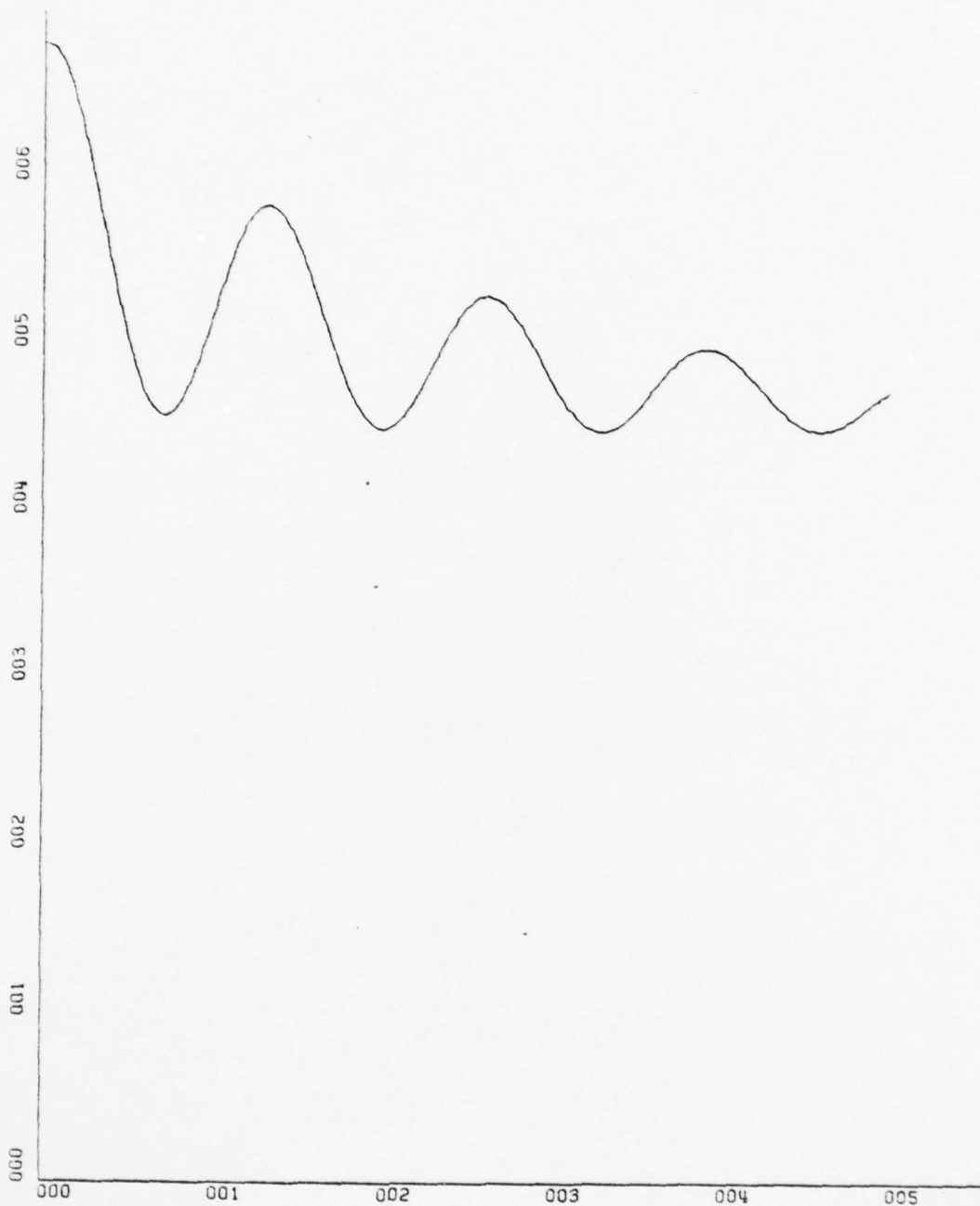
Figure 6 - LINEAR DRAFT TRANSIENT



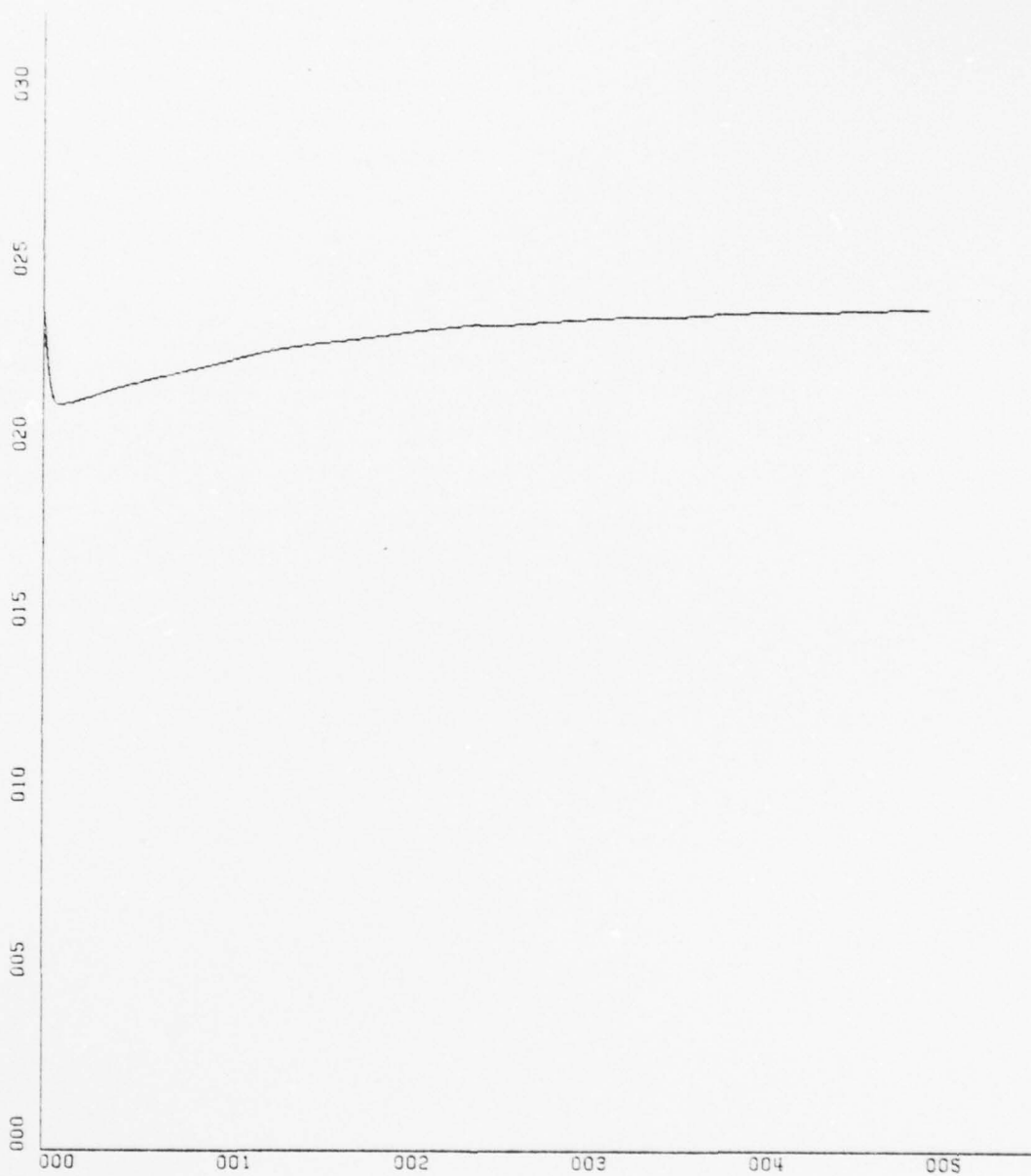


X-SCALE=1.00E+00 UNITS INCH.  
Y-SCALE=2.00E-02 UNITS INCH.  
PLOT IS CG ACCEL (GEES)  
CAB SES LINEAR 2 DOF MODEL

Figure 7 - LINEAR C.G. ACCELERATION



X-SCALE=1.00E+00 UNITS INCH.  
Y-SCALE=1.00E-01 UNITS INCH.  
PLOT IS PITCH ANGLE  
CAB SES LINEAR 2 DOF MODEL  
Figure 8 - LINEAR PITCH TRANSIENT



X-SCALE=1.00E+00 UNITS INCH.  
Y-SCALE=5.00E+00 UNITS INCH.  
30 KNOT RUN  
PLOT IS PLENUM PRESSURE

Figure 9 - 6 DOF PLENUM PRESSURE TRANSIENT

AD-A070 368

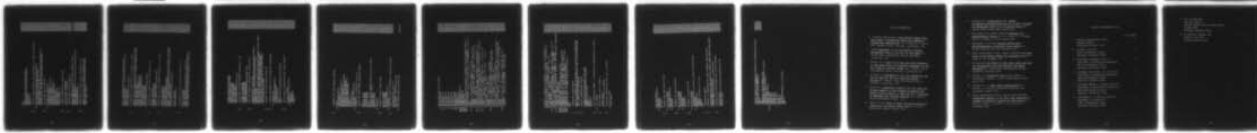
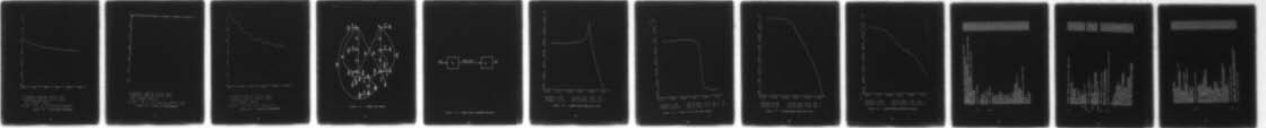
NAVAL POSTGRADUATE SCHOOL MONTEREY CA  
DEVELOPMENT AND TIME DOMAIN VALIDATION OF A LOW-ORDER, CONSTANT--ETC(U)  
MAR 79 L W BARNES

F/G 13/10

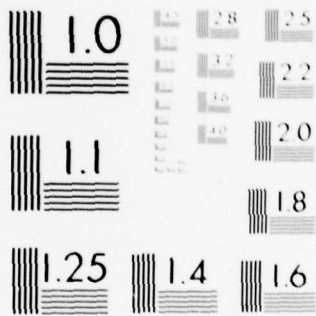
UNCLASSIFIED

NL

2 OF 2  
AD  
A070368

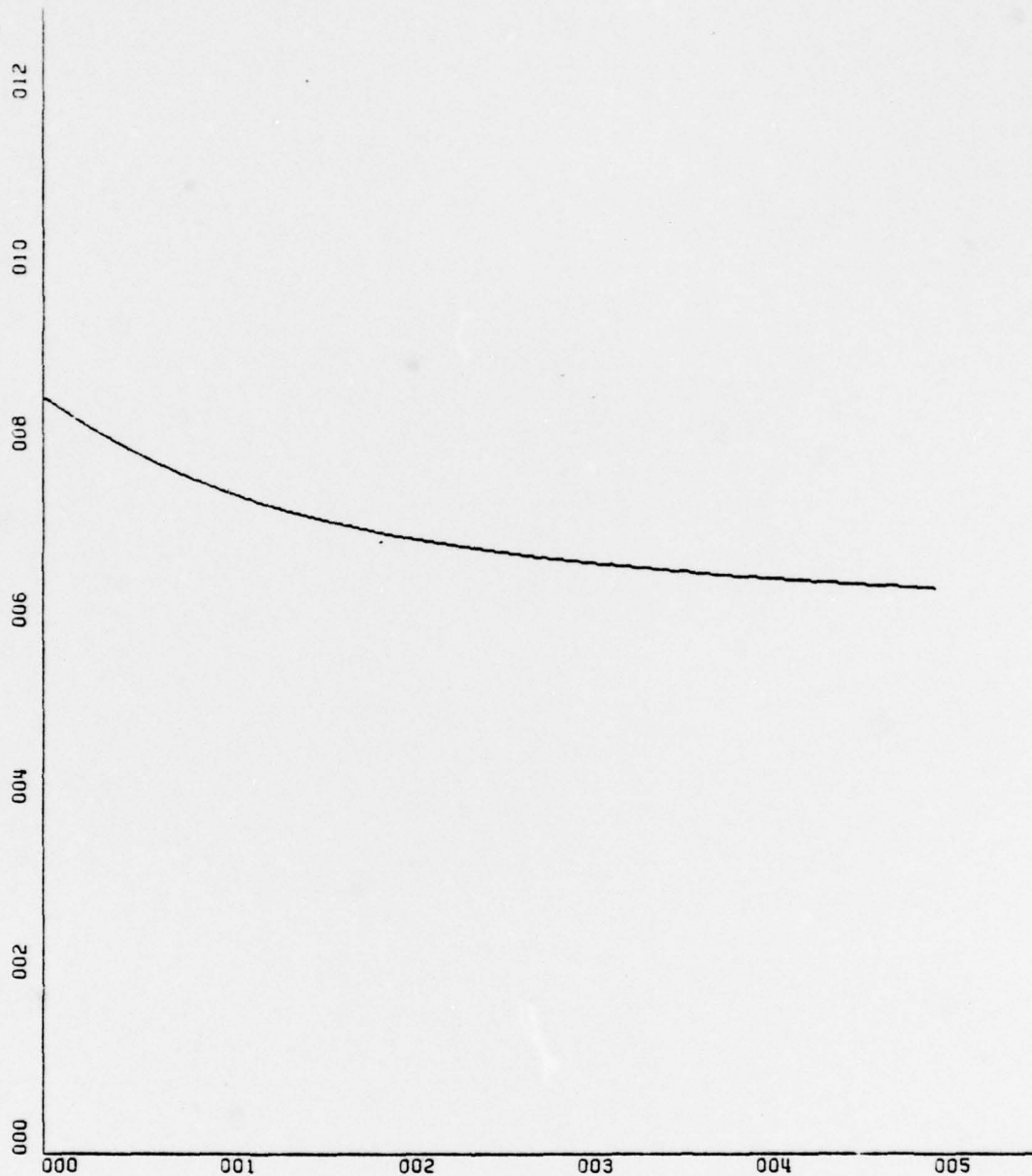


END  
DATE  
FILMED  
8-79  
DDC



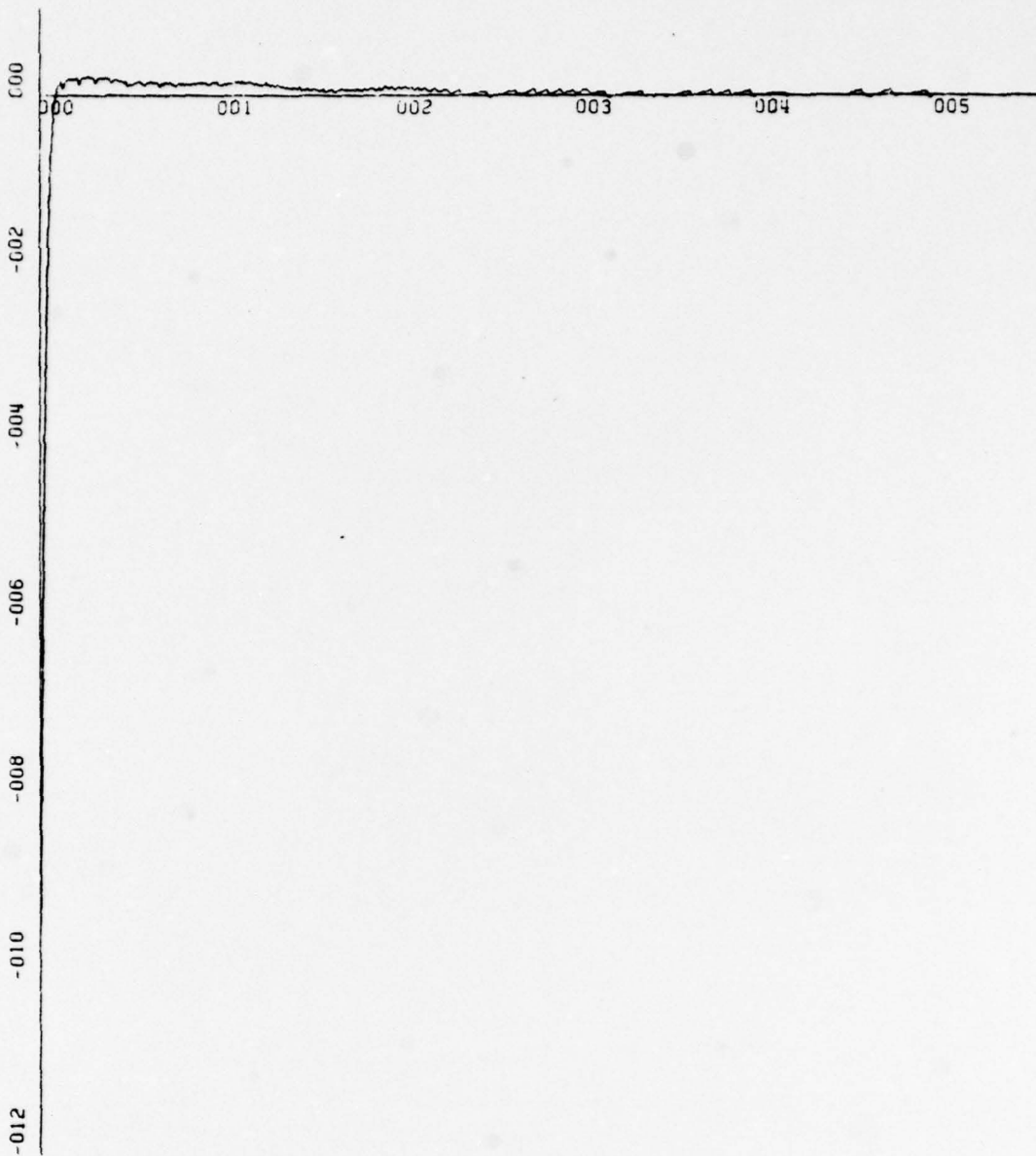
MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A





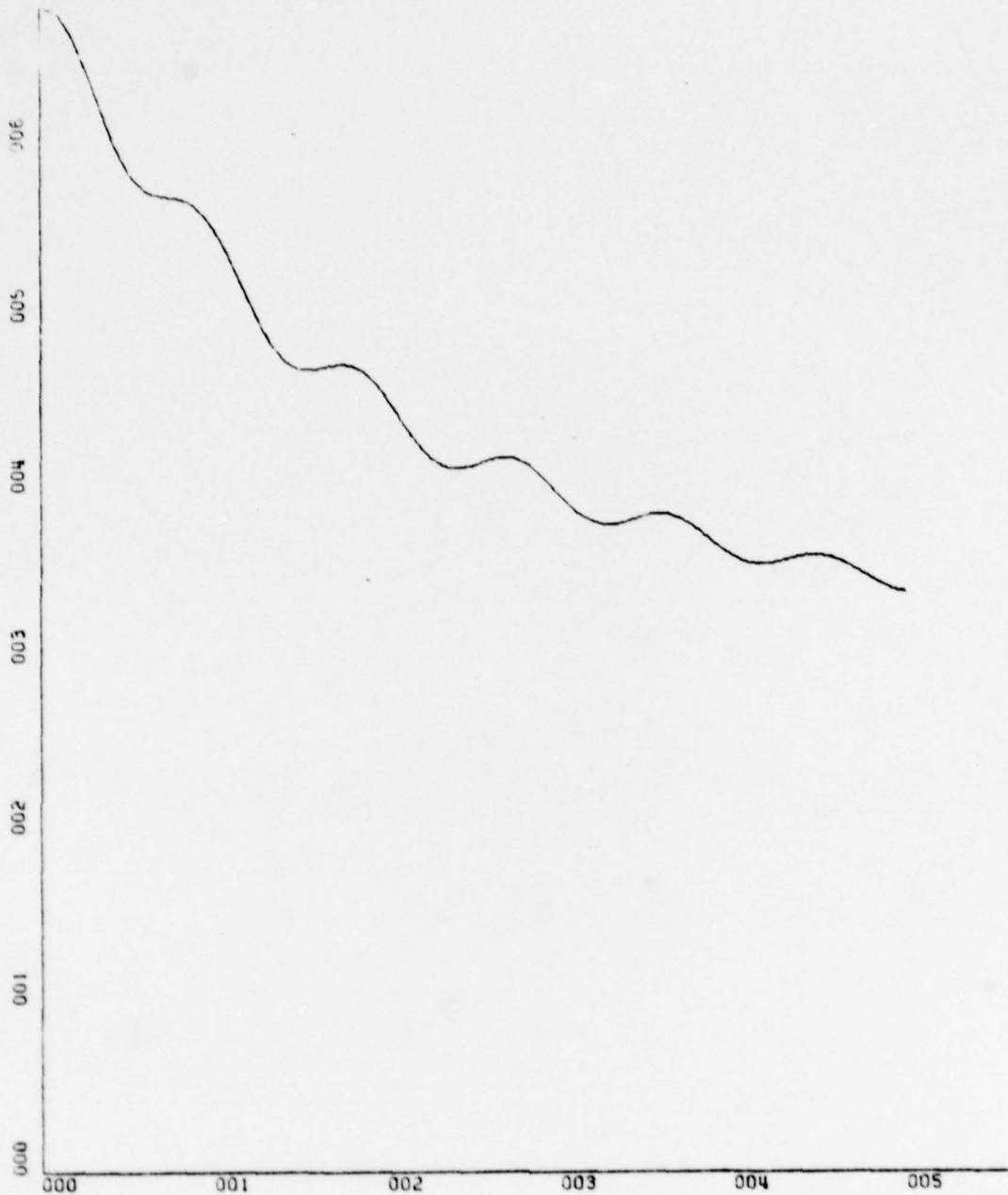
X-SCALE=1.00E+00 UNITS INCH.  
Y-SCALE=2.00E+00 UNITS INCH.  
30 KNOT RUN  
PLOT IS Z DISPLACEMENT

Figure 10 - 6 DOF DRAFT TRANSIENT



X-SCALE=1.00E+00 UNITS INCH.  
Y-SCALE=2.00E-02 UNITS INCH.  
30 KNOT RUN  
PLOT IS C.G. ACCELERATION

Figure 11 - 6 DOF C.G. ACCELERATION



X-SCALE=1.00E+00 UNITS INCH.  
Y-SCALE=1.00E-01 UNITS INCH.  
30 KNOT RUN  
PLOT IS PITCH ANGLE

Figure 12 - 6 DOF PITCH TRANSIENT

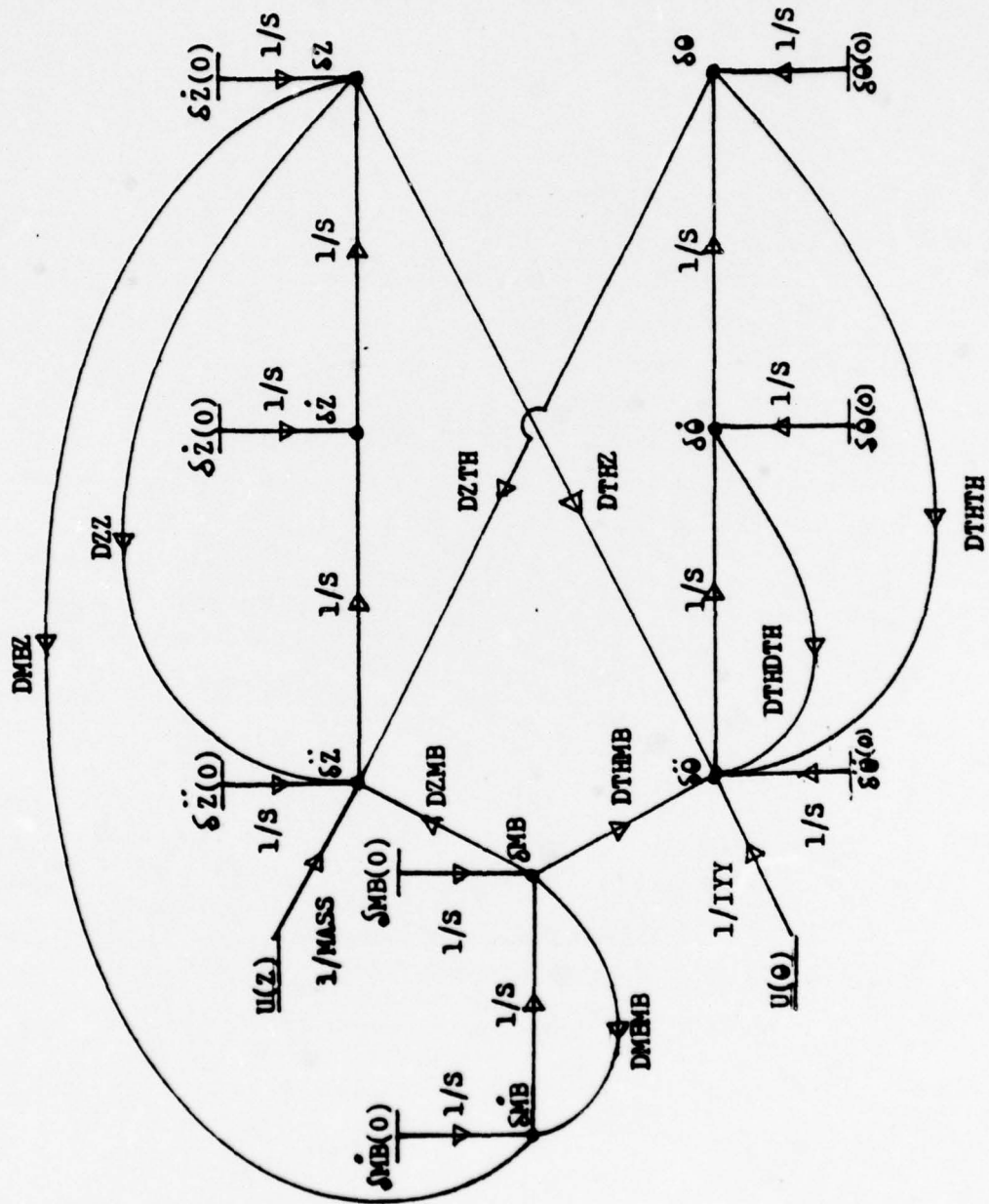


Figure 13 - SIGNAL FLOW GRAPH

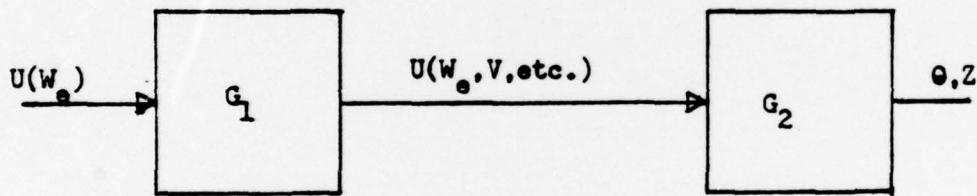
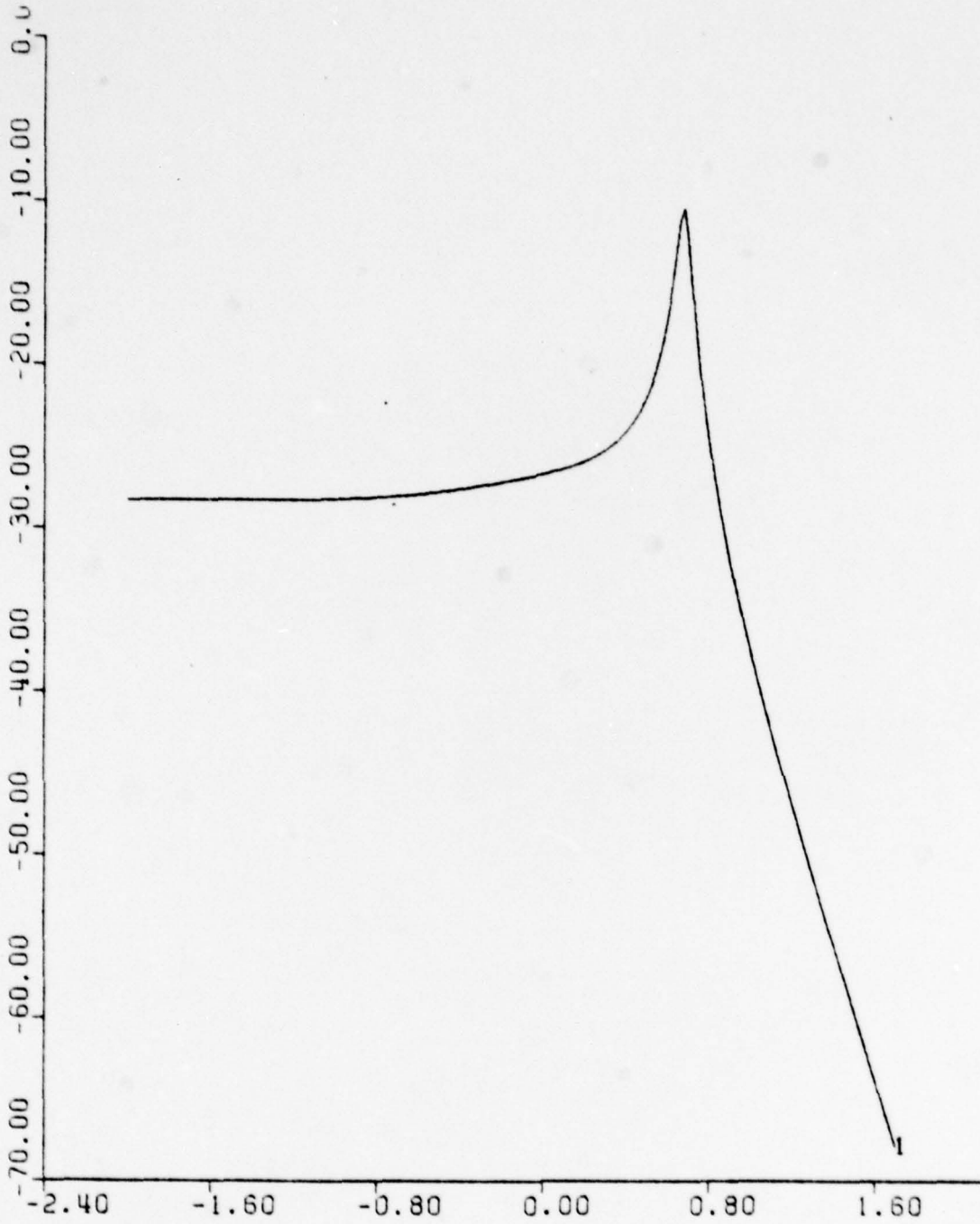


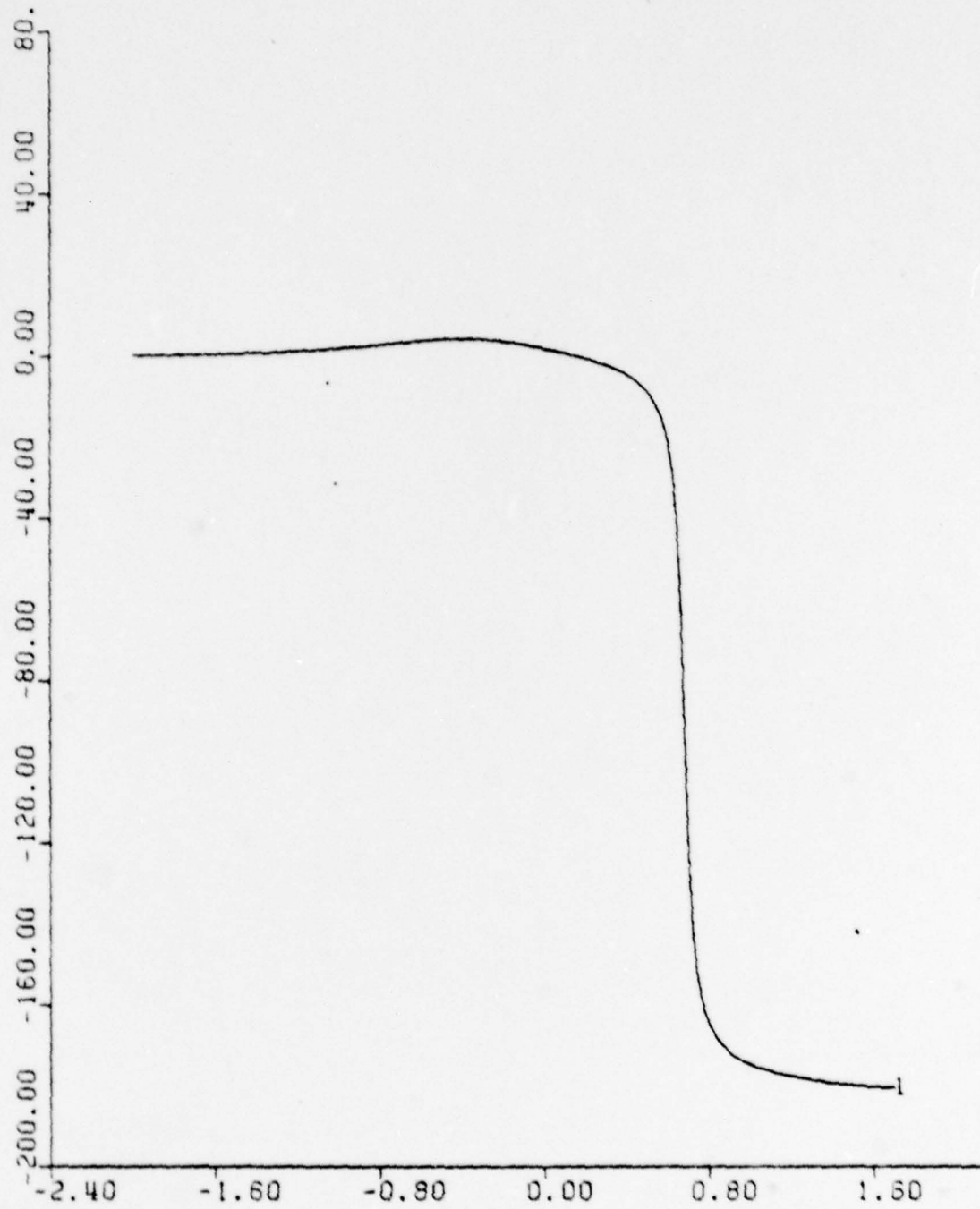
Figure 14 - HEAVE PITCH TRANSFER FUNCTION





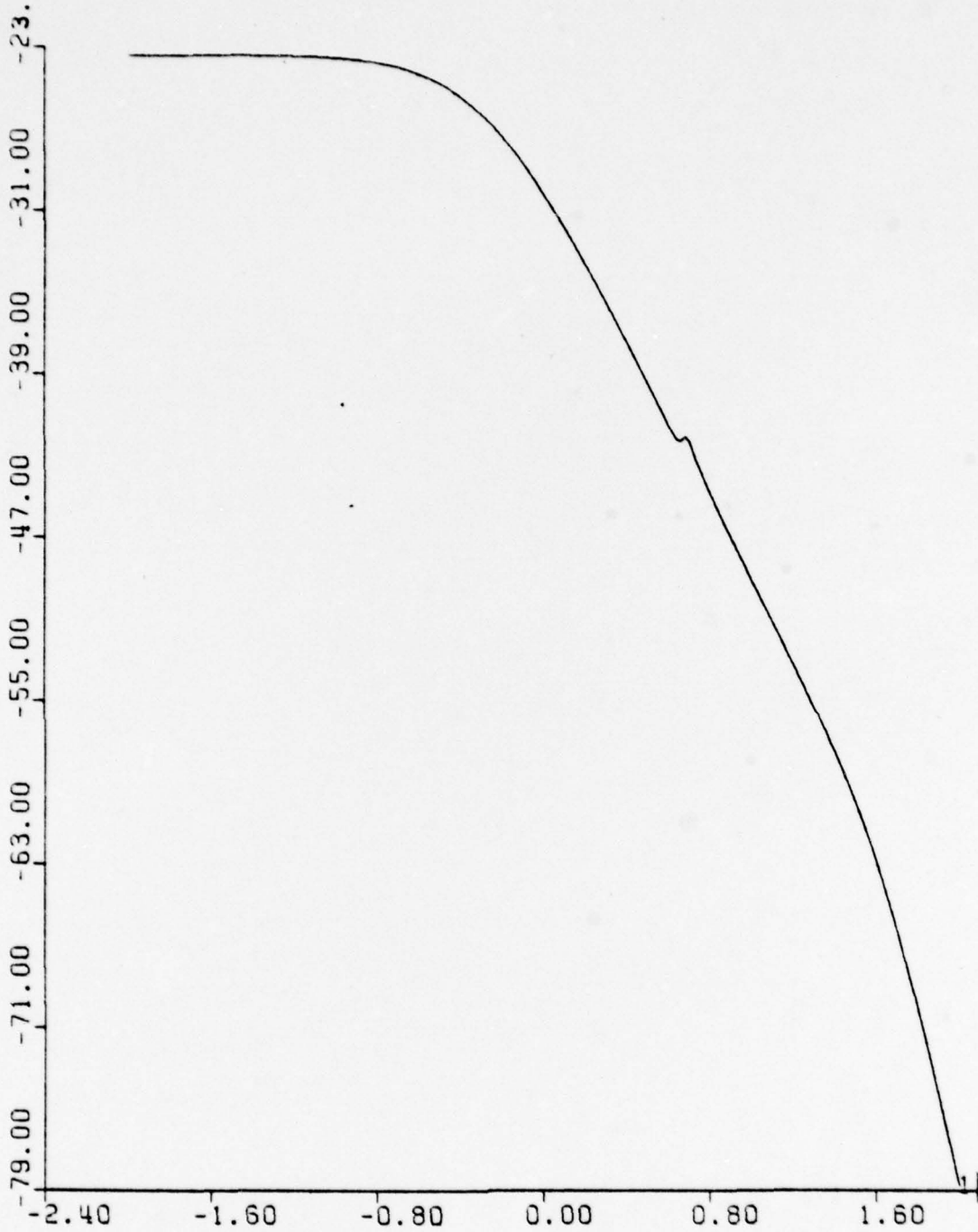
XSCALE= 0.80            UNITS/INCH    RUN   NO. 1  
YSCALE= 10.00          UNITS/INCH    PLOT NO. 1

Figure 15 - LINEAR PITCH BODE PLOT (MAG)



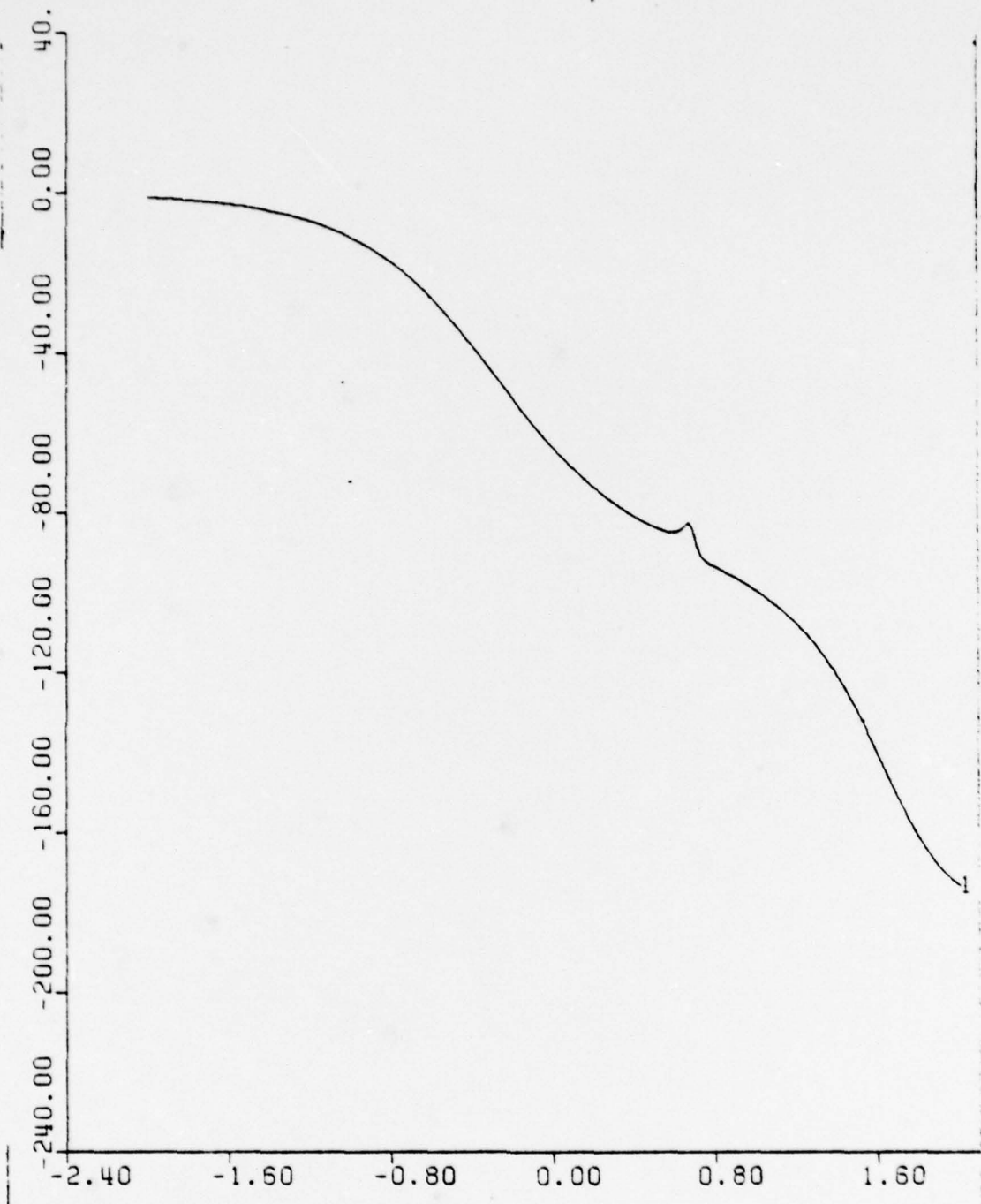
XSCALE = 0.80      UNITS/INCH    RUN NO. 1  
 YSCALE = 40.00    UNITS/INCH    PLOT NO. 2

FIGURE 10 - LINEAR FITCH BODE PLOT (PHASE)



XSCALE= 0.80            UNITS/INCH    RUN    NO. 1  
 YSCALE= 8.00            UNITS/INCH    PLOT NO. 1

Figure 17 - LINEAR HEAVE BODE PLOT (MAG)



XSCALE= 0.80            UNITS/INCH    RUN    NO. 1  
YSCALE= 40.00        UNITS/INCH    PLOT NO. 2

Figure 18 - LINEAR HEAVE BODE PLOT (PHASE)



SES00010  
 SES00020  
 SES00030  
 SES00040  
 SES00050  
 SES00060  
 SES00070  
 SES00080  
 SES00090  
 SES00100  
 SES00110  
 SES00120  
 SES00130  
 SES00140  
 SES00150  
 SES00160  
 SES00170  
 SES00180  
 SES00190  
 SES00200  
 SES00210  
 SES00220  
 SES00230  
 SES00240  
 SES00250  
 SES00260  
 SES00270  
 SES00280  
 SES00290  
 SES00300  
 SES00310  
 SES00320  
 SES00330  
 SES00340  
 SES00350  
 SES00360  
 SES00370  
 SES00380  
 SES00390  
 SES00400  
 SES00410  
 SES00420  
 SES00430  
 SES00440  
 SES00450  
 SES00460  
 SES00470  
 SES00490

DIMENSION QUTVEC(300,6), PLJTV(300), TIME(300), QPOINT(6)  
 DIMENSION ZI(2), THETA(2), AMBI(2), PBBARI(2)  
 COMMON/INTEG/X(6), XDOT(6), T, H, NPASS  
 COMMON/DERIV/DZ2, DZTH, DZMB, DTHZ, DTHGH, DTHMB, DTHDTH, DMBMB, DMBZ,  
 1DPBDZ, DPBMB, ACCEL, PACCEL  
 DATA QUTVEC, PLJTV, TIME/1800\*0.0, 300\*0.0, 300\*0.0, 300\*0.0/  
 WRITE(6,9606)  
 WRITE(6,9605)

CC

PHYSICAL CONSTANTS

G=32.2  
 GAMMA=1.4  
 PA=2116.0  
 PI=3.141593  
 RHO=2.0  
 RHOA=0.002378

CC

CRAFT DIMENSIONS

WIDTH=10.0  
 AL1=10.3  
 AL2=9.96  
 AL3=11.2  
 AL4=8.26  
 AL5=AL1/2.0  
 AL6=AL2/2.0  
 AL7=4.27  
 AL8=17.1  
 DR1=61.0  
 DR2=68.5  
 WS10=0.2  
 WS20=0.52  
 CN=0.9  
 ALPR=15.72  
 ALPWL=19.65  
 ALDIFF=ALPWL-ALPR  
 ABDIFF=ALDIFF\*WIDTH  
 XCPO=ALPWL/2.0-(119.6/12.0)  
 ABW=ALPWL\*WIDTH  
 ABR=ALPR\*WIDTH  
 BUBHGT=1.915  
 VN=(ALPR+ALPWL)/2.0\*BUBHGT\*WIDTH  
 ZS=2.5  
 QIO=35.0  
 EN=5.0  
 A3S=0.7088  
 AIY=9320



```

SES00500
SES00510
SES00520
SES00530
SES00540
SES00550
SES00560
SES00570
SES00580
SES00590
SES00600
SES00610
SES00620
SES00630
SES00640
SES00650
SES00660
SES00670
SES00680
SES00690
SES00700
SES00710
SES00720
SES00730
SES00740
SES00750
SES00760
SES00770
SES00780
SES00790
SES00800
SES00810
SES00820
SES00830
SES00840
SES00850
SES00860
SES00870
SES00880
SES00890
SES00900
SES00910
SES00920
SES00930
SES00940

```

ANGULAR CONVERSION FACTORS AND CONVERSIONS

CC

```

RADEG=360.0/(2.0*PI)
DEGRAD=(2.0*PI)/360.0
DR1=DR1*DEGRAD
DR2=DR2*DEGRAD
NORD=6
DO 01 I=1,NORD
  XDOT(I)=0.0
  X(I)=0.0
  OPOINT(I)=0.0
CONTINUE
01 READ(5,9501) I,PLOT
9501 FORMAT(I1)

```

INPUT PROBLEM PARAMETERS

CC

```

READ(5,9502) I,LIST
FORMAT(I1)
READ(5,9500) TI,TF,NPTS,NSTEP
WRITE(6,9610) TI,TF,NPTS,NSTEP
9500 READ(5,9503) AKP,XCP
9503 FORMAT(2F10.4)

```

INPUT INITIAL OPERATING POINT

CC

```

READ(5,9505) A,ALD,THETA,PBBAR,V
WRITE(6,9615) A,ALD,THETA,PBBAR,V

```

CALCULATE INTERMEDIATE VARIABLES AND CONVERSIONS

CC

```

I=0
J=1
AMASS=M/G
ALD=ALD/12.0
THETA=THETA*DEGRAD
AKOMP=2.0*AL2*AL2*A33S
ALD1=ALD-AL5*THETA
ALD2=ALD+AL6*THETA
WS1=WS10+(ALD1/(2.0*TAN(DR1)))
WS2=WS20+(ALD2/(2.0*TAN(DR2)))
AK1=2.0*RHO*G*AL1
AK2=2.0*RHO*G*AL2
AK3=WIDTH/(SIN(31*DEGRAD))
AK4=WIDTH/(SIN(32*DEGRAD))
XSEAL1=(ALD-AL3*THETA)/SIN(31.0*DEGRAD)
XSEAL2=(ALD+AL4*THETA)/SIN(32.0*DEGRAD)

```

SES00950  
 SES00960  
 SES00970  
 SES00980  
 SES00990  
 SES01000  
 SES01010  
 SES01020  
 SES01030  
 SES01040  
 SES01050  
 SES01060  
 SES01070  
 SES01080  
 SES01090  
 SES01100  
 SES01110  
 SES01120  
 SES01130  
 SES01140  
 SES01150  
 SES01160  
 SES01170  
 SES01180  
 SES01190  
 SES01200  
 SES01210  
 SES01220  
 SES01230  
 SES01240  
 SES01250  
 SES01260  
 SES01270  
 SES01280  
 SES01290  
 SES01300  
 SES01310  
 SES01320  
 SES01330  
 SES01340  
 SES01350  
 SES01360  
 SES01370  
 SES01380  
 SES01390  
 SES01400  
 SES01410  
 SES01420

ASEAL1=WIDTH\*XSEAL1  
 ASEAL2=WIDTH\*XSEAL2  
 WSPL1=WS10\*AL1  
 WSPL2=WS20\*AL2  
 XCP=XCP0+(ALDIFF\*ALD/BUHGT)/2.0+XCPC  
 AB=ABW-(ABW-ABR)\*(ALD/BUHGT)  
 VB=VN-AB\*ALD  
 PB=PA+PBBAR  
 AMB=RHOA\*VB/(PB/PA)\*\*(GAMMA)  
 QIN=EN\*(QIO-PBBAR)  
 AL=QIN/(CN\*SQRT(2.0\*PBBAR/RHOA))  
 ZI(J)=ALD  
 THETA1(J)=THETA  
 AMBI(J)=AMB  
 PBBARI(J)=PBBAR

C  
 C  
 CALCULATE FORCES AND MOMENTS

HPRES=-AB\*PBBAR  
 HBF=-AK1\*ALD1\*WS1  
 HBA=-AK2\*ALD2\*WS2  
 HSF=-PBBAR\*ASEAL1  
 HSA=-PBBAR\*ASEAL2  
 AKP1=-RHO\*THETA\*AKP\*V\*V\*PI\*2.0  
 AKP2=-RHO\*THETA\*AKP\*V\*V\*PI\*2.0  
 HPP=AKP1\*WSPL1  
 HPA=AKP2\*WSPL2  
 PPRRES=-XCP\*HPRES  
 PBF=-AL5\*HBF  
 PBA=AL6\*HBA  
 PPLAN=AL7\*(HPP+HBA)  
 PLSF=AL3-XSEAL1/2.0  
 PLSA=AL4+XSEAL2/2.0  
 PSF=-HSF\*PLSF  
 PSA=HSA\*PLSA  
 IF(I.GE.1) GO TO 10  
 RES1=W+HBF+HBA+HSF+HSA+HPP+HPA+HPRES  
 RES2=PBF+PBA+PSF+PSA+PPLAN+PPRES  
 ACCCEL=RES1/AMASS  
 PACCEL=RES2/AIYY  
 IF(ILIST.NE.1) GO TO 6

C  
 C  
 LIST FORCES, MOMENTS, AND RESIDUALS

WRITE(6,9620) W,HBF,HBA,HSF,HSA,HPP,HPA,HPRES,RES1  
 WRITE(6,9625) PBF,PBA,PSF,PSA,PPLAN,PPRES,RES2  
 INPUT FINAL OPERATING POINT

SES01430  
 SES01440  
 SES01450  
 SES01460  
 SES01470  
 SES01480  
 SES01490  
 SES01500  
 SES01510  
 SES01520  
 SES01530  
 SES01540  
 SES01550  
 SES01560  
 SES01570  
 SES01580  
 SES01590  
 SES01600  
 SES01610  
 SES01620  
 SES01630  
 SES01640  
 SES01650  
 SES01660  
 SES01670  
 SES01680  
 SES01690  
 SES01700  
 SES01710  
 SES01720  
 SES01730  
 SES01740  
 SES01750  
 SES01760  
 SES01770  
 SES01780  
 SES01790  
 SES01810  
 SES01820  
 SES01830  
 SES01840  
 SES01850  
 SES01860  
 SES01870  
 SES01880  
 SES01890  
 SES01900

```

6 I=1
  J=2
  READ(5,9510) WF,ALD,THETA,PBBAR
  WRITE(6,9615) WF,ALD,THETA,PBBAR,V
  AMASS=WF/G
  WSTEP=W-WP
  GO TO 5

  C OUTPUT FORCES, MOMENTS, AND RESIDUALS AT FINAL OPER POINT
  C
  C
10 RES1=WF*HBF+HBA+HSF+HSA+HPPF+HPA+HPRES
  RES2=PBPF+PBA+PSF+PSA+PPLAN+PPRES
  IF(ILIST.NE.1) GO TO 11
  WRITE(6,9620) WF,HBF,HBA,HSF,HSA,HPPF,HPA,HPRES,RES1
  WRITE(6,9625) PBPF,PBA,PSF,PSA,PPLAN,PPRES,RES2

  C INITIALIZE STATE VECTORS
  C
  C
11 QPOINT(1)=ZI(1)*12.0
  QPOINT(2)=ACCEL/G
  QPOINT(3)=THETA(1)*RADES
  QPOINT(4)=PACCEL
  QPOINT(5)=AMBI(1)/RHOA
  QPOINT(6)=PBBARI(1)
  ALD0=ZI(1)*12.
  THETA0=THETA(1)
  AMB0=AMBI(1)
  PBBAR0=PBBARI(1)

  C COMPUTE SENSITIVITY COEFFICIENTS
  C
  C
SIN31=SIN(31.J*DEGRAD)
SIN32=SIN(32.J*DEGRAD)

  C DERIVATIVES OF PBBAR AND MB
  C
  C
DPBDZ=GAMMA*(AB-2.0*ABDIFF*ALD/BUBHGT)*PB/VB
DPBMB=GAMMA*PB/AMB
DMBPP=-RHOA*(EN+CN*AL/(RHOA*SQRT(2.0)*PBBAR/RHOA))
DMBZ=DMBPP*DPBDZ
DMBMB=DMBPP*DPBMB

  C DERIVATIVES OF HEAVE FORCES W/RESPECT TO Z
  C
  C
DHBPF=-AK1*(((ALD-AL5*THETA)/TAN(DR1)+HS10)
DHBZ=-AK2*(((ALD+AL6*THETA)/TAN(DR2)+HS20)
DHBZ=(DHBPF+DHBZ)
  
```

SESO1910  
 SESO1920  
 SESO1930  
 SESO1940  
 SESO1950  
 SESO1960  
 SESO1970  
 SESO1980  
 SESO1990  
 SESO2000  
 SESO2010  
 SESO2020  
 SESO2030  
 SESO2040  
 SESO2050  
 SESO2060  
 SESO2070  
 SESO2080  
 SESO2090  
 SESO2100  
 SESO2110  
 SESO2120  
 SESO2130  
 SESO2140  
 SESO2150  
 SESO2160  
 SESO2170  
 SESO2180  
 SESO2190  
 SESO2200  
 SESO2210  
 SESO2220  
 SESO2230  
 SESO2240  
 SESO2250  
 SESO2260  
 SESO2270  
 SESO2280  
 SESO2290  
 SESO2300  
 SESO2310  
 SESO2320  
 SESO2330  
 SESO2340  
 SESO2350  
 SESO2360  
 SESO2370  
 SESO2380

DHSPZ=-AK3\*PBBAK-AK3\*(ALD-AL3\*THETA)\*DPBDZ  
 DHSAZ=-AK4\*(PBBAK+2.)-AK4\*(ALD+AL4\*THETA)\*DPBDZ  
 DHSZ=DHSPZ+DHSZ  
 DHPBZ=-AB\*DPBDZ  
 DZZ=(DHBZ+DHSZ+DHPBZ)/AMASS

CCC

DERIVATIVES OF HEAVE FORCES W/RESPECT TO THETA

DHBPTH=AL1\*AL5\*RHO\*G\*((ALD-AL5\*THETA)/FAN(DR1)+#S19)  
 DHBATH=-AL2\*AL5\*RHO\*G\*((ALD-AL5\*THETA)/FAN(DR2)+#S26)  
 DHSPTH=AK3\*AL3\*PBBAK  
 DHSATH=-AK4\*AL4\*(PBBAK+2.0)  
 DHPPTH=-RHO\*AKP\*\*V\*V\*WSP1\*PI  
 DHPATH=-RHO\*AKP\*\*V\*V\*WSP2\*PI  
 DHBPTH=DHBPTH+DHBATH  
 DHSPTH=DHSPPTH+DHSATH  
 DHPPTH=DHPPPTH+DHPATH  
 DZTH=(DHBTH+DHSPTH+DHPPTH)/AMASS

CCC

DERIVATIVE OF HEAVE FORCE W/RESPECT TO MB

DHPMB=-AB\*DPBMB  
 DHSFMB=-ASEAL1\*DPBMB  
 DHSAMB=-ASEAL2\*DPBMB  
 DZMB=(DHPMB+DHSFMB+DHSAMB)/AMASS

CCC

DERIVATIVES OF PITCH MOMENTS W/RESPECT TO THETA

DPBPTH=-AL5\*DHBPTH  
 DPBATH=AL6\*DHBATH  
 DPBTH=DPBPTH+DPBATH  
 DPPLTH=AL7\*(DHPPTH+DHPATH)  
 DPSPTH=-PBBAK\*(PLSA\*AL3\*WIDTH/SIN31-ASEAL1/2.0\*SIN31)  
 DPSATH=-PBBAK\*(PLSA\*AL4\*WIDTH/SIN32-ASEAL2/2.0\*SIN32)  
 DTPTH=(DPSPTH+DPSATH)  
 DTHTH=(DPBTH+DPPLTH+DTPTH)/AIYY  
 DPDMP=-AKDMP\*V  
 DTHDTH=DPDMP/AIYY

C

DERIVATIVES OF PITCH MOMENTS W/RESPECT TO Z

DPBPZ=-AL5\*DHPBZ  
 DPBAZ=AL6\*DHPBAZ  
 DPPBZ=-YCP\*DHPBZ-ALDIPP\*HPPBZ-(2.0\*BU\*HGT)  
 DPSPZ=PBBAK\*(PLSF\*WIDTH/SIN31-ASEAL1/2.0\*SIN31)  
 DPSAZ=-PBBAK\*(PLSA\*WIDTH/SIN31+ASEAL2/2.0\*SIN32)

CCC



SES02390  
 SES02400  
 SES02410  
 SES02420  
 SES02430  
 SES02440  
 SES02450  
 SES02460  
 SES02470  
 SES02480  
 SES02490  
 SES02500  
 SES02510  
 SES02520  
 SES02530  
 SES02540  
 SES02550  
 SES02560  
 SES02570  
 SES02580  
 SES02590  
 SES02600  
 SES02610  
 SES02620  
 SES02630  
 SES02650  
 SES02660  
 SES02670  
 SES02680  
 SES02690  
 SES02700  
 SES02710  
 SES02720  
 SES02730  
 SES02740  
 SES02750  
 SES02760  
 SES02770  
 SES02780  
 SES02790  
 SES02800  
 SES02810  
 SES02820  
 SES02830  
 SES02840  
 SES02850  
 SES02860

```

DPSFPZ=ASEAL1*PLSF*DPBDZ
DPSAPZ=-ASEAL2*PLSA*DPBDZ
DPSFZ=DPSFZ+DPSFPZ
DPSAZ=DPSAZ+DPSAPZ
DPSZ=(DPSFZ+DPSAZ)
DPBZ=DPBFZ+DPBAZ
DTHZ=(DPSZ+DPBZ+DPPBZ)/AIYY

DERIVATIVE OF PITCH MOMENT W/RESPECT TO MB
C C C
DPPBMB=-XCP*DHPBMB
DPSFMB=-PLSF*DHSFMB
DPSAMB=PLSA*DHSAMB
DTHMB=(DPPBMB+DPSFMB+DPSAMB)/AIYY
C C C
LIST THE VARIOUS SENSITIVITY COEFFICIENTS
IF (ILIST.NE.1) GO TO 12
WRITE(5,9640) DHBFBZ, DHBFBZ, DHSFZ, DHSAZ, DHPBZ, DHBFBZ,
1 DHBATH, DHSFTH, DHSATH, DHPPTH, DHPATH, DHPBMB,
2 DHSFMB, DHSAMB
WRITE(6,9645) DPBFTH, DPBATH, DPPLTH, DPSFTH, DPSATH, DPBFBZ, DPBAZ,
1 DPSFZ, DPSAZ, DPFBZ, DPBMB, DPBMB, DPBMB, DPBMB, DPBMB,
WRITE(6,9650) DPBDZ, DPBMB, DMBPB, DMBZ, DMBMB,
WRITE(6,9630) DZZ, DZTH, DZMB, DTHH, DTHMB,
1 DMBZ, DMBMB, DPBDZ, DPBMB
PREPARE FOR TIME DOMAIN SOLUTION
C C C C C C
COMPUTE VARIABLES FOR INTEGRATION SUBROUTINE
12 RANGE=TF-TI
ACCEL=ACCEL-WSTEP/AMASS
QPOINT(2)=ACCEL/G
H=RANGE/NSTEP
T=TI
NPASS=IFIX(FLOAT(NSTEP)/FLOAT(NPTS))
IP=1
LOAD INITIAL CONDITIONS INTO OUTPUT MATRIX
C C C
DO 15 I=1,NORD
OUTVEC(IP,I)=QPOINT(I)
CONTINUE
15 TIME(IP)=T
ICOUNT=NPTS
NPTS=1
  
```



```

C C C COMMENCE THE FINE DOMAIN SOLUTION
25 CALL DEQRKF (MORD)
NPTS=NPTS+1
QPOINT(1)=ALD)+X(1)*12.0
QPOINT(2)=XDOT(2)/G
QPOINT(3)=(THEIAB)+X(3))*RADEG
QPOINT(4)=XDOT(4)*RADEG
QPOINT(5)=(AMB0)+X(5))/EHOA
QPOINT(6)=PBBAR0+X(6)
IP=IP+1
TIME(IP)=T
DO 30 I=1,NORD
OUTVEC(IP,I)=QPOINT(I)
30 CONTINUE
IP(NPTS.LT.(ICOUNT+1)) GO TO 25
C C C OUTPUT THE TIME DOMAIN SOLUTION RESULTS
K=0
WRITE(6,9600)
WRITE(6,9605)
WRITE(6,9655)
DO 35 I=1,NPTS
K=K+1
WRITE(6,9660) TIME(I), (OUTVEC(I,J), J=1, NORD)
IF(K.LT.70) GO TO 35
WRITE(6,9660)
WRITE(6,9655)
K=0
35 CONTINUE
C C C PREPARE TO PLOT OUTPUT DATA
DO 85 I=1,NORD
WRITE(6,9600)
DO 40 J=1,NPTS
PLOTV(J)=OUTVEC(J,I)
40 CONTINUE
C C C CHECK FOR PLOTT OR VERSATEC PLOTTING DESIRED
IF(IPLT.ME.1) GO TO 44
IF(I.EQ.5) GO TO 85
CALL VERSAP (NPTS, TIME, PLOTV)
GO TO 35
44 CALL PLOTP(TIME, PLOTV, NPTS, 0)
SES02870
SES02880
SES02890
SES02900
SES02910
SES02920
SES02930
SES02940
SES02950
SES02960
SES02970
SES02980
SES02990
SES03000
SES03010
SES03020
SES03030
SES03040
SES03050
SES03060
SES03070
SES03080
SES03090
SES03100
SES03110
SES03120
SES03130
SES03140
SES03150
SES03160
SES03170
SES03180
SES03190
SES03200
SES03210
SES03220
SES03230
SES03240
SES03250
SES03260
SES03270
SES03120
SES03130
SES03280

```

```

45 GO TO (45,50,55,60,65,70),I
   WRITE (6,9665)
50 GO TO 80
   WRITE (6,9670)
55 GO TO 80
   WRITE (6,9675)
60 GO TO 80
   WRITE (6,9680)
65 GO TO 80
   WRITE (6,9685)
70 GO TO 30
   WRITE (6,9695)
80 GO TO 60
   WRITE (6,9605)
85 CONTINUE
   WRITE (6,9600)
9500 FORMAT (2F10.1,2I10)
9505 FORMAT (5F10.4)
9510 FORMAT (4F10.4)
9600 FORMAT (1H1)
9605 FORMAT (//,20X,'TWO-DEGREE OF FREEDOM CAB SES LINEAR MODEL',/)
9610 FORMAT (//,1X,PI = ,F10.1//,1X,TP = ,F10.1//,1X,NO OF INTEGRATION STEPS = ,
2I10)
9615 FORMAT (//,1X,'OPERATING CONDITION',//,1X,
1,WEIGHT = ,F10.4//,1X,'DRAFT = ,F10.4//,1X,'PITCH',
2,ANGLE = ,F10.4//,1X,'PLENUM PRESSURE = ,F10.4//,1X,
3,SPEED = ,F10.4//,1X,'HBA',7X,'HSA',7X,
9620 'HPF',7X,'HBP',7X,'HBA',7X,'HSP',7X,'HSA',7X,
1,HPRES = ,5X,'HPRES',7X,'HPRES',7X,'HPRES',7X,'HPRES',7X,
9625 'PBA',7X,'PBA',7X,'PBA',7X,'PBA',7X,'PBA',7X,'PBA',7X,
1,PPRES = ,6X,'RES2',7X,'RES2',7X,'RES2',7X,'RES2',7X,
9630 'DZZ',7X,'DZZ',7X,'DZZ',7X,'DZZ',7X,'DZZ',7X,
1,DZMB = ,E11.4//,1X,'DTHZ = ,E11.4//,1X,
2,E11.4//,1X,'DTH = ,E11.4//,1X,'DTHMB = ,E11.4,
3//,1X,'DHBZ = ,E11.4//,1X,
4,DHMB = ,E11.4//,1X,
5,DPBZ = ,E11.4//,1X,
9640 'DPB2 = ,E11.4//,1X,
1,HEAVE SENSITIVITY COEFFICIENTS',//,1X,
2,E11.4//,1X,'DHSAZ = ,E11.4//,1X,
3,DHPBZ = ,E11.4//,1X,
4,DHPB = ,E11.4//,1X,
5,E11.4//,1X,'DHPFB = ,E11.4//,1X,
7,DHPBMB = ,E11.4//,1X,
8,E11.4//,1X,
9645 'DHPBMB = ,E11.4//,1X,
1,DPBPTH = ,E11.4//,1X,
2,DPPLTH = ,E11.4//,1X,

```

```

SES03290
SES03300
SES03310
SES03320
SES03330
SES03340
SES03350
SES03360
SES03370
SES03380
SES03390
SES03400
SES03410
SES03420
SES03430
SES03440
SES03450
SES03460
SES03470
SES03480
SES03490
SES03500
SES03510
SES03520
SES03530
SES03540
SES03550
SES03560
SES03570
SES03580
SES03590
SES03600
SES03610
SES03620
SES03630
SES03640
SES03650
SES03660
SES03670
SES03680
SES03690
SES03700
SES03710
SES03720
SES03730
SES03750
SES03760

```

```

3  DPSATH = , E11.4 / , 1X 'DPBPZ = , E11.4 / , 1X 'DPBAZ = ',
4  E11.4 / , 1X 'DPSFZ = , E11.4 / , 1X 'DPSAZ = , E11.4 / , 1X,
5  'DPPBZ = , E11.4 / , 1X 'DPPB3 = , E11.4 / , 1X,
6  // , 1X 'DPSFMB = , E11.4 / , 1X 'DPSAMB = , E11.4,
7  // , 1X 'DTHDTH = , E11.4 // , 1X 'DPSAMB = , E11.4,
8  // , 1X 'DTHDTH = , E11.4 // , 1X 'DPSAMB = , E11.4,
9650 1  'FORMAT( / , 1X 'PLENH PRESSURE AND MASS SENS. COEFF. ' , // , 1X,
2E11.4 / , 1X 'DPBMB = , E11.4 / , 1X 'DMPBPB = ,
9655 1  'FORMAT( / , 1X 'DMBZ = , E11.4 / , 1X 'DMBMB = , E11.4 // , 1X,
9660 1  'FORMAT( / , 1X 'PBBAR' , 4 // , 1X 'THETA (DEG) THETADOT',
9665 1  'FORMAT( / , 1X 'PBBAR' , 4 // , 1X 'THETA (DEG) THETADOT',
9670 1  'FORMAT( / , 1X 'PBBAR' , 4 // , 1X 'THETA (DEG) THETADOT',
9675 1  'FORMAT( / , 1X 'PBBAR' , 4 // , 1X 'THETA (DEG) THETADOT',
9680 1  'FORMAT( / , 1X 'PBBAR' , 4 // , 1X 'THETA (DEG) THETADOT',
9685 1  'FORMAT( / , 1X 'PBBAR' , 4 // , 1X 'THETA (DEG) THETADOT',
9695 1  'FORMAT( / , 1X 'PBBAR' , 4 // , 1X 'THETA (DEG) THETADOT',
          STOP
          END
SUBROUTINE DEQRKF (NORD)
PURPOSE: GENERATE THE SOLUTIONS OF A SYSTEM OF SIMULTANEOUS
FIRST ORDER DIFFERENTIAL EQUATIONS USING A FOUR-POINT FIXED-
STEP RUNGE-KUTTA ALGORITHM.
INITIAL BOOKKEEPING SECTION
DIMENSION XI (6), P (6), Q (6), R (6), S (6)
COMMON /INTEG/ X (6), XDOT (6), T, H, NPASS
REAL*8 P, Q, R, S, KDP
NTERM=0
KDP=0.5D0
NITER=0
CALL SUBROUTINE DYNMIC TO EVALUATE THE DERIVATIVES AT TIME T
05 CALL DYNMIC
BEGIN RUNGE-KUTTA SOLUTION
NTERM=NTERM+1
GO TO (6,15,25,35),NTERM
SAVE X(I), COMPUTE P(I) AND X(I) +0.5*P(I)
6 DO 10 I=1,NORD
  XI (I) =X (I)

```

SES03770  
 SES03780  
 SES03790  
 SES03800  
 SES03810  
 SES03820  
 SES03830  
 SES03840  
 SES03850  
 SES03860  
 SES03870  
 SES03880  
 SES03890  
 SES03900  
 SES03910  
 SES03920  
 SES03930  
 SES03940  
 SES03950  
 SES03960  
 SES03970  
 SES03980  
 SES03990  
 SES04000  
 SES04010  
 SES04020  
 SES04030  
 SES04040  
 SES04050  
 SES04060  
 SES04070  
 SES04080  
 SES04090  
 SES04100  
 SES04110  
 SES04120  
 SES04130  
 SES04140  
 SES04150  
 SES04160  
 SES04170  
 SES04180  
 SES04190  
 SES04200  
 SES04210  
 SES04220  
 SES04230  
 SES04240



```

P(I) = XDOT(I)*H
X(I) = X(I) + P(I)*KDP
10 CONTINUE
T = T + H*KDP
GO TO 5

C C C
C COMPUTE Q(I) AND X(I) + 0.5*Q(I)
15 DO 20 I = 1, NORD
Q(I) = XDOT(I)*H
X(I) = X(I) + Q(I)*KDP
20 CONTINUE
GO TO 5

C C C
C COMPUTE R(I) AND X(I) + R(I)
25 DO 30 I = 1, NORD
R(I) = XDOT(I)*H
X(I) = X(I) + R(I)
30 CONTINUE
T = T + H*KDP
GO TO 5

C C C
C COMPUTE S(I) AND X(I) + H
35 DO 40 I = 1, NORD
S(I) = XDOT(I)*H
X(I) = X(I) + (1./6.)*(P(I) + 2.*Q(I) + 2.*R(I) + S(I))
40 CONTINUE
NITER = NITER + 1
NTERM = 0
IF(NITER.LT.NPASS) GO TO 05
RETURN
END

C C C C
SUBROUTINE DYNMIC
PURPOSE: TO EVALUATE THE STATE VARIABLE DERIVATIVES
COMMON/DERIV/DZZ,DZTH,DZMB,DPHZ,DTHH,DTHM,DTHDTH,DMBB,DMBZ,
1 DPBDZ,DPBMB,ACCEL,PACCEL
COMMON/INTEG/X(6),XDOT(6),T,H,NORD,NPASS
EVALUATE THE STATE MATRIX AND OUTPUT VARIABLE
C C C
XDOT(1) = X(2)
XDOT(2) = DZZ*X(1) + DZTH*X(3) + DZMB*X(5) + ACCEL
XDOT(3) = X(4)

```

```

SE$04250
SE$04260
SE$04270
SE$04280
SE$04290
SE$04300
SE$04310
SE$04320
SE$04330
SE$04340
SE$04350
SE$04360
SE$04370
SE$04380
SE$04390
SE$04400
SE$04410
SE$04420
SE$04430
SE$04440
SE$04450
SE$04460
SE$04470
SE$04480
SE$04490
SE$04500
SE$04510
SE$04520
SE$04530
SE$04540
SE$04550
SE$04560
SE$04570
SE$04580
SE$04590
SE$04600
SE$04610
SE$04620
SE$04630
SE$04640
SE$04650
SE$04660
SE$04670
SE$04680
SE$04690
SE$04700
SE$04710
SE$04720

```

SES04730  
SES04740  
SES04750  
SES04760  
SES04770

```
XDOT (4) =DTHZ*X (1) +DTHTH*X (3) +DTHMB*X (5) +DTHDTH*X (4) +PACCEL  
XDOT (5) =DMBZ*X (1) +DMBMB*X (5)  
X (6) =DPBDZ*X (1) +DPBMB*X (5)  
RETURN  
END  
SUBROUTINE VERSAP (NUMPTS, X, Y)  
DIMENSION X (300), Y (300), RTB (12), ITB (28)  
EQUIVALENCE (PI, FILE, RTB (5))  
REAL*8 TITLE (12)  
READ (5, 9515) TITLE  
FORMAT (6A8)  
RTB (1) = 0.0  
RTB (2) = 0.0  
RTB (3) = 0.0  
RTB (4) = 0.0  
DO 1 I = 1, 12  
1 ITB (I) = 0  
ITB (3) = 6  
ITB (4) = 7  
CALL DRAMP (NUMPTS, X, Y, ITB, RTB)  
RETURN  
END
```

95 15

1



LIST OF REFERENCES

1. Leo, D.G., and Boncal, R., XR-3 Surface Effects Ship Test Craft: A Mathematical Model and Simulation Program with Verification, M.S. Thesis, U. S. Naval Post Graduate School, Monterey, California, 1973
2. Forbes, Validation of the Six Degree of Freedom Mathematical Model of the XR-3 in Calm Water, M.S. Thesis, Naval Postgraduate School, Monterey, California, 1974
3. Menzel, R.F., Study of the Roll and Pitch Transients in Calm Water using the Simulated Performance of the XR-3 Loads and Motions Program, M.S. Thesis, Naval Postgraduate School, Monterey, California, 1975
4. Finley, R.A., Refinements of the Seal Subroutines and Fan Air Maps for the XR-3 Loads and Motions Program, M.S. Thesis, Naval Postgraduate School, Monterey, California, 1974
5. Riedel, R.G., Sensitivity Study of the XR-3 Loads and Motions Computer Program Sidewall Parameters and forces on Roll Behavior in Calm Sea and a Comparison to Testcraft Turn Maneuver Behavior, M.S. Thesis, Naval Postgraduate School, 1977
6. Grant, U.S., Jr., Study of Heave Acceleration/Velocity Control for the Surface Effect Ship, M.S. Thesis, Naval Post Graduate School, 1974

7. McIntyre, L. F., Investigation of a Linear Two-Degree-of-freedom Simulation for the XR-3 Captured Air Bubble (CAB) Craft in the Frequency Domain, M.S. Thesis, Naval Postgraduate School, 1977
8. Rhor Marine Inc., Report TT00013A, Stability and Maneuverability Report, by E. H. Price, R. C. Stoner, and N. L. Wener, p. 2-2, 31 August 1978
9. Department of the Navy, Surface Effects Ship Aero/Hydrodynamics Technology Design Manual, SES Project PMS-304, Vol. II, February 1976.
10. Naval Postgraduate School, Report NPS67-78-001PR, Seal Loads of the Surface Effect Ship Testcraft XR-3, D.M. Layton, P 43, November 1977.
11. Moloney, R. W., The Effect of Seal Shape Variations Upon the Performance of the XR-3 Captured Air Bubble Testcraft, M.S. Thesis, Naval Postgraduate School, Monterey, California, 1975
12. Riedel, R. G., project EE 4900, Project report to Professor A. Gerba Jr., Naval Postgraduate School, June, 1977.
13. Barnaby, K. G., Basic Naval Architecture, Fifth Edition, p. 336-339, Hutchinson Scientific and Technical, London, 1967.
14. Naval Postgraduate School, Report NPS62-78-008PR, Sensitivity Analysis of the XR-3 Heave Equations to Changes in Plenum Air Leakage and Influx Rates, A Gerba Jr., and G. J. Thaler, p 28, and 54-57, September 1978.

INITIAL DISTRIBUTION LIST

	No. Copies
1. Defense Documentation Center Cameron Station Alexandria Virginia 22314	2
2. Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3. Department Chairman, Code 52 Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	1
4. Professor Alex Gerba, Jr., Code 52Gz Department of Electrical Engineering Naval Postgraduate School Monterey California 93940	5
5. Professor George J. Thaler, Code 52Tr Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	5
6. Professor D. M. Layton, Code 57ln Department of Aeronautics Naval Postgraduate School Monterey California 93940	1

7. Mr. H. Robertson 6  
PHS 304, Code 141  
Surface Effects Ships Project Office  
PO Box 34401  
Bethesda, Maryland 20034
8. Lt Leslie W. Barnes, USN 1  
Route 7, Box 412E  
Tucson, Arizona 95706