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DYNAMIC HEAVE-PITCH ANALYSIS OF AIR CUSHION LANDING SYSTEMS

K. M. Captain, A. B. Boghani, and D. N. Wormley

Prepared by
FOSTER-MILLER ASSOCIATES, INC.
Waltham, Mass. 02154
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16. Abstract

This report describes the first two phases of a program to develop analytical tools for evaluating the dynamic performance of Air Cushion Landing Systems (ACLS). In the first phase, the heave (vertical) motion of the ACLS was analyzed, and in the second phase, the analysis was extended to cover coupled heave-pitch motions. The mathematical models developed through this program are based on a fundamental analysis of the body dynamics and fluid mechanics of the aircraft-cushion-runway interaction. The analysis takes into account the air source characteristics, flow losses in the feeding ducts, trunk and cushion, the effects of fluid compressibility, and dynamic trunk deflections, including ground contact.

A computer program, based on the heave-pitch analysis, has been developed to simulate the dynamic behavior of an ACLS during landing impact and taxi over an irregular runway. The program outputs include ACLS motions, loadings, pressures and flows as a function of time. To illustrate program use, three basic types of simulations have been carried out. The results provide an initial indication of ACLS performance during (i) a static drop, (ii) landing impact, and (iii) taxi over a runway irregularity.

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Table of Contents

List of Illustrations

List of Illustrations (Continued)

Principal Analysis Nomenclature

a	Horizontal distance between inner and outer trunk attachment points
A	Orifice area
A_{ch}	Cushion area
A_{ph}	Heave drag area of cushion
A_{tkcn}	Trunk-ground contact area
b	Vertical distance between trunk attachment points
$\overline{B}_z$	Damping constant for each trunk segment
CC	Horizontal distance of CG from center of cushion
CG	Center of gravity
C_d	Discharge coefficient
C_{enf}	Distance of center of aerodynamic heave drag area from CG
d	Distance between trunk attachment points
del_x	Width of straight trunk segment
Forcn	Force
Forct	Total vertical pressure force transmitted to aircraft
F	Trunk damping force
GG	Vertical distance of CG from center of cushion
g	Gravity acceleration
h_y	Equilibrium height of trunk cross section
Inert	Pitch moment of inertia of aircraft about CG
ℓ	Peripheral trunk length
ℓ_p	Peripheral distance from inner trunk attachment to first row of orifices

L_s	Straight section length of cushion
M	Number of straight trunk segments in one quarter of trunk periphery
M_a	Mass supported by ACLS
N	Number of curved trunk segments in one quarter of trunk periphery
N_h	Number of trunk orifices per row
N_r	Number of rows of trunk orifices
P	Pressure
P_{ch}	Cushion pressure (gage)
P_{fan}	Fan pressure rise
P_{tk}	Trunk pressure (gage)
Q	Volume flow rate
Q_{chat}	Cushion-to-atmosphere volume flow
Q_{fan}	Fan volume flow
Q_{plat}	Bleed volume flow
Q_{plch}	Plenum-to-cushion volume flow
Q_{pltk}	Plenum-to-trunk volume flow
Q_{tkat}	Trunk-to-atmosphere volume flow
Q_{tkch}	Trunk-to-cushion volume flow
R_1	Outer radius of curvature of trunk
R_2	Inner radius of curvature of trunk
S_h	Trunk orifice row spacing
t	Time
Torf	Trunk-ground contact friction torque
Torn	Pressure torque

Torqt	Trunk damping torque
V	Heave velocity
V_{ch}	Total cushion volume
V_{plm}	Plenum volume
V_{tk}	Trunk volume
$X_{ch}(i)$	Distance of center of cushion pressure of ith segment from CC
X_{cg}	X-coordinate of CG
X_{cc}	X-coordinate of center of cushion
$X_{cx}(i)$	Distance of center of ith segment from CC
$X_h(i)$	X-coordinate of center of ith segment
$X_{tk}(i)$	Distance of center of trunk pressure of ith segment from CC
Y_{cg}	Y-coordinate of CG
Y_{cc}	Y-coordinate of center of cushion
$Y_{gh}(i)$	Hard surface clearance for ith segment
$Y_g(i)$	Ground elevation corresponding to ith segment
$Y_h(i)$	Y-coordinate of center of ith segment
β	Angle subtended by curved segment of the trunk
$\delta(i)$	Angular position of ith curved segment
K	Polytropic expansion constant
ϕ	Pitch angle, positive clockwise
ϕ_1	Angle subtended by outer trunk segment (atmosphere side)
ϕ_2	Angle subtended by inner trunk segment (cushion side)
ϕ_3	Angle subtended by cushion side of trunk deformation
ϕ_4	Angle subtended by atmosphere side of trunk deformation
ρ	Air density
μ	Coefficient of friction between the trunk and the ground

DYNAMIC HEAVE-PITCH ANALYSIS OF AIR CUSHION LANDING SYSTEMS

By K. M. Captain, A. B. Boghani, and D. N. Wormley
Foster-Miller Associates, Inc.

1. Introduction

As part of the effort to advance Air Cushion Landing System (ACLS) technology, NASA has initiated a program to develop analytical tools to help evaluate ACLS dynamic performance. This report describes the first two phases of this program, which are now complete.

The objective of these phases was to formulate a fundamental analysis of the dynamic behavior of the ACLS and develop a computer program to carry out the dynamic simulation. First, the heave (vertical) motion of the ACLS was analyzed, and the analysis was then extended, and a coupled heave-pitch model was formulated.

The mathematical models are based on a fundamental analysis of the body dynamics and fluid mechanics of the aircraft-cushion-runway interaction. The analysis takes into account the air source characteristics (fan, etc.), flow losses in the feeding ducts, trunk and cushion, the effects of fluid compressibility, and dynamic trunk deflections, including ground contact. The computer program developed is capable of simulating the dynamic motion of an ACLS-equipped aircraft caused by landing impact and taxi over an irregular runway, using input data such as cushion and trunk geometry, aircraft weight, fan characteristics, runway surface profile, etc.

The program can be used in three principal ways:

1. To determine static ACLS characteristics (equilibrium height, stiffness, static pressures, etc.), aid in fan

selection, and determine allowable limits for equilibrium cushion loading.

2. To evaluate dynamic landing and taxiing performance (g loading, heave and pitch motion, trunk deflections, hard surface clearance, etc.), including the vibration caused by runway irregularities.

3. To determine optimum values of design parameters (e.g., hole sizes and configuration, trunk shape, etc.) for improved dynamic performance (i.e., design guidelines).

The types of performance results that can be obtained from the computer program, which is described in the Appendices, are shown in Table I. Illustrative simulations of a scale model ACLS have been carried out and are presented in Section 3. These simulations show the results obtained from the program for three typical cases of interest a zero speed heave drop test, a 22.4 m/s (50 mph) landing impact, and taxi over an irregular runway.

During the next phase of this program, the analysis will be extended to include coupled heave-pitch-roll simulations, and the analytical models will be verified and refined based on results obtained with a test cushion at NASA-Langley. After model verification, a series of additional simulations are planned to investigate a variety of potentially attractive ACLS configurations and develop guidelines for improved designs.

TABLE I. Simulation Capabilities

	Heave Performance	Heave-Pitch Performance
Determination of Static Characteristics	(a) Load-deflection curves and stiffness. (b) Fan flow and power requirements. (c) Maximum load capacity and fan stall margin.	(a) Load-deflection and torque-rotation curves for cushion. (b) Heave and pitch stiffness. (c) Fan flow and power requirements. (d) Equilibrium conditions (pitch angle, trunk contact area, pressures, flows, etc.)
Dynamic Performance Evaluation	(a) Simulation of zero attitude drop test. (b) Estimation of landing impact heave vibration (g loading, trunk deflection, hard surface clearance, etc.).	(a) Simulation of drop tests with initial pitch angle. (b) Estimation of ACLS landing impact performance (g loading, heave and pitch motion, hard surface clearance, etc.). (c) Estimation of taxiing and ground handling dynamic performance (e.g., g loads during rough runway operation, effects of crossing specified obstacles, etc.).
Development of Design Guidelines	(a) Determination of effects of fan characteristics (including stall behavior) on landing impact absorption. (b) Determination of effects of trunk geometry and exit hole configuration on cushion performance. (c) Evaluation of plenum bleeding and direct cushion feeding schemes.	(a) Determination of effects of fan characteristics (including stall behavior) on landing impact absorption. (b) Determination of effects of trunk geometry and exit hole configuration on cushion performance. (c) Evaluation of plenum bleeding and direct cushion feeding schemes. (d) Effects of CG position on ACLS performance.

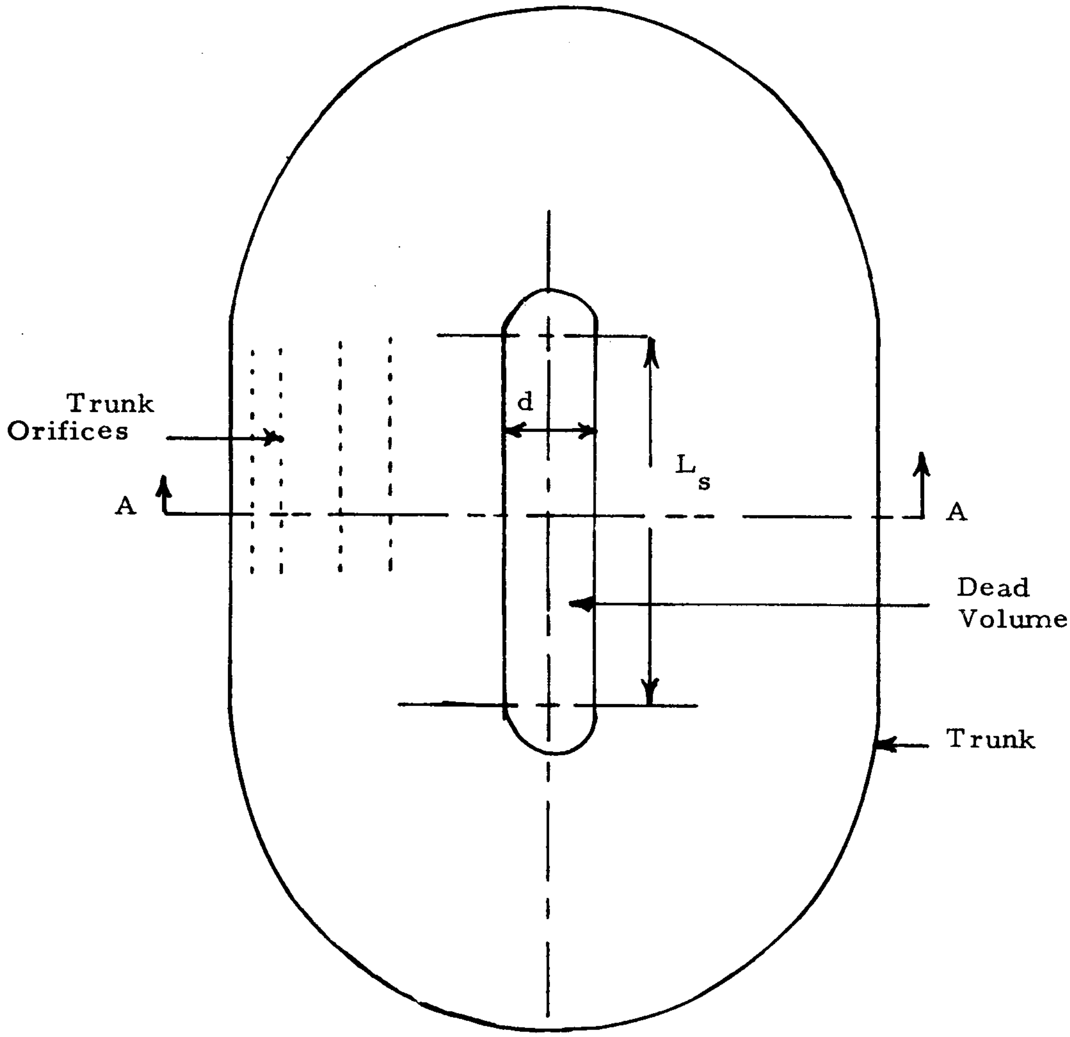
2. Analysis

The analysis outlined herein is the generalized pitch-heave analysis, further details of which are given in Appendix C. The pure heave analysis - a special case of the heave-pitch analysis - is obtained by setting the torque and angular motion terms to zero.

2.1 Basic Configuration

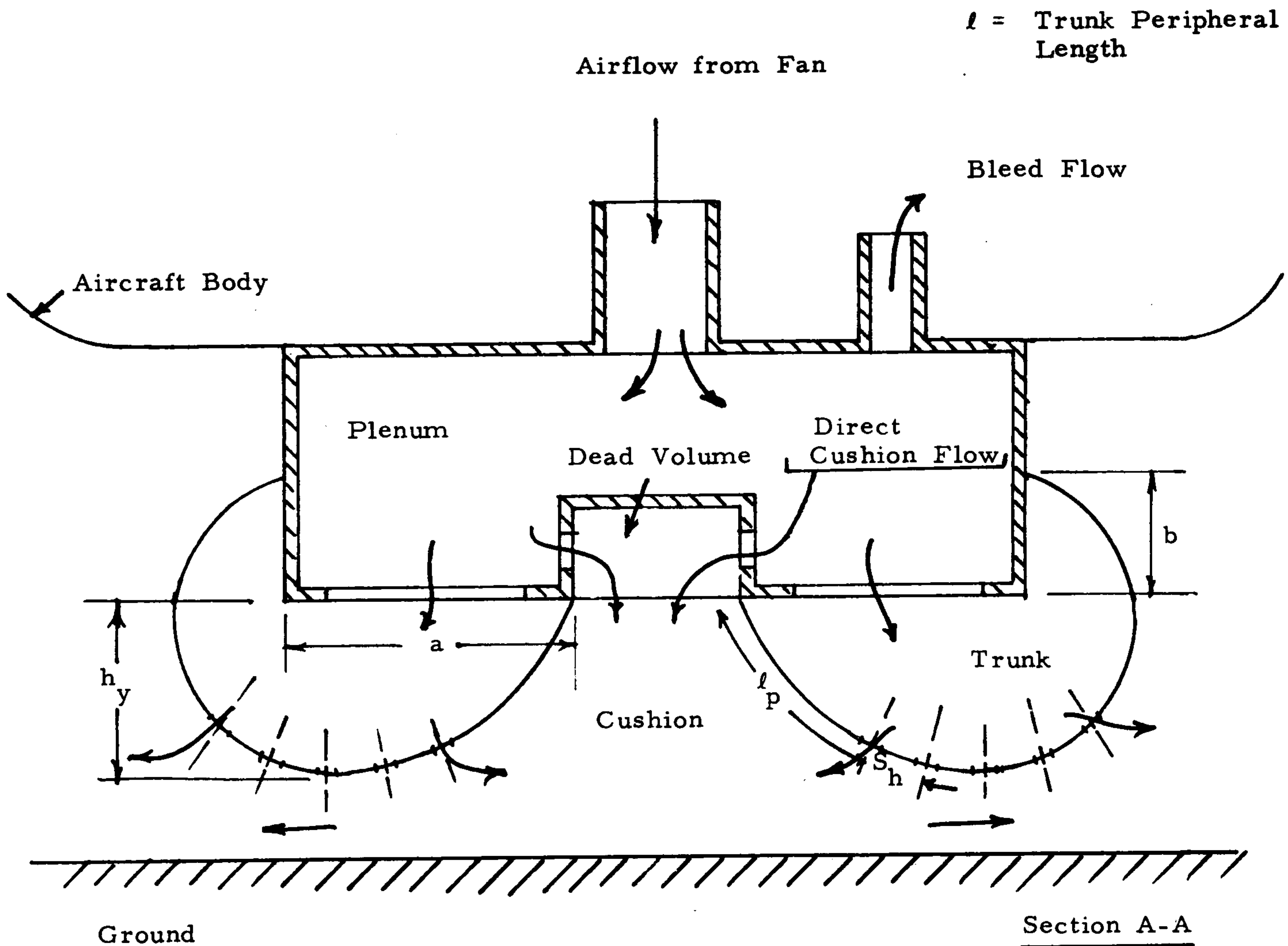
The basic ACLS configuration analyzed is shown in Figure 1. The model includes four primary subsystems - i.e., the fan, the feeding system, the trunk and the cushion. The configuration of these systems has been chosen sufficiently general so that they can represent a wide variety of practical designs. Air from the fan flows through the ducts and plenum (feeding system) and enters the trunk. The trunk has several rows of orifices that communicate with the cushion and atmosphere. Thus, the airflow from the trunk has two components - one part entering the cushion and the other leaking directly to the atmosphere. The cushion flow exhausts to the atmosphere through the clearance gap formed between the trunk and ground. In addition to the basic flows described above, two other flows have been included in the model, for generality. These are the plenum bleed flow and the direct cushion flow. Plenum bleeding causes some of the air to flow directly from plenum (fan outlet) to atmosphere, and has been used in some designs to improve the dynamic characteristics of the air supply system. Direct flow from the plenum to the cushion can also improve dynamic response.

In plan, the cushion has an oval shape, made up of a rectangular section with semicircular ends. a and b are the horizontal and vertical distances between the points of attachment of the trunk to the aircraft body. The initial (undeformed) trunk shape is defined in terms of the above two parameters, and the perimeter ℓ and height h_y



(a) Plan View

Figure 1. Basic ACLS Configuration



(b) Front View in Cross-Section (Section A-A in Figure 1(a))

Figure 1 (Concluded). Basic ACLS Configuration as shown. S_h is the (uniform) spacing between the rows of peripherally distributed orifices. The number and orientation of the orifices can be selected independently in terms of the number of orifice rows (N_r), the number of orifices per row (N_h), and the orientation parameter (ℓ_p). The cushion volume consists of two parts: an active (dynamically varying) region and a dead (static) region. The active cushion volume depends only on the trunk shape and ground profile, and is computed by the program from cushion geometry. The dead volume (shown in Figure 1) includes recesses in the cushion cavity, and is a design variable.

2.2 Assumptions

Order-of-magnitude analyses and available test data have provided the initial basis for determining the principal assumptions of the heave-pitch analysis. These assumptions are summarized below.

(a) Computation of the trunk and cushion parameters (trunk volume, cushion area, etc.) is carried out by dividing the trunk and cushion into segments, as shown in Figure 2. The parameters are first calculated for each individual segment, and then added together to obtain parameter values for the full cushion.

The ground under any particular segment is considered parallel to the hard surface, and at an elevation corresponding to the ground profile at the segment center projection on the reference plane (as shown in Figure 3). This assumption represents the ground surface and the hard structure of the cushion by a series of short, parallel sections which, when chosen sufficiently

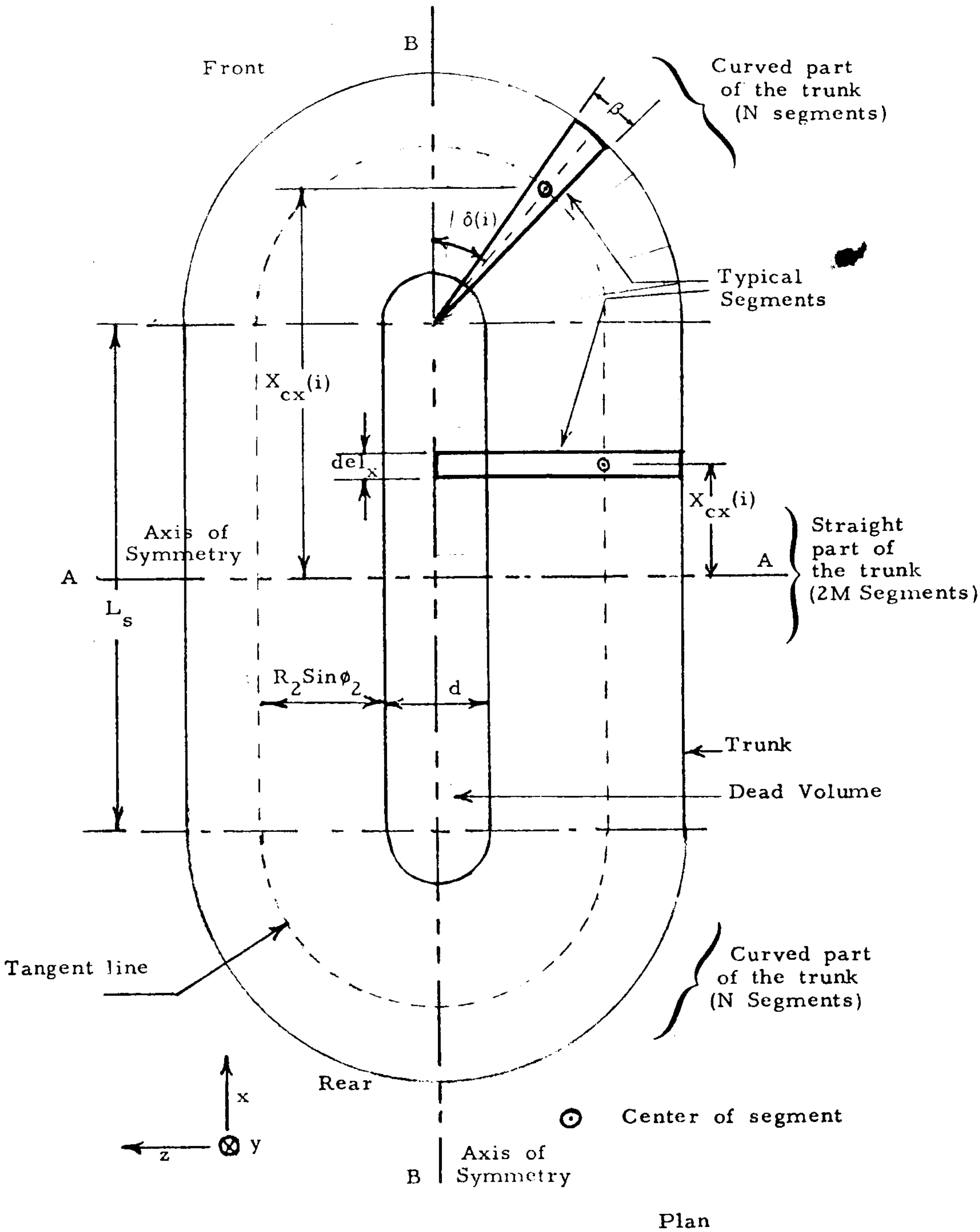


Figure 2. Division of Trunk into Segments

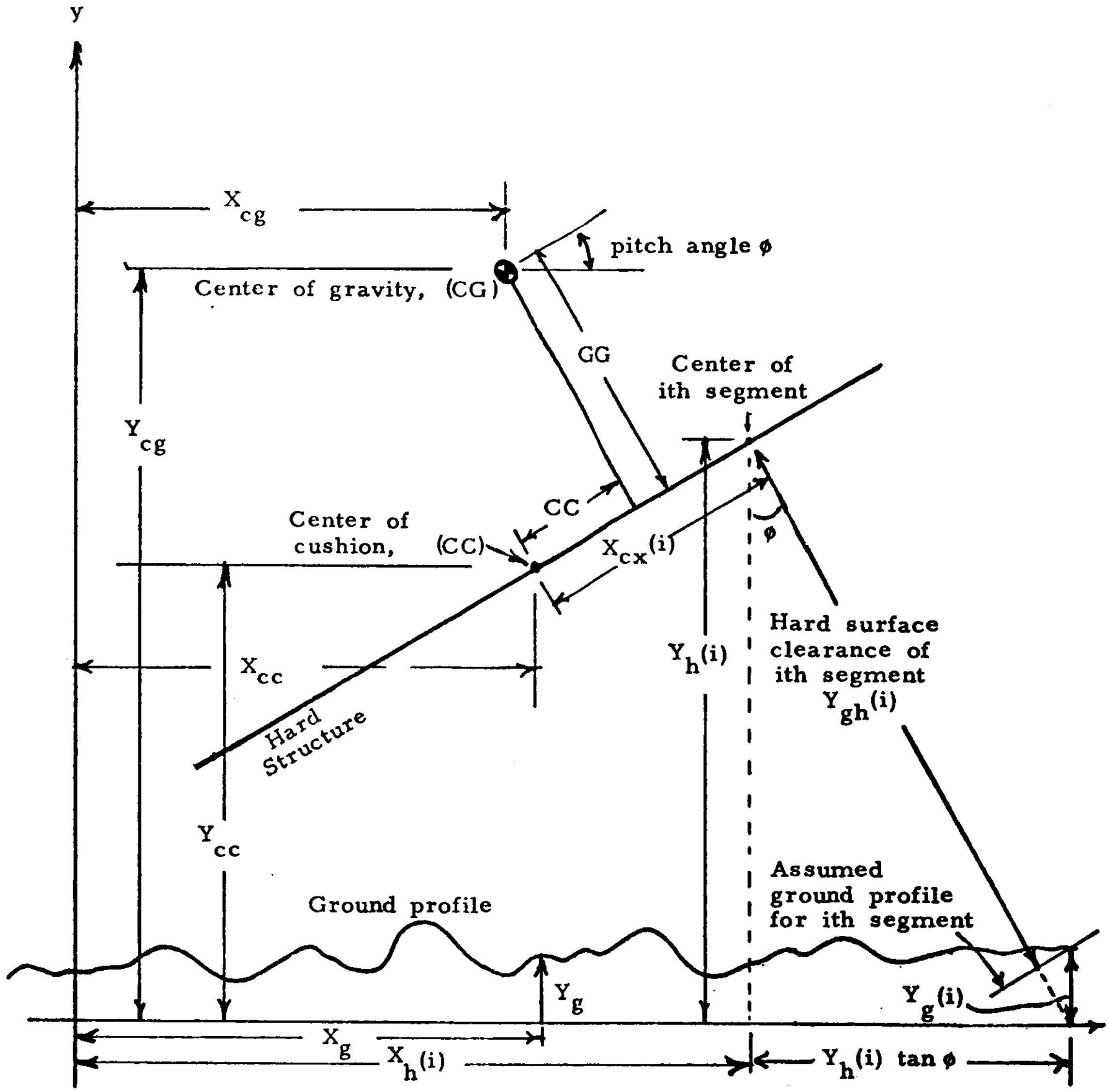


Figure 3. Hard Surface Clearance for Segment

small, closely approximate the actual ground profile and hard surface orientation.

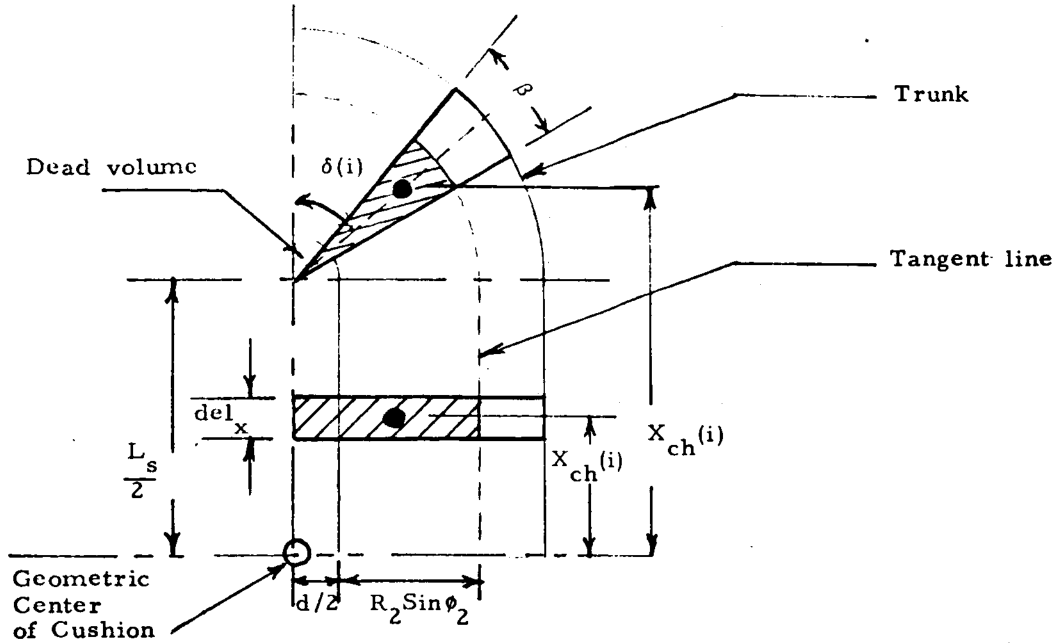
The two types of segments are shown in Figure 2: Rectangular segments in the straight portion of the cushion, and pie-shaped sections at the curved ends.

The trunk and cushion pressure force components for each segment are found from the products of the appropriate pressures and areas, and are represented by concentrated forces acting at the respective centers of pressure, as shown in Figure 4.

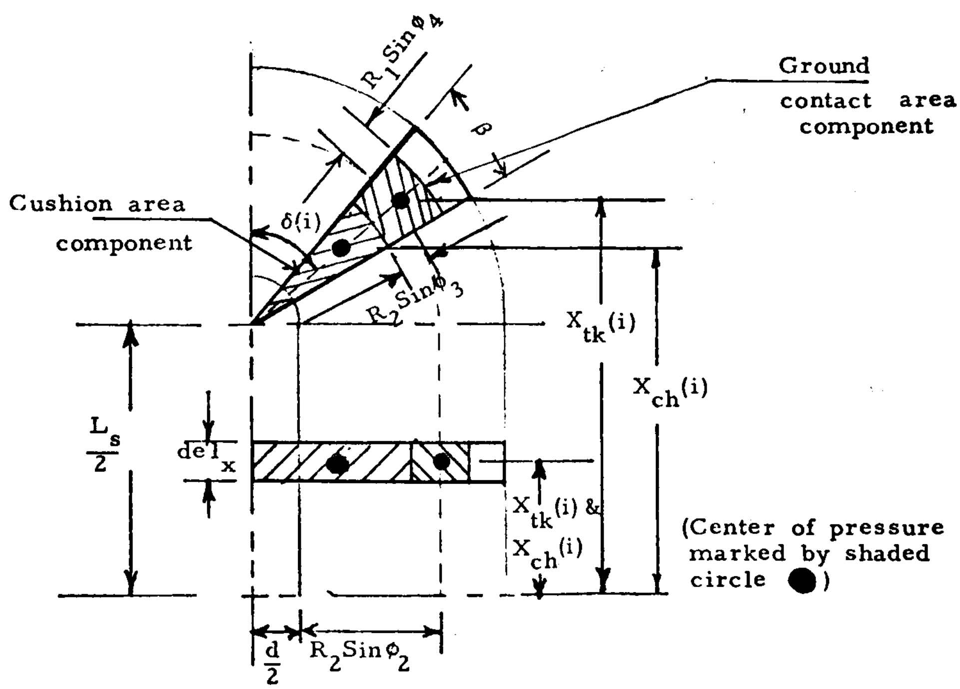
(b) The flow analysis is based on a lumped parameter model of the ACLS as shown in Figure 5. Plenum, trunk and cushion pressures are assumed uniform (though unequal and dynamically varying). The plenum, trunk and cushion cavities are represented by their capacitance (volume). Pressure losses in the ducts and in the entrance and exit regions of the chambers are represented in terms of lumped orifice resistances.

(c) For typical ACLS designs, the fractional pressure drop across the orifices ($\Delta p/p$) is small (usually less than 0.1), and changes in air density across the orifices will be negligible. Therefore, the orifice flow Q can be found from the incompressible flow quadratic relationship

$$Q = C_d A \sqrt{\frac{2\Delta p}{\rho}}$$



a) No Trunk Contact with Ground



b) Trunk Contacting Ground

Figure 4. The Positions of Centers of Pressure

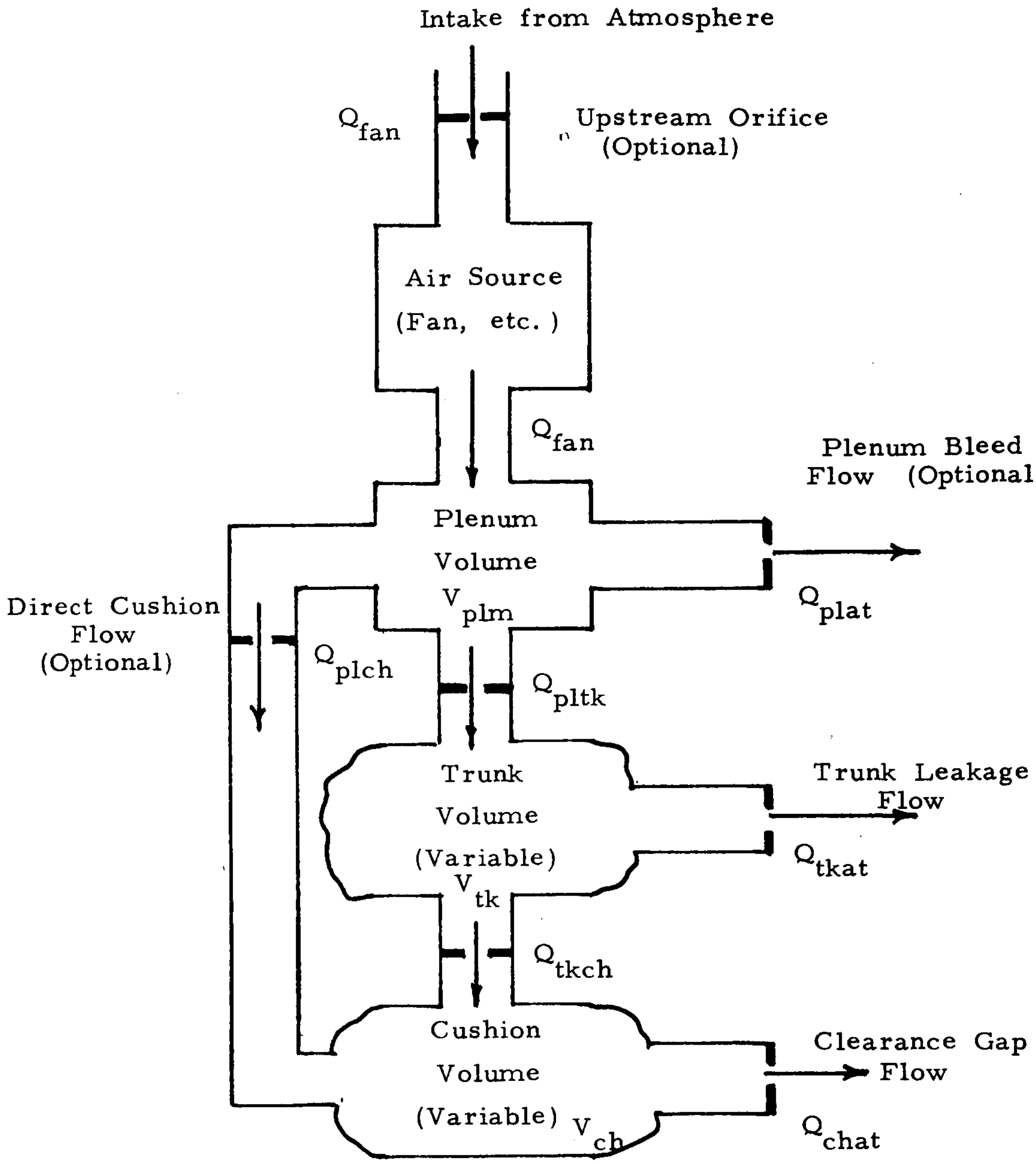


Figure 5. ACLS Flow Model

where

C_d - discharge coefficient
A - orifice area
ρ - mean air density
and Δp - pressure drop across orifice.

Within the chambers, however, air compressibility cannot be neglected, because dynamic density changes ($d\rho/dt$) will be significant. Therefore the effects of density changes in the plenum, trunk and cushion are included in the analysis. Density changes are determined from pressure changes through the polytropic relationship p/ρ^K = constant, where the exponent K lies between 1 (isothermal expansion) and 1.4 (adiabatic expansion).

(d) The trunk is modeled as a massless unstretchable membrane capable of bending freely. Initial calculations carried out for selected trunks of current interest indicate that the deforming pressure forces are very large compared to the inertia of the trunk material, so that changes in trunk shape will occur almost instantaneously, and the massless approximation will be valid.

With the assumption of no trunk stretch,* the trunk length around the cushion periphery will be constant. This means that, for uniform motion, every trunk element will remain in the same lateral position, since any lateral trunk motion would require peripheral stretching of

*For elastic trunks, the inelastic "frozen" trunk model described, requires modifications to include elastic effects.

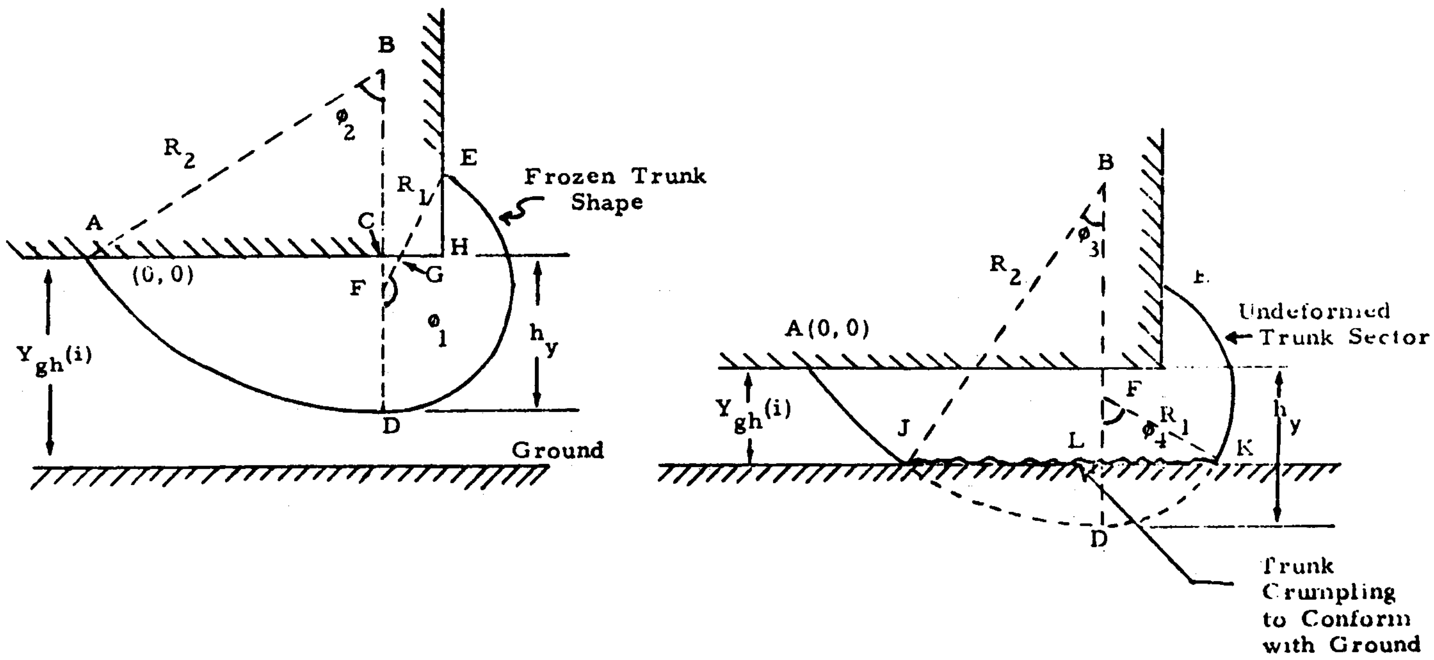
the trunk membrane. Therefore, to a first approximation, the shape of the trunk cross section, when out of ground contact, is "frozen" (i. e., independent of the pressure) and depends only on the initial prefabricated trunk shape (Figure 6a). When ground contact occurs (Figure 6b), the trunk material in the contact zone conforms with the ground surface by crumpling, while the part of the trunk not touching the ground remains undeformed. Initial observations of the deformation characteristics of the two trunks cited earlier support the idealized model of trunk behavior described above.

(e) The air source is characterized in terms of a static pressure-flow relationship, with hysteresis losses included to represent the effects of stall. The general source characteristic is shown in Figure 7. Curve AB represents the normal (unstalled) operating regime, while curve CD represents the stalled characteristic. The shape of the curves depends on the type of the air source, and by selecting an appropriate stall point A, recovery point C and curve shapes AB and CD, a variety of stalling and non-stalling* air sources including axial and centrifugal fans can be simulated.

For any pressure, the flow is found by using the appropriate (unstalled or stalled) characteristic. At the start of the simulation (stall-free

*When point C coincides with point A, stall is suppressed.

Sector	Peripheral Length	Sector
I = ABD	ℓ_1 = DE	VI = BDJ
II = ABC	ℓ_2 = AD	VII = BJL
III = EDF	ℓ = AE	VIII = DFK
IV = EGH		IX = FLK
V = CFG		

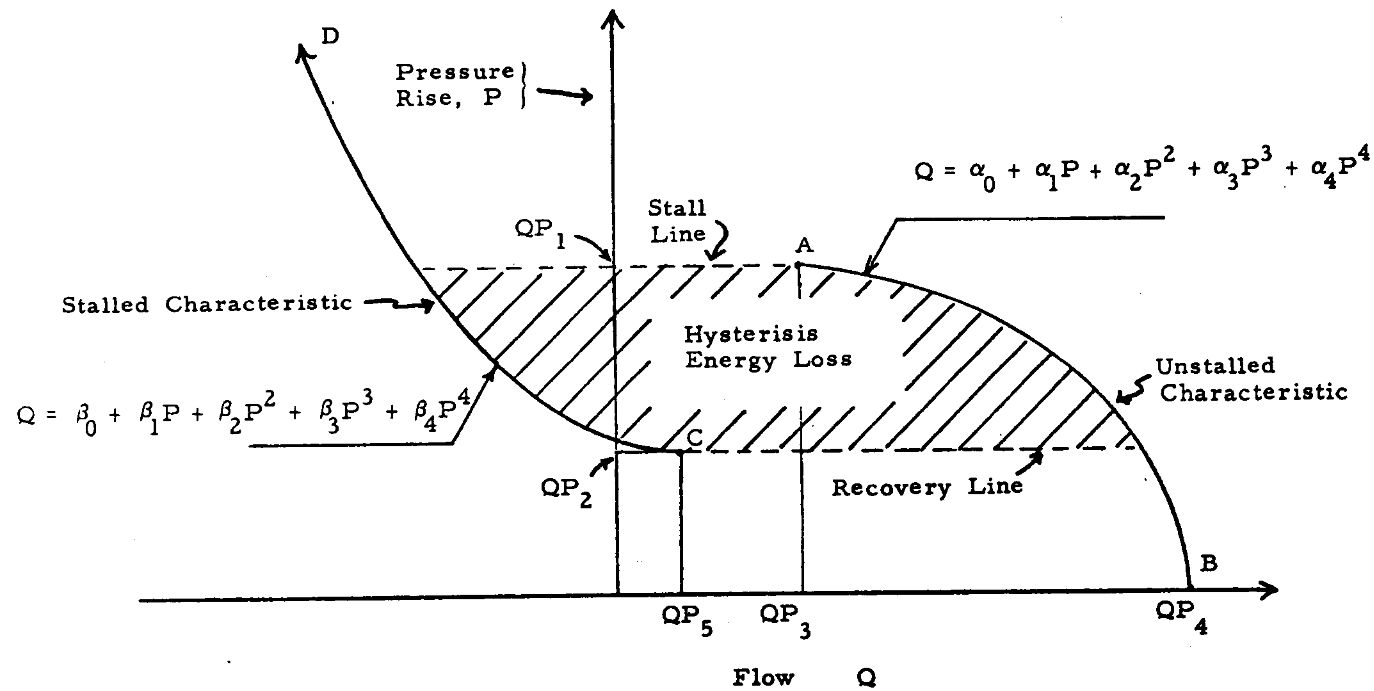


a) No Ground Contact

b) With Ground Contact

Trunk Deformation Model

Figure 6



General Air Source Characteristics

Figure 7

initial conditions), the appropriate pressure-flow relationship is given by curve AB. When the pressure exceeds the stall pressure QP1, the flow decreases suddenly, and it is found from the stalled characteristic CD. Stalled operation along characteristic CD continues as long as the pressure is above the recovery pressure QP2. When the pressure drops below QP2, the flow increases suddenly (i.e., recovery), and the pressure-flow relationship is given by the unstalled characteristic AB. The above discussion indicates that downstream pressure variations large enough to cause stall and recovery result in a net energy loss due to hysteresis (see Figure 7).

The present analysis is based on the initial assumption that the fan flow changes simultaneously with pressure. In practice, however, the effects of fluid inertance will introduce lags in the flow, particularly during the stall and recovery transitions. The effects of these lags will be to slow down fan stall and recovery, and hence slow down passage around the hysteresis loop shown in Figure 7. However, since typical fan flow lags are estimated to be small compared to the characteristic periods of ACLS motion, the lags will have only a small affect on the predictions of overall landing dynamics and aircraft g loading. Subsequently, detailed stall investigations may require a more advanced model which includes fluid inertance and flow lags. The basis for development of this improved model will be established through dynamic fan tests scheduled later in the program.

(f) Five mechanisms of energy dissipation are included in the analysis.

(i) Fan stall and recovery losses (see above).

(ii) Aerodynamic drag of the cushion.* A square law relationship is assumed, such that the drag force F is given by

$$F = C_D A_p \frac{1}{2} \rho V^2$$

where

C_D	-	heave drag coefficient
A_p	-	projected area on which C_D is defined
ρ	-	ambient air density

and

V	-	heave velocity cushion.

(iii) Damping due to trunk crumpling during ground contact (see Figure 6). In this case, the damping force F is assumed to be linearly proportional to the trunk segment deformation velocity, V_s. The trunk damping force acting on the aircraft is thus given by

$$F = \sum_i \left(\overline{B}_z V_s \right)_i$$

*Drag relationships are preliminary and primarily valid for zero speed drops. In subsequent phases, more detailed models of the aerodynamic characteristics are planned for inclusion in the model.

where $\overline{B}_z$ is the damping constant for each trunk segment, and the summation is carried out over all the segments. The damping constant is estimated for the trunk sizes and configurations of interest by dimensional analysis, using test data obtained with prototype cushions. The trunk damping force also develops a torque around the CG.

(iv) Energy losses in the orifices.

(v) Friction losses due to trunk-ground contact. The friction force which arises at the trunk-ground interface results in a horizontal retarding force and torque at the CG.

(g) Because of the presence of brake tread material, trunk imperfections, ground irregularities, etc., sealing of the trunk orifices and the cushion-to-atmosphere exit area will not be complete, even when the trunk is in ground contact. The effects of incomplete orifice closure are taken into account in the analytical model through blockage factors that allow some leakage flow to occur even when the orifices are nominally closed.

2.3 Analytical Development

The analysis provides

(a) The relationships that determine the static cushion characteristics (pressures, flows, etc.) existing at equilibrium. These relationships are also used to determine the initial conditions for the simulation.

(b) The differential equations of flow and motion (state equations) from which the pressures, flows, displacements, accelerations, etc. can be determined as functions of time.

2.3.1 Static Model

The equilibrium conditions are found as follows:

(a) By applying the steady-state flow continuity equations to the plenum, trunk and cushion cavities (see Figure 5).

$$Q_{fan} = Q_{plat} + Q_{pltk} + Q_{plch}$$

$$Q_{pltk} = Q_{tkch} + Q_{tkat}$$

$$Q_{chat} = Q_{plch} + Q_{tkch}$$

(b) By satisfying the fan flow constraints,

$$Q_{fan} = f(P_{fan})$$

i.e., where the fan flow Q_{fan} and pressure rise P_{fan} are determined from the characteristic fan curve.

(c) From the static force balance equation

$$Forcn = (P_{ch}A_{ch} + P_{tk}A_{tkcn}) \cos\phi$$

where Forcn - aircraft weight (in equil.)

P_{ch} - cushion pressure

A_{ch} - cushion area

P_{tk} - trunk pressure

A_{tkcn} - trunk area in ground contact

ϕ - pitch angle.

(d) From the static torque balance equation,

$$\text{Torn} = 0 = \sum_{i=1}^{2(M+N)} \Big[2P_{ch} \left(A_{ch}(i)\right)\left(X_{ch}(i) - CC\right)$$

$$+ 2P_{tk} \left(A_{tkcn}(i)\right)\left(X_{tk}(i) - CC\right)\Big]$$

where Torn - torque about CG (zero in equilibrium)

$A_{ch}(i)$ - cushion area corresponding to ith segment

$A_{tkcn}(i)$ - trunk contact area corresponding to ith segment

$X_{ch}(i)$ - distance between the center of pressure of the ith segment of the cushion and the geometric center of the cushion.

$X_{tk}(i)$ - distance between the center of pressure of the ith segment of the trunk and the geometric center of the cushion.

2.3.2 State Equations

The state equations are derived from the dynamic ACLS model (Figure 8) as follows.

1. Plenum Flow Continuity

The net inflow equals the rate of increase of fluid mass within the plenum

$$\frac{d}{dt}(\rho V_{plm}) = \left(Q_{fan} - Q_{plat} - Q_{pltk} - Q_{plch}\right)\rho$$

where ρ is the mean air density

2. Trunk Flow Continuity

Similar to (1) above

$$\frac{d}{dt}(\rho V_{tk}) = \left(Q_{pltk} - Q_{tkch} - Q_{tkat}\right)\rho$$

3. Cushion Flow Continuity

$$\frac{d}{dt}(\rho V_{ch}) = \left(Q_{plch} + Q_{tkch} - Q_{chat}\right)\rho$$

4. Force Balance about the cg

$$M_a \frac{d^2}{dt^2} Y_{cg} = (P_{ch}A_{ch} + P_{tk}A_{tkcn}) \cos\phi$$

$$- M_a g - \underbrace{\frac{1}{2} C_D A_{ph} \rho \left(\frac{dY_{cg}}{dt}\right)^2}_{\text{Aerodynamic Drag Component}}$$

$$\underbrace{\text{Forct}}_{\text{Trunk Damping Component}}$$

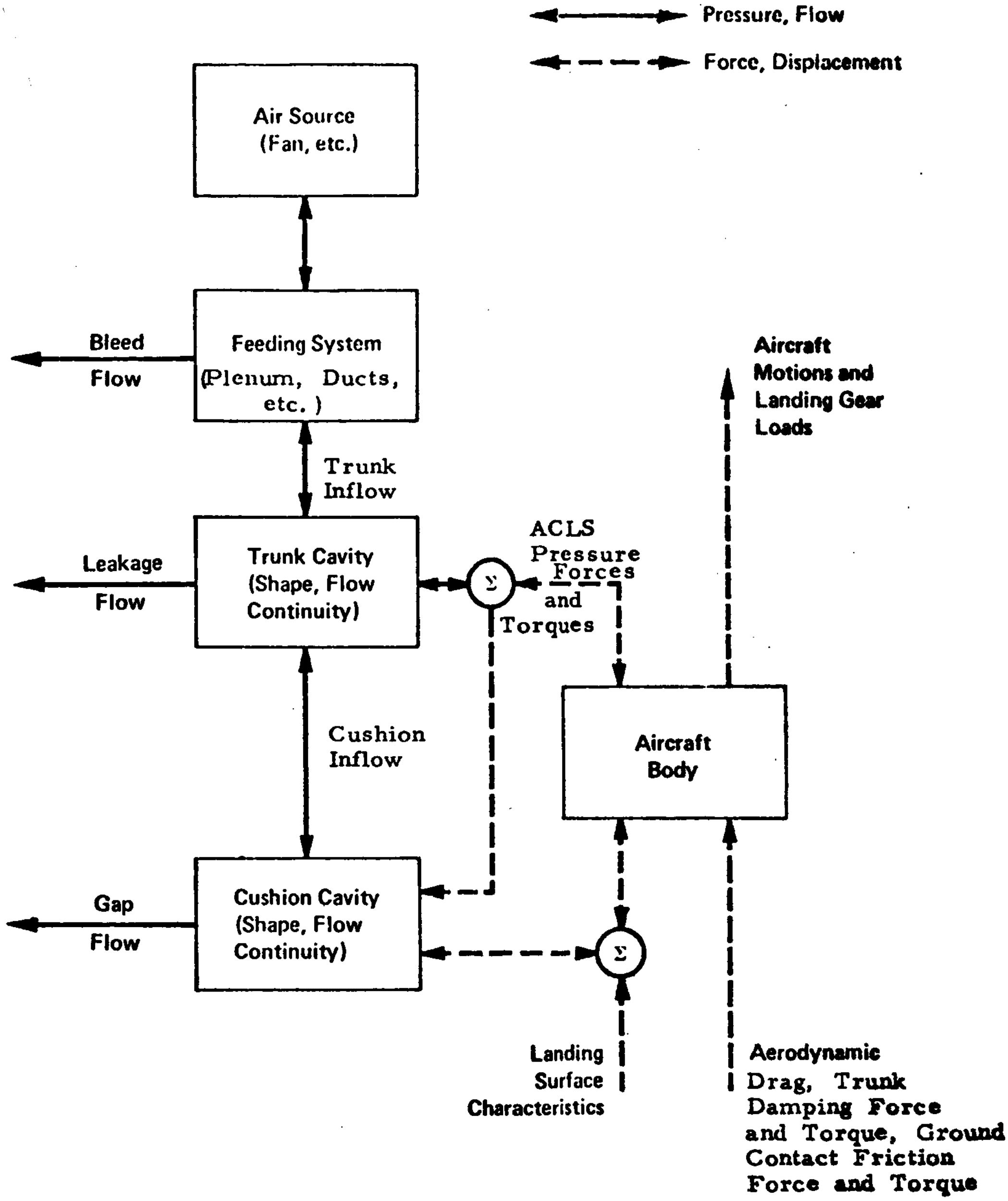


Figure 8. Dynamic ACLS Model

where

$$\text{Forct} = 2 \sum_{i=1}^{2(M+N)} \text{Forct}(i)$$

and

$$\text{Forct}(i) = \begin{cases} \dfrac{B_z}{4(M+N)} \left(\dfrac{dY_{cg}}{dt} + \dfrac{d\phi}{dt} \left(X_{cx}(i) - CC \right) \right) & \text{if the ith segment is in ground contact} \\ 0 & \text{if the ith segment is not in ground contact.} \end{cases}$$

5. Torque Balance around the cg

$$\text{Inert} \cdot \frac{d^2\phi}{dt^2} = 2 \sum_{i=1}^{2(M+N)} P_{ch} A_{ch}(i) \left(X_{ch}(i) - CC \right)$$

$$+ \; 2 \sum_{i=1}^{2(M+N)} P_{tk} A_{tkcn}(i) \left(X_{tk}(i) - CC \right)$$

$$+ \underbrace{\text{Torf}}_{\text{Ground friction torque}}$$

$$+ \underbrace{\frac{1}{2} C_D A_{ph} \rho \left(\frac{dY_{cg}}{dt} \right)^2 C_{enf}}_{\text{Torque due to Aerodynamic Drag force}}$$

$$- \underbrace{\text{Torqt}}_{\text{Trunk Damping Torque}}$$

where

$$\text{Torf} = -2 \sum_{i=1}^{2(M+N)} P_{tk} A_{tkcn}(i)\ \mu \left(Y_{gh}(i) + GG \right)$$

$$\text{Torqt} = 2 \sum_{i=1}^{2(M+N)} \text{Torqt}(i)$$

where

$$\text{Torqt}(i) = \begin{cases} \dfrac{B_z}{4(M+N)} \left(\dfrac{dY_{cg}}{dt} + \dfrac{d\phi}{dt} \left(X_{cx}(i) - CC \right) \right) \left(X_{tk}(i) - CC \right) & \text{if the ith segment is in ground contact} \\ 0 & \text{if the ith segment is not in contact} \end{cases}$$

3. Illustrative Simulations

A computer program incorporating the heave and heave-pitch analysis has been developed. With this program, the dynamic behavior of an ACLS-equipped aircraft (g loading, trunk deflection, cushion pressure, etc.) can be determined for landing impact and taxi over an irregular runway, using input data such as cushion and trunk geometry, aircraft weight, fan characteristics, runway surface profile, etc. The organization and use of the computer simulation program is described in Appendix A.

Three types of illustrative simulations have been carried out, to demonstrate the capabilities of the program. They are

(a) A drop test simulation. (zero forward speed, pure heave. Torque and angular motion terms = 0.)

(b) A landing impact simulation. (With forward speed and initial angle of attack.)

(c) A simulation of aircraft dynamics when crossing a runway obstacle.

In the above simulations, the input parameters corresponded to a model cushion that will be tested in a subsequent phase of this program to verify and refine the analytical model. The general geometry of the model cushion is defined by Figure 1 and the detailed geometric input parameters are listed in Appendix F. The computations have been made in English units and converted to SI units.

3. 1 Drop Test Simulation

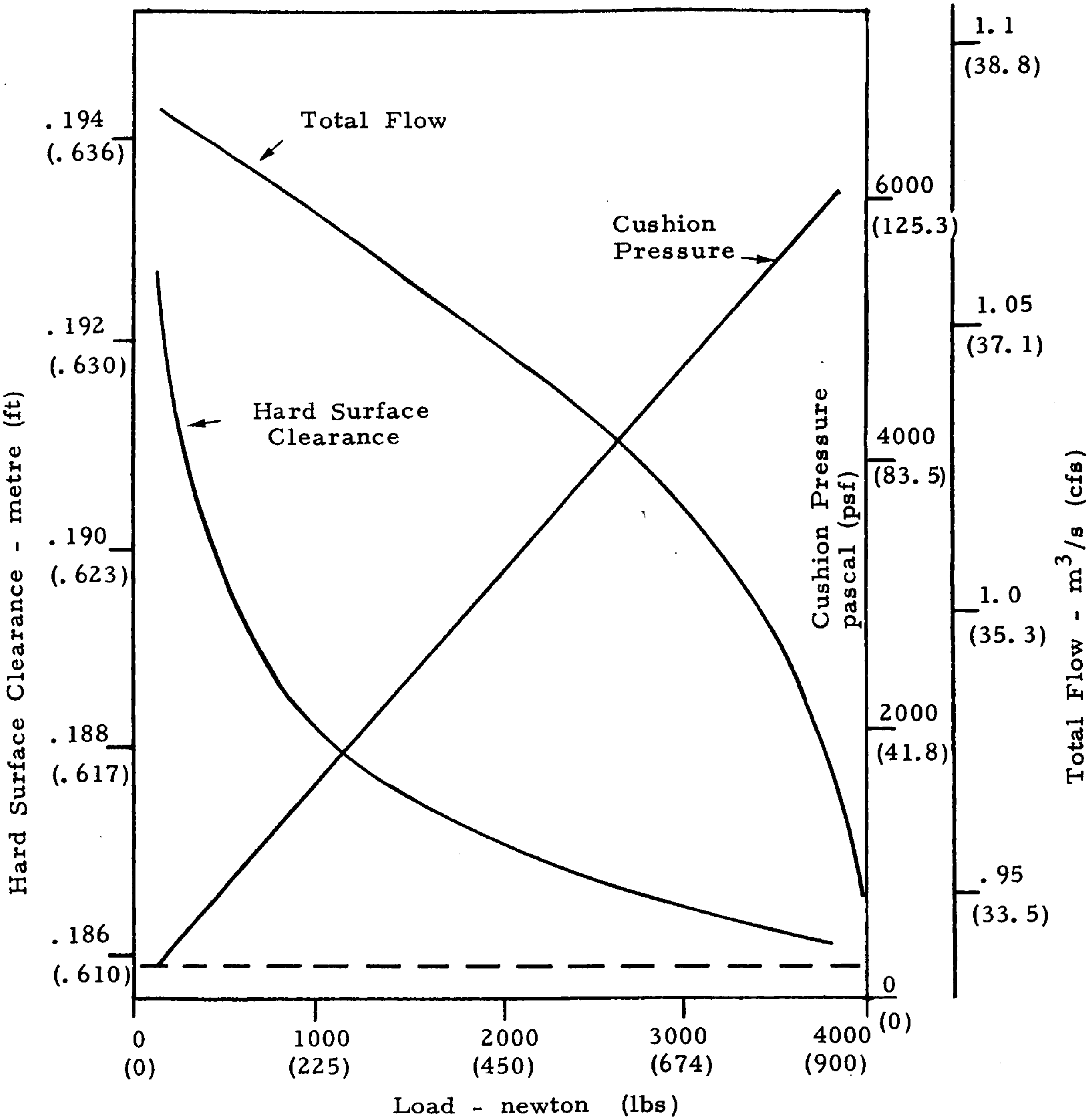
The drop test simulation of the cushion has been carried out for a static load of 1220 newtons (275 lbs.) and a drop height of 0. 152m (6 in.). The corresponding impact velocity is about 1. 5m/sec. (5 ft/sec.). The simulation results are shown in Figures 9 through 13.

The static characteristics show that the cushion pressure increases with load, and the flow and hard surface clearance decrease with load, as expected. The maximum load capacity of the cushion (i. e., the peak load for which stall-free fan operation is possible) is about 4000 newtons (900 lbs.), which is about three times the static load. The time history of cushion motion shows that the peak trunk deflection is about 38 mm (1.5 in), which is well within the static hard surface clearance of 185 mm (0.611 ft). The period of one cycle of oscillation is about 0.15-0.2 sec, which corresponds to a characteristic heave frequency of about 5-6 hz. The peak acceleration is about 50 m/s^2 (5 g). At impact, the cushion pressure increases to about four times its equilibrium value, and this causes the fan to stall. As the pressure drops, the fan recovers, and remains in the stall-free operating regime throughout the remainder of the simulation. Prolonged heave motion excited by repeated fan stall and recovery is thus inhibited. Although the impact disturbance begins to die out after the initial bounce (i. e., the system is dynamically stable), the low cushion damping indicates that several additional cycles will be required before the cushion reaches equilibrium.

3.2 Landing Impact Simulation

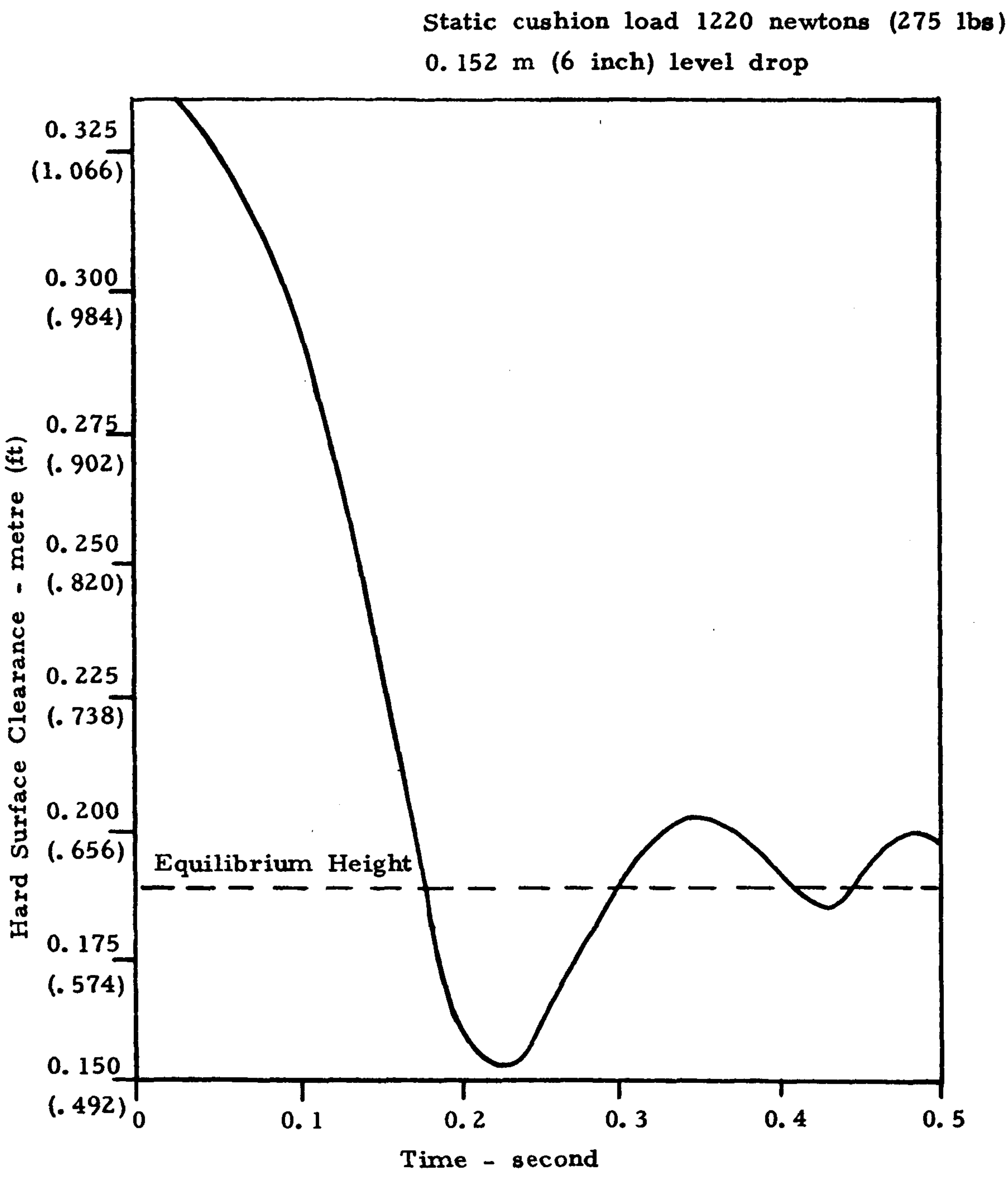
The landing impact simulation has been carried out for a static load of 1220 newtons (275 lbs), and an initial cg height of 0.52 m (1.7 ft) (touchdown sink speed of 1.52 m/s). The touchdown (forward) speed was chosen at 22.4 m/s (50 mph), with an initial angle of attack of 5°. The simulation results are shown in Figures 14 through 18.

The static characteristics (Figure 14) illustrate that the cg elevation increases as the load reduces. The slope of the load-deflection curve (stiffness) is smaller for a non-zero pitch angle than for a zero pitch angle, because non-uniform trunk contact results in a lower restoring force than uniform trunk contact.



ACLS Static Characteristics

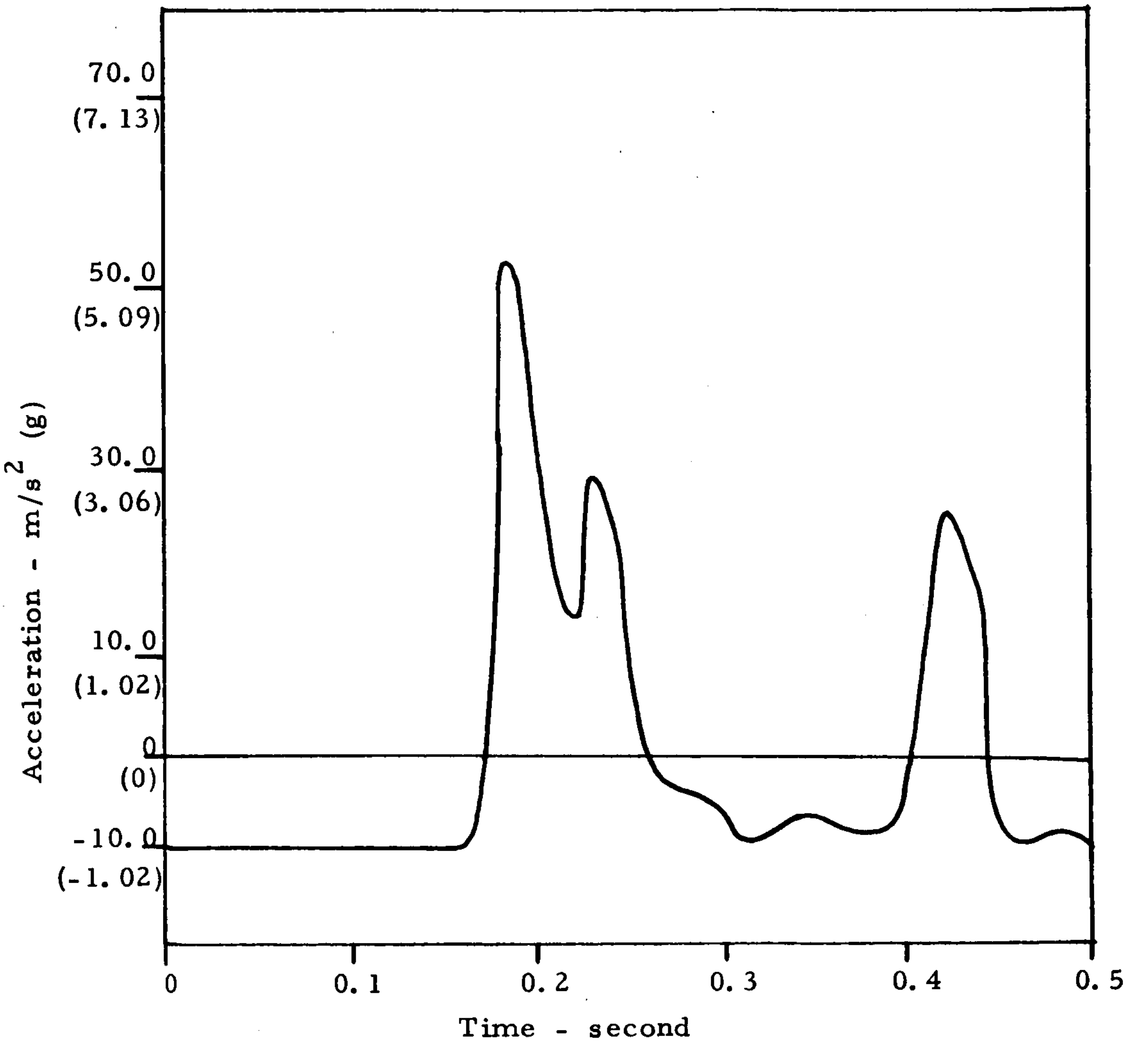
Figure 9



Time History of Cushion Motion

Figure 10

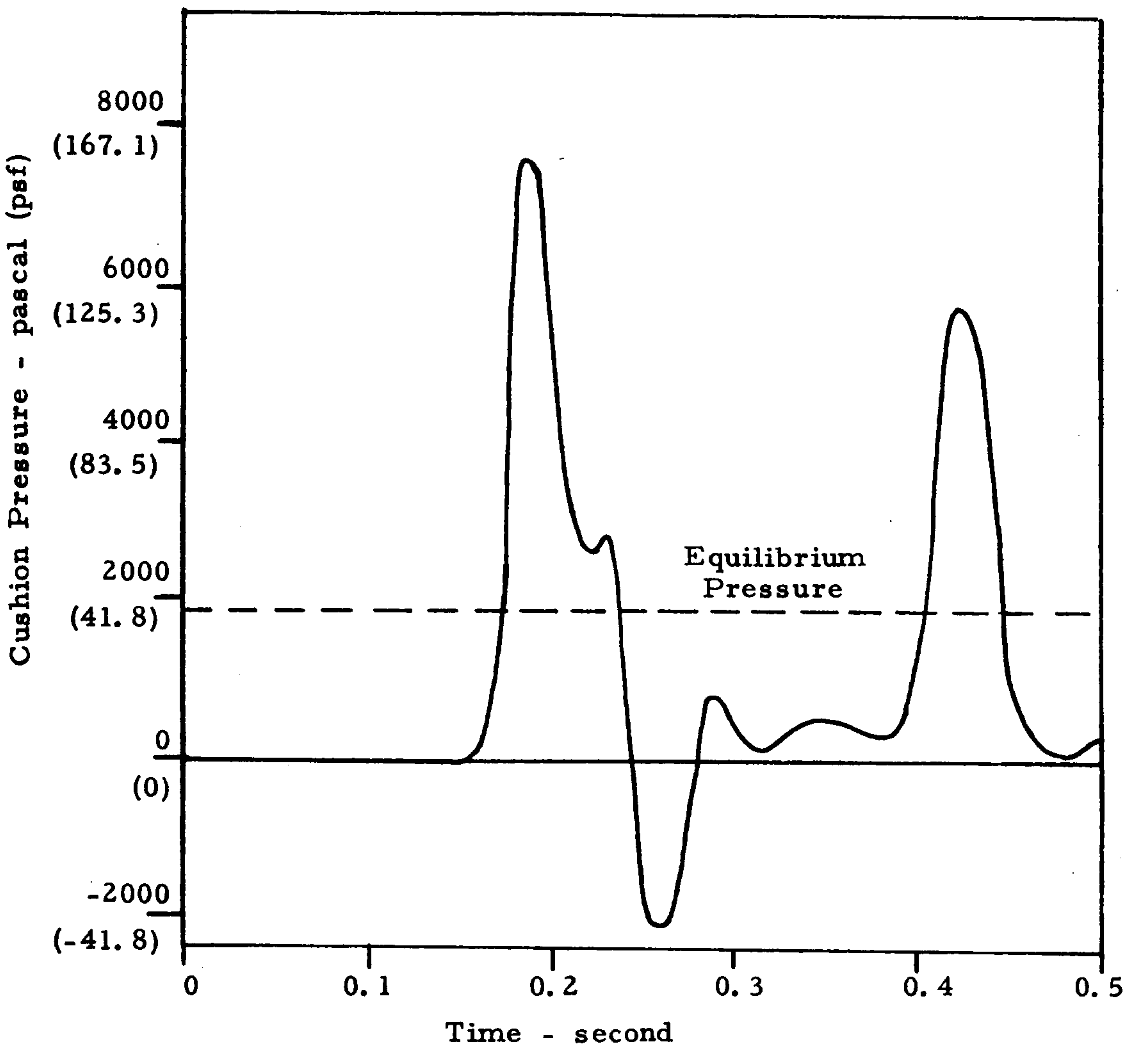
Static cushion load 1220 newtons (275 lbs)
0.152 m (6 inch) level drop



Time History of Acceleration

Figure 11

Static cushion load 1220 newtons (275 lbs)
0.152 m (6 inch) level drop

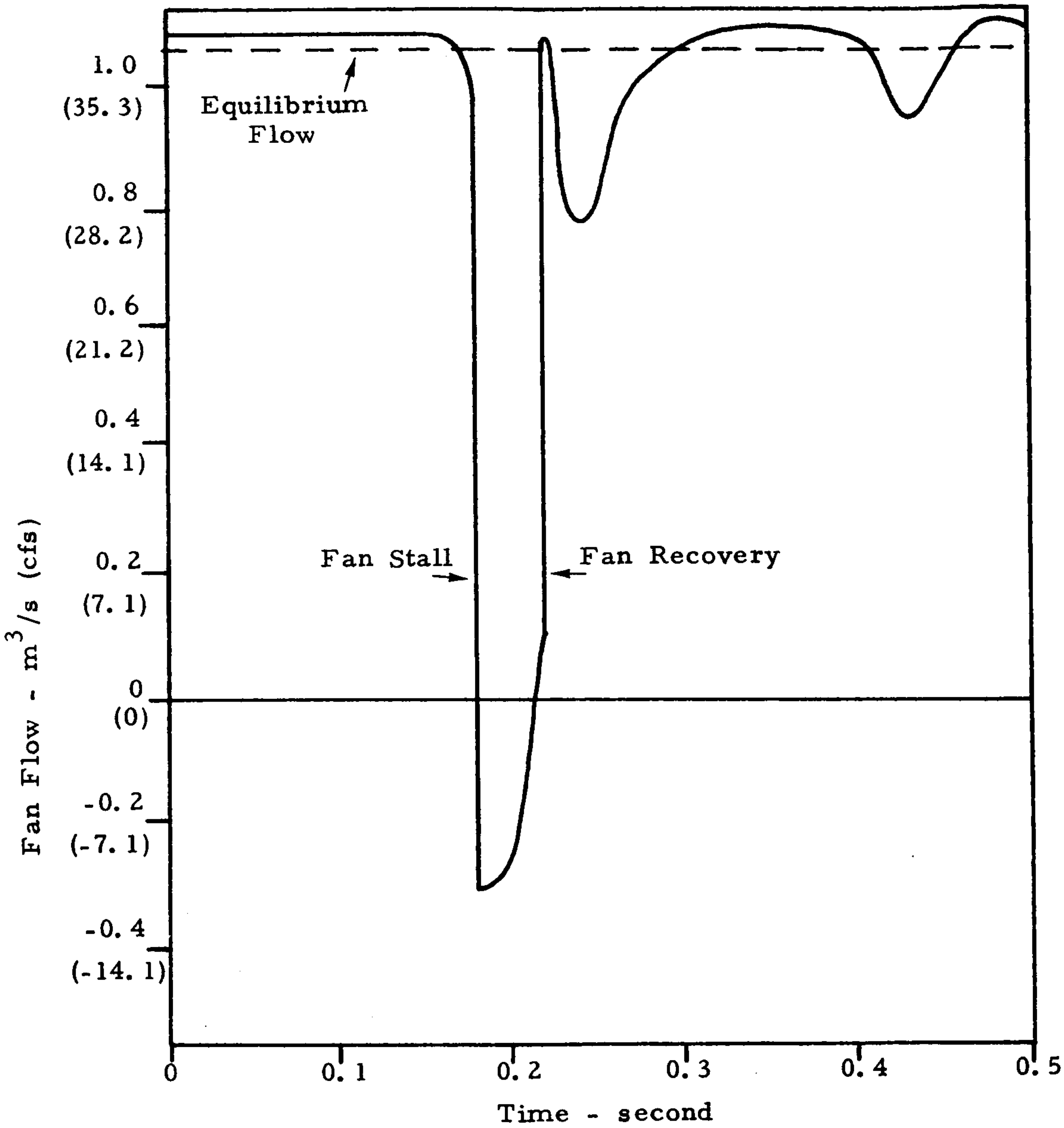


Time History of Cushion Pressure

Figure 12

Static cushion load 1220 newtons (275 lbs)

0.152 m (6 inch) level drop



Time History of Fan Flow

Figure 13

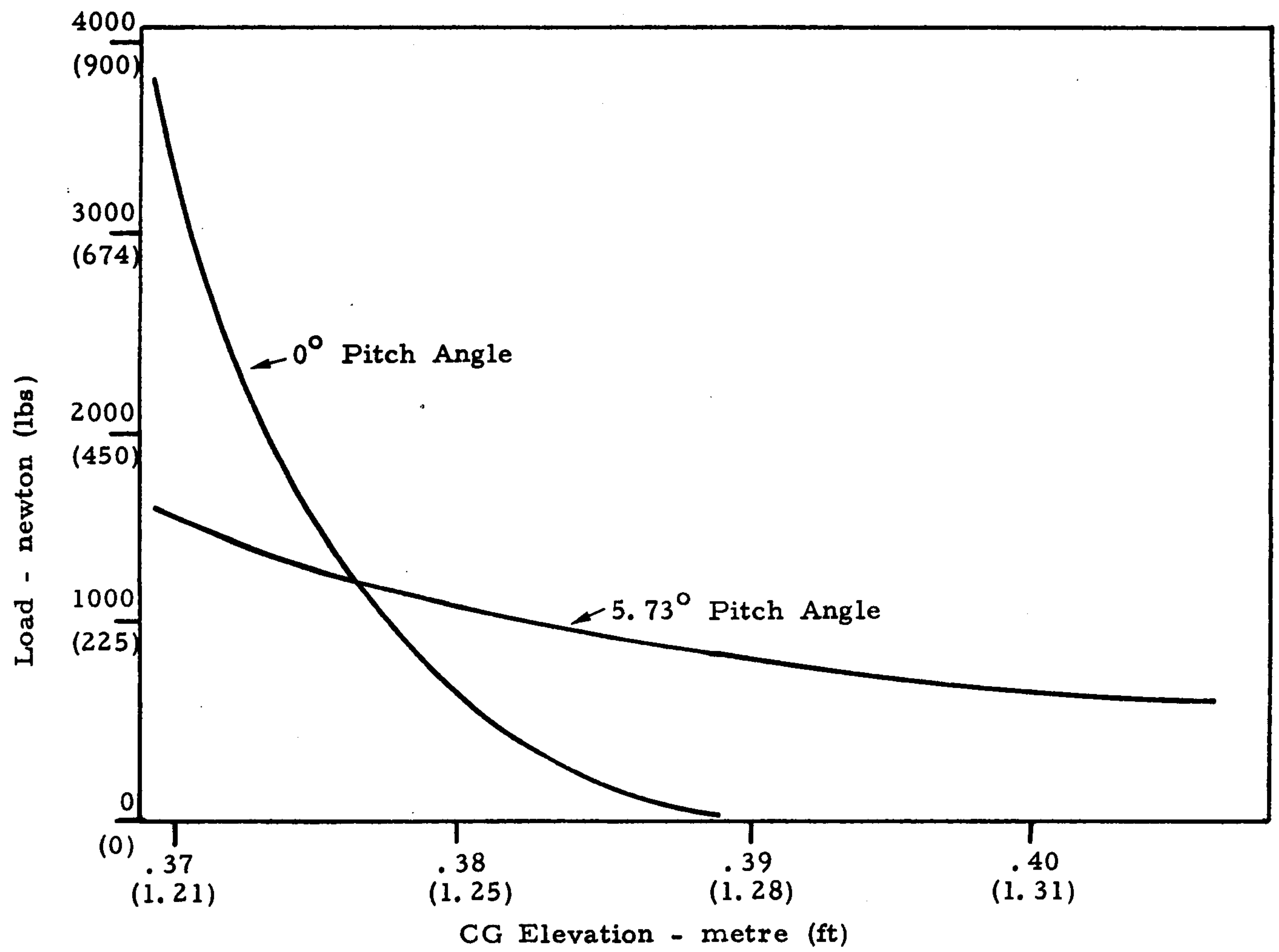


Figure 14. ACLS Static Characteristics

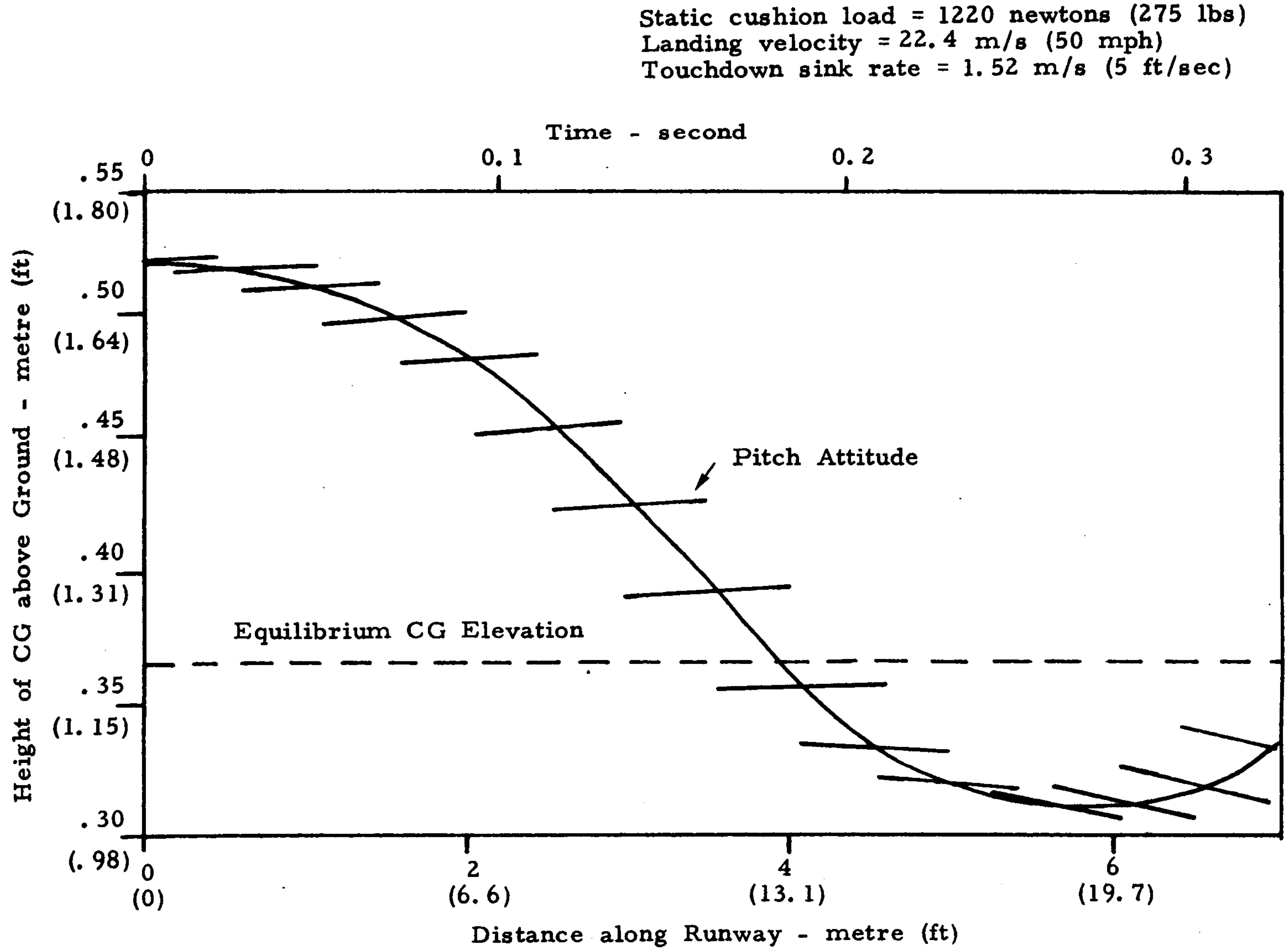


Figure 15. Cushion Motion during Landing Impact

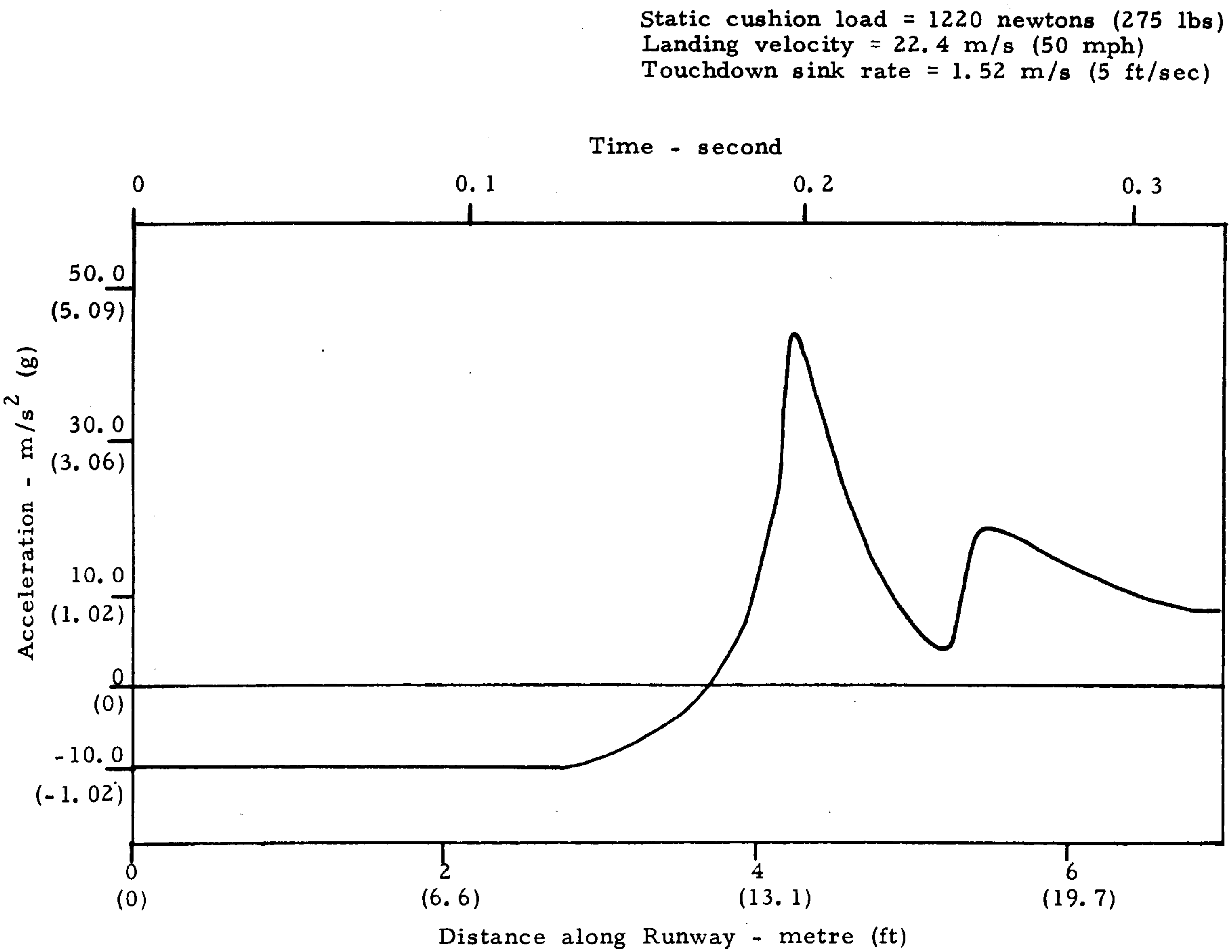


Figure 16. Acceleration during Landing Impact

Static cushion load = 1220 newtons (275 lbs)
Landing velocity = 22.4 m/s (50 mph)
Touchdown sink rate = 1.52 m/s (5 ft/sec)

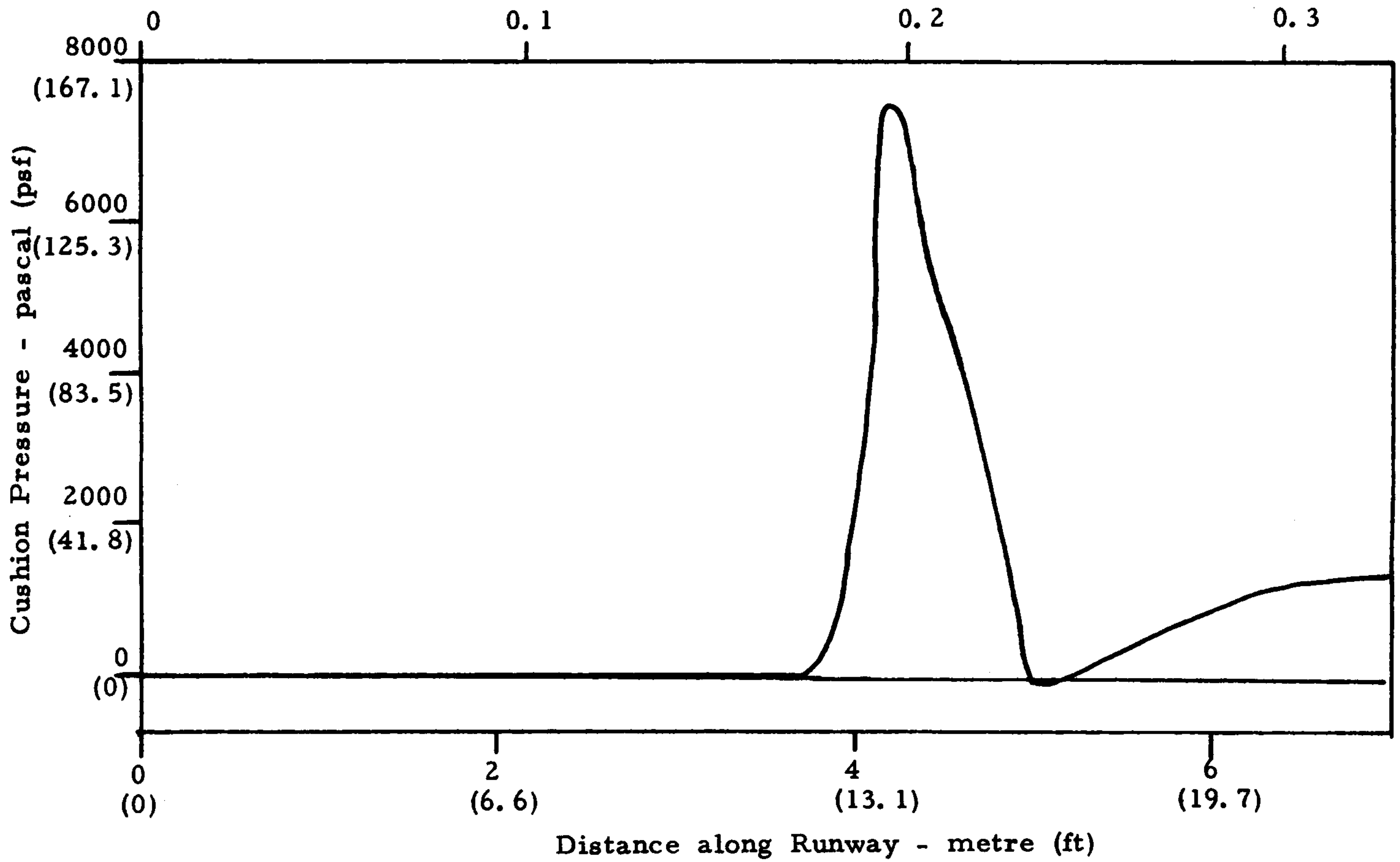


Figure 17. Cushion Pressure during Landing Impact

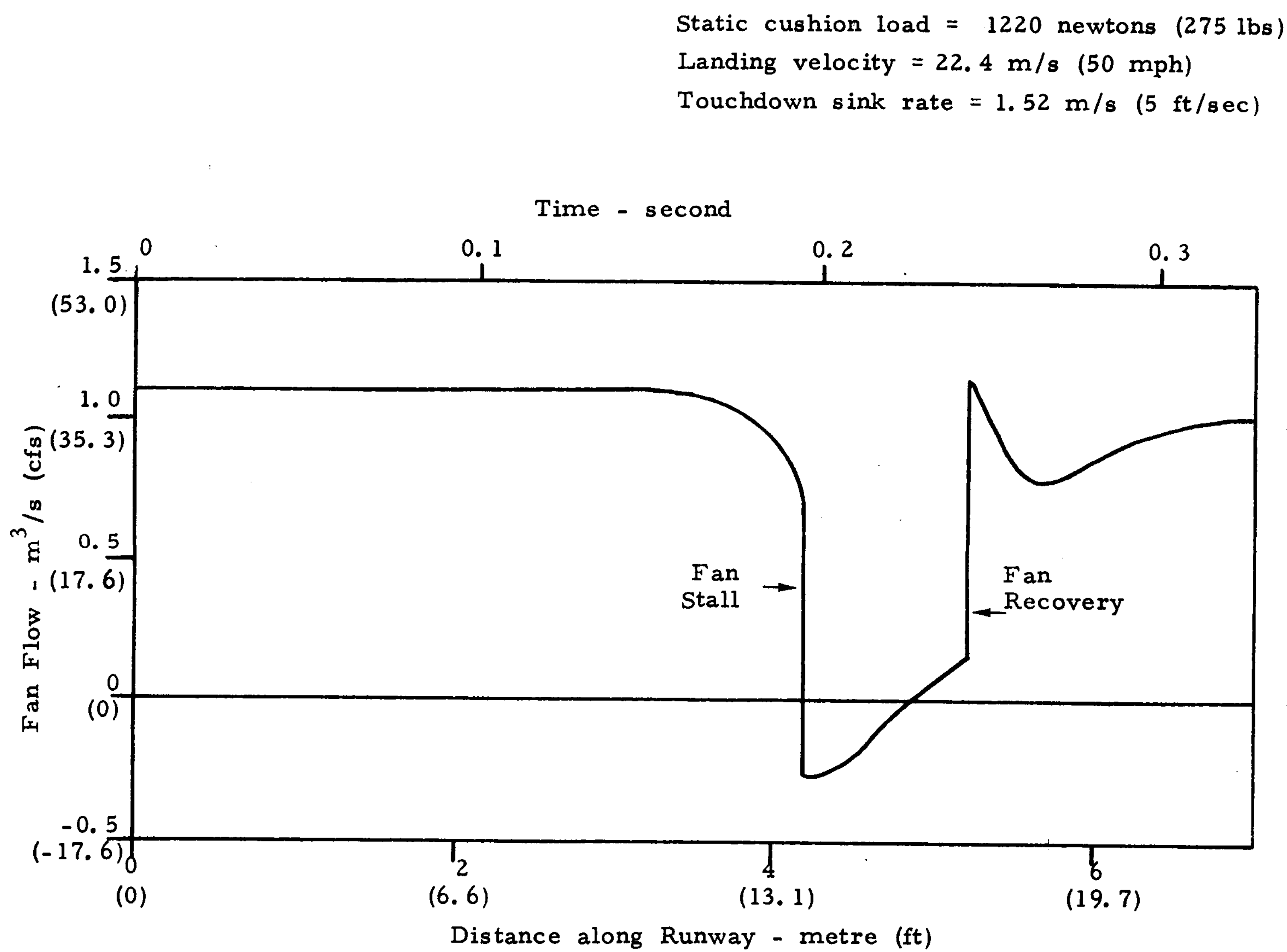


Figure 18. Fan Flow during Landing Impact

Figure 18 shows the time history of heave-pitch motion caused by landing impact. Initially, the cushion has a positive angle of attack. As it touches the ground, a clockwise torque acts upon it and causes the nose to pitch down. This torque arises because the rear of the cushion touches the runway before the front. After touchdown, the cushion begins to recover, and the heave and pitch motions begin to damp out.

Figures 16, 17 and 18 show the acceleration, cushion pressure and flow during landing. The pressure and acceleration build up as the aircraft descends. The increasing cushion pressure, however, causes the fan to stall, which reduces its output, and subsequently decreases the pressure and acceleration. As the pressure drops below the stall pressure, the fan recovers and the pressure and acceleration build up to a second peak, and then approach their respective equilibrium values.

3.3 Obstacle Crossing Simulation

The obstacle crossing simulation has been carried out for a static load of 1220 newtons (275 lbs). Prior to obstacle impact, the aircraft is assumed to be moving straight and level, with a velocity of 22.4 m/s (50 mph). The obstacle is represented by a rectangular cleat 0.4 m (1.3 ft) long and 89 mm (3.5 in) high. The simulation results are shown in Figures 19 through 22.

The time history of heave-pitch motion (Figure 19) shows that the aircraft (cushion) begins to pitch forward (clockwise) as the cushion first impacts the obstacle. This is because the friction force due to obstacle contact and the unbalanced (vertical) pressure force acting on the rear trunk give rise to a clockwise torque about the cg. The entry of the obstacle into the cushion also causes the cushion and trunk pressure force components to increase, which results in an upward heave motion of the aircraft. The upward motion continues

Static cushion load = 1220 newtons (275 lbs)
Taxiing velocity = 22.4 m/s (50 mph)
Irregularity = 0.4 m (1.3 ft) long, 89 mm
(3.5 inch) high cleat

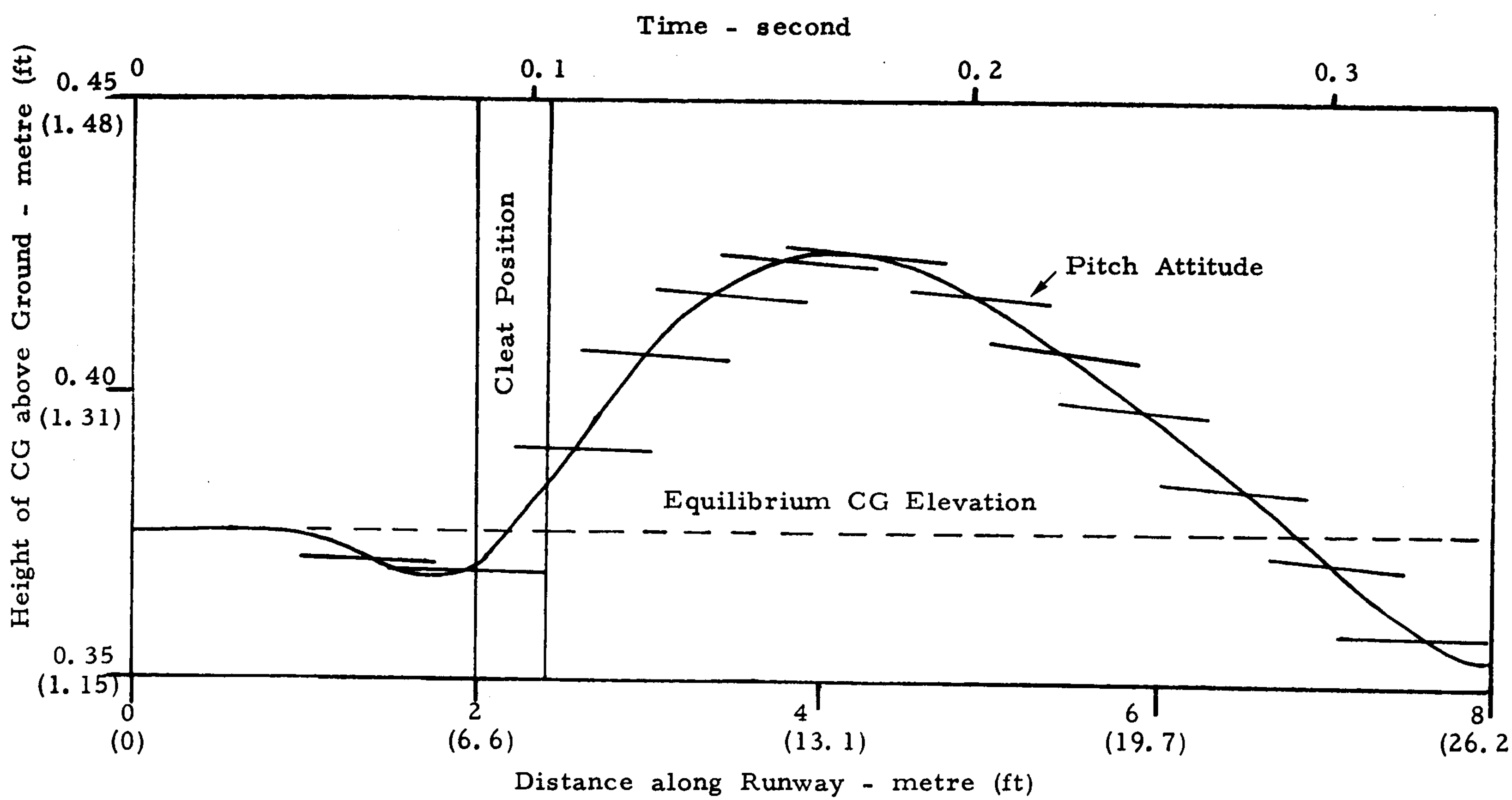


Figure 19. Cushion Motion during Taxi over Irregularity

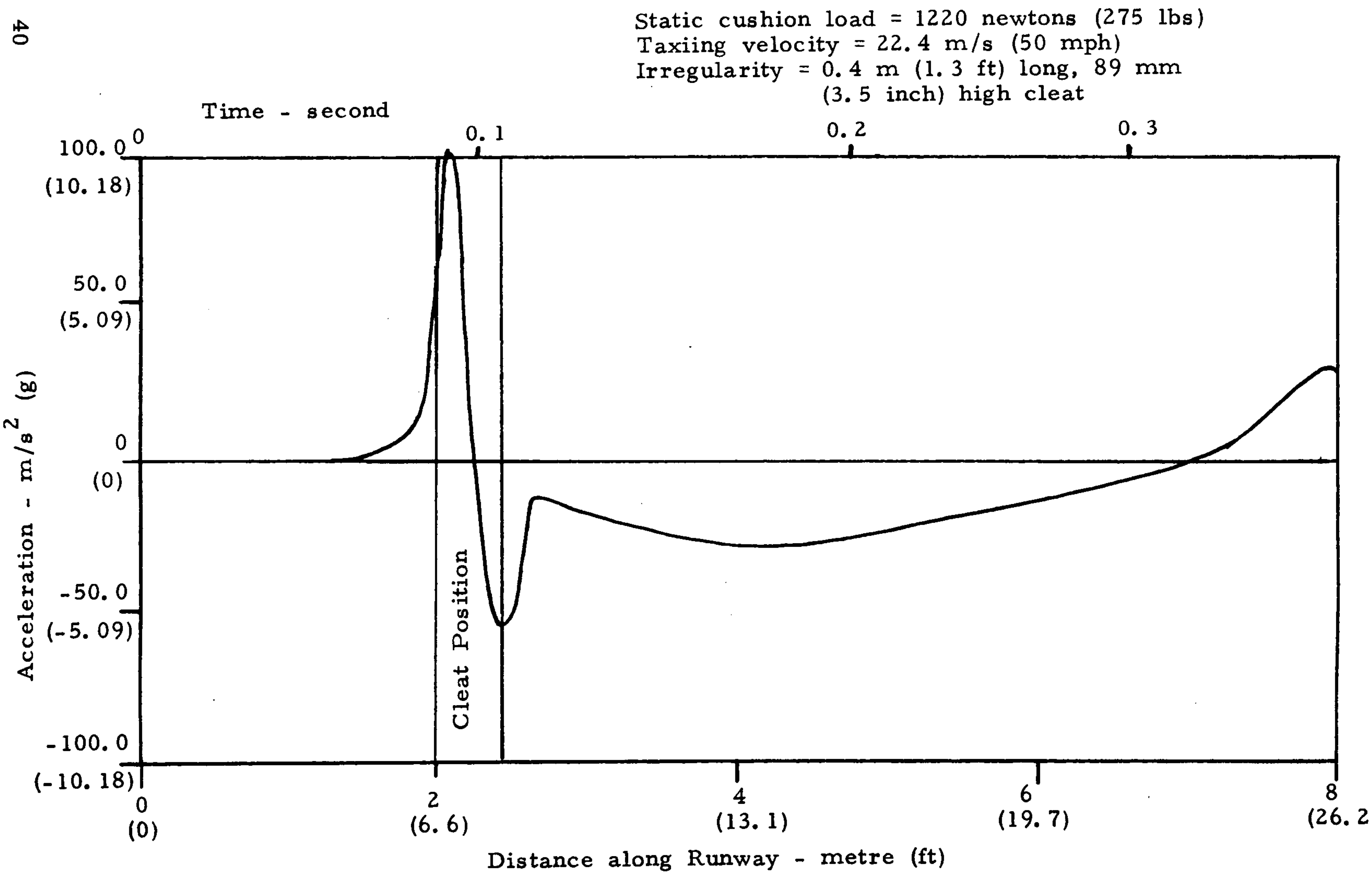


Figure 20. Acceleration during Taxi Over Irregularity

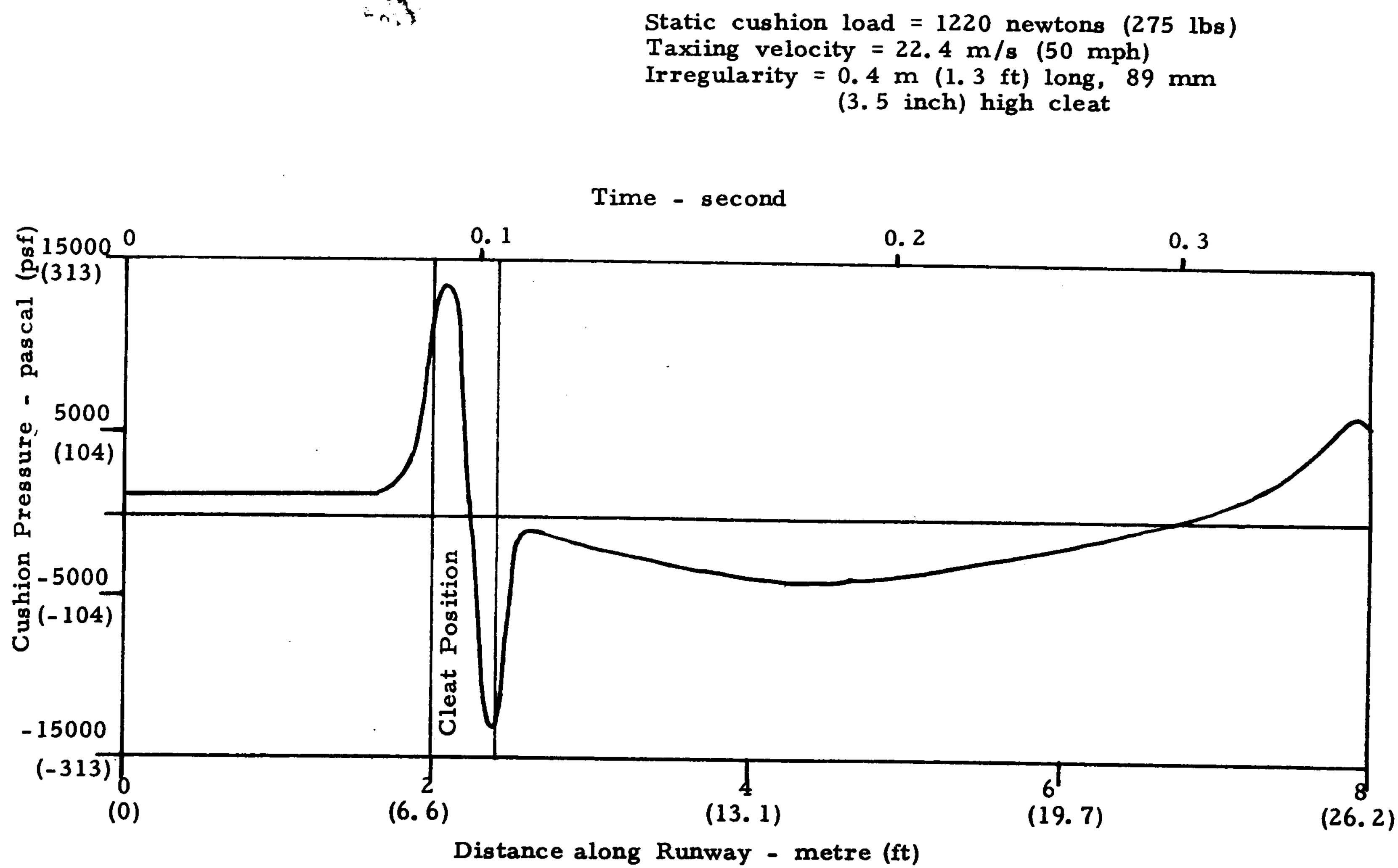


Figure 21. Cushion Pressure during Taxi Over Irregularity

Static cushion load = 1220 newtons (275 lbs)
Taxiing velocity = 22.4 m/s (50 mph)
Irregularity = 0.4 m (1.3 ft) long, 89 mm (3.5 inch) high cleat

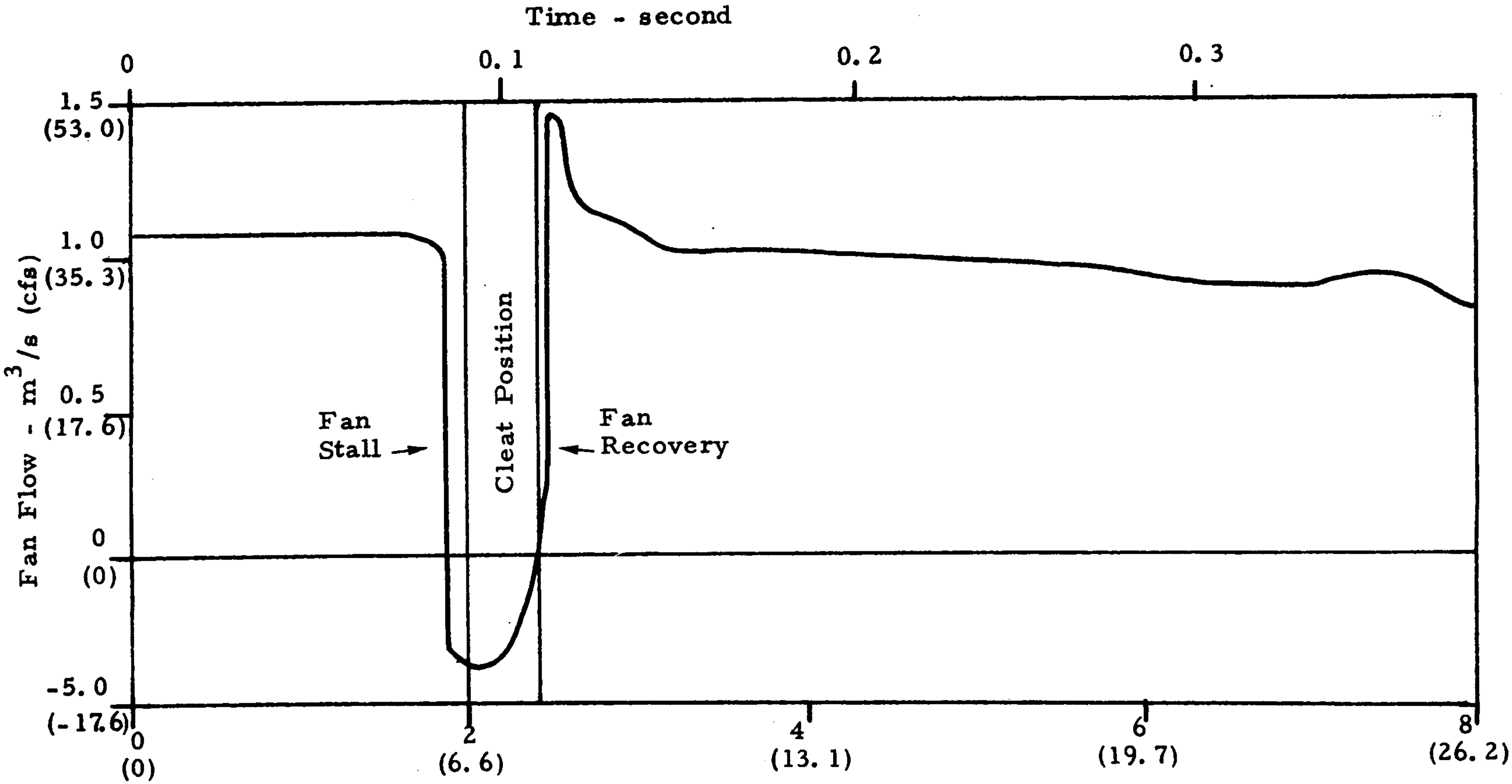


Figure 22. Fan Flow during Taxi Over Irregularity

until after the trunk leaves the ground. The upward force components then vanish, and the aircraft begins to descend. The initial pitching torque causes the pitch angle to build up to a maximum of about 7°, when the leading edge of the cushion contacts the ground and provides the restoring torque that causes the pitch disturbance to die out. The heave disturbance also begins to damp out.

Figures 20, 21 and 22 show the accelerations, cushion pressure and flow while crossing the obstacle. Initially, as the cushion impacts the obstacle, the pressure and heave acceleration build up. The increasing cushion pressure, however, causes the fan to stall, which reduces its output and subsequently decreases the pressure and acceleration. As the pressure drops below the stall pressure, the fan recovers, and the pressures and accelerations reach another peak at the second bounce, and then approach their equilibrium values.

4. Conclusion

The effort described in this report has been directed at developing fundamental analytical models of the heave and the heave-pitch motion of Air Cushion Landing Gear. These models have been implemented in a computer program delivered to NASA. The program is capable of simulating the dynamic heave and heave-pitch behavior (aircraft g loading and motion, trunk deflection, pressures, etc.) of an ACLS-equipped aircraft caused by landing impact and taxi over an irregular runway, using input data such as aircraft weight, ACLS geometry, fan characteristics, runway surface profile, etc. Three types of illustrative simulations have been carried out to demonstrate the capabilities of the program. The illustrative results show how drop tests, landing impact and rough runway operation can be simulated.

In the next phase of this program, a coupled heave-pitch-roll analysis will be developed. Also, experimental verification and refinement of the analysis using test data obtained at NASA-Langley with a model cushion will be performed. After the program capabilities have been verified, more extensive simulations are planned, to investigate a variety of potentially attractive cushion configurations and to develop guidelines for improved ACLS designs.

APPENDIX A - PROGRAM ORGANIZATION AND USE

The overall structure of the computer program developed for simulating the heave-pitch dynamics of the air cushion landing systems is described in this Appendix, along with instructions on its usage. Appendices B, D, E and F described various aspects of the program in greater details.

A. 1 Program Organization

The ACLS heave-pitch model is simulated as follows:

(a) The input data is read in.

(b) Initial geometry calculations are carried out.

(c) The static characteristics are computed and printed.

(d) The initial conditions for the dynamic simulation are determined.

(e) The state equations are integrated numerically to determine the time history of ACLS pressure and motion following landing impact.

The computer program that simulates ACLS heave-pitch dynamics is listed in Appendix E. The flow diagram is shown in Figure A. 1, and the computing sequence is described below.

(a) Data Input and Conversion

Initially, subroutine PROGIO is called which reads the input data cards through five other subroutines. Each card contains alphanumeric data which includes the name of each parameter, its value, and dimension. The input parameters are printed directly after they are read. Some of the less frequently altered parameters are specified directly in the main program. The input data is then converted, in this case, to ft-lb-sec units prior to the computations.

(b) Initial Geometry Calculations

Subroutine TRUNK calculates the trunk shape parameters (radii of curvature, subtended angles, etc.) from the input parameters ℓ, h_y, a, b, d and L_s (see Figure 1). Subroutine SEGMNT divides the trunk into a (user specified) number of segments and calculates the segment center distance from the center of the cushion. Subroutine SHAPE1 then calculates the trunk cross section area, trunk volume, cushion area, trunk-to-cushion orifice area, trunk-to-atmosphere orifice area, and distance of the center of cushion pressure for each segment, when the trunk is out of ground contact.

These three subroutines, TRUNK, SEGMENT and SHAPE1, are called only once in the program. The values of areas and volumes assessed by SHAPE1 are independent of ACLS motion. Another subroutine, SHAPE2, is called in the program whenever updated values of areas and volumes are required.

(c) Static Characteristics

Subroutine FLOW1 is called next. This subroutine calculates the static characteristics, i.e., the height of the aircraft center of gravity from the ground, pitch angle, gap area, plenum, trunk and cushion pressures, and total flow for various combinations of aircraft load and position of the center of gravity. This is accomplished by calling six subroutines; COORDN, PROFILE, CLRNCE, SHAPE2, FORCE and CMPCRV. The first four subroutines calculate the required areas and volumes of the ACLS for a particular combination of CG height and pitch angle. Subroutine FORCE calculates the torque and load developed

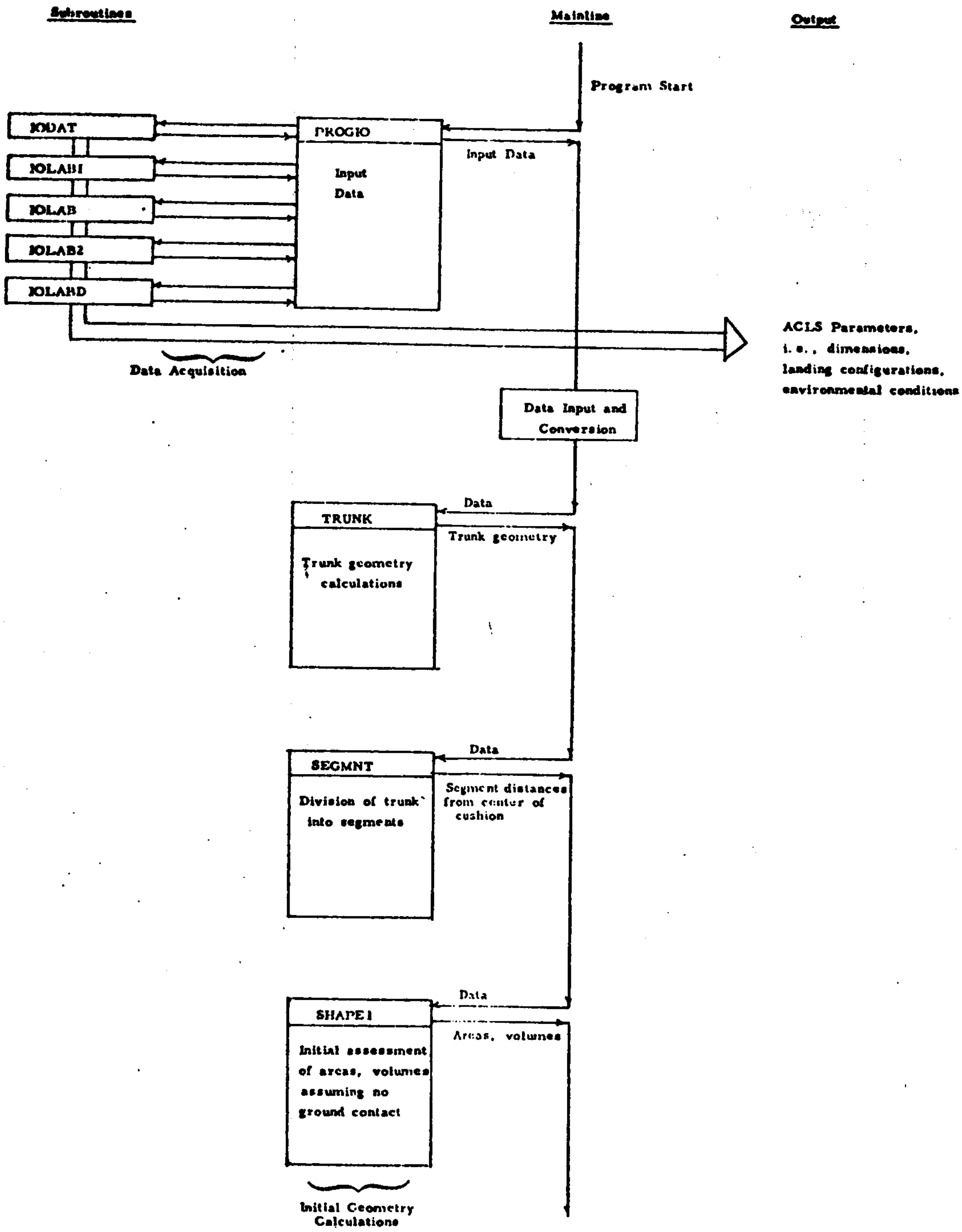
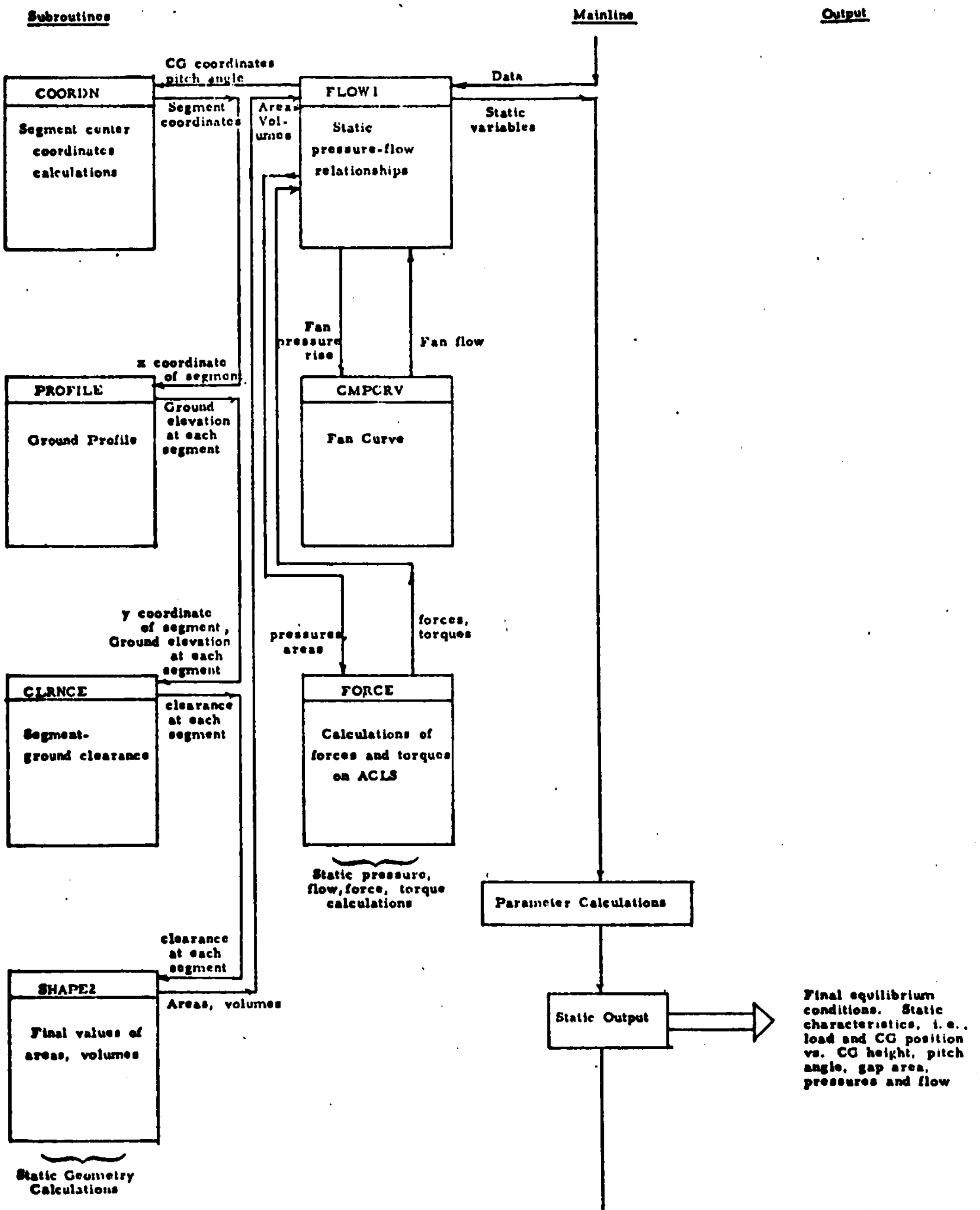
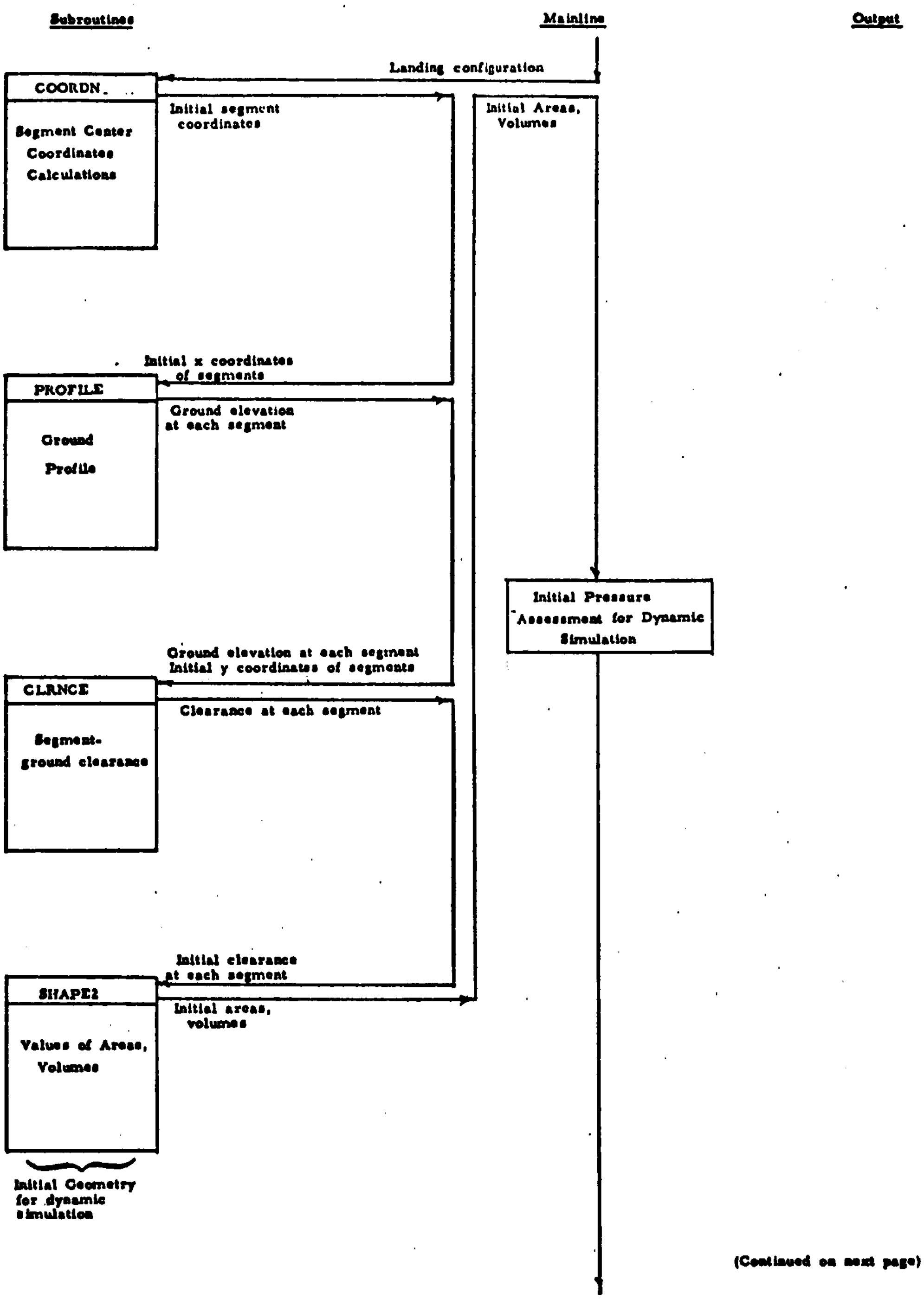


Figure A. 1 Program Flow Diagram - Initialization (Continued on next page)



(Continued on next page)

Figure A.1 (Continued). Program Flow Diagram - Static Part



(Continued on next page)

Figure A. 1 (Continued). Program Flow Diagram - Initial Conditions

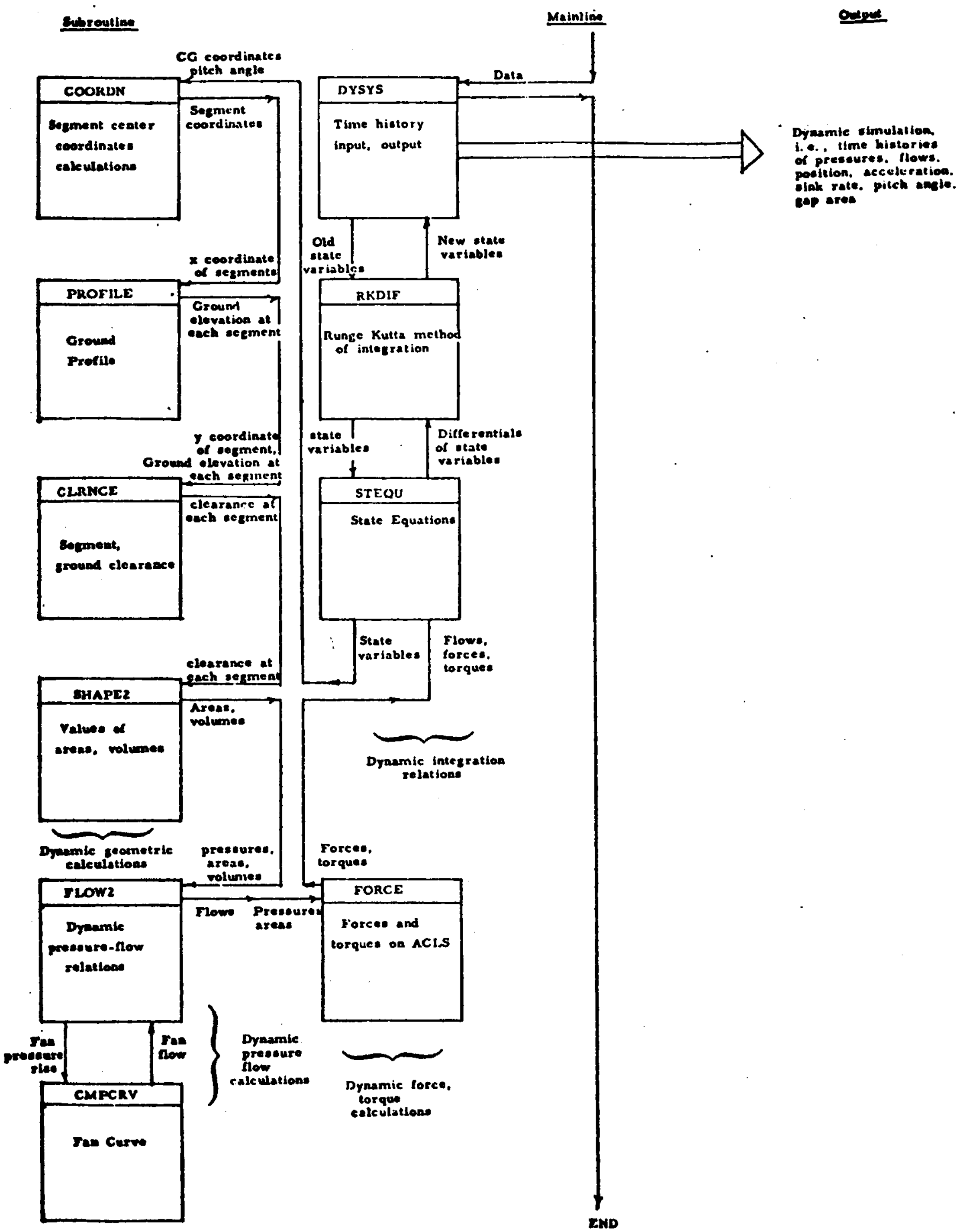


Figure A. 1 (Concluded). Program Flow Diagram - Dynamic Part by the particular configuration and CMPCRV supplies the fan characteristics to FLOW1.

The static characteristics are used to determine the final equilibrium values of the aircraft CG height above the ground, pitch angle, areas, volumes, pressures, flows and stiffness for the input value of aircraft weight and CG position. The static characteristics (10 values) and the final equilibrium values are then printed.

(d) Initial Conditions

Initial values of the state variables are needed to start the Runge-Kutta integration in the dynamic simulation. The initial values of CG coordinates, pitch angle, sink rate, horizontal velocity and pitch (rotational) velocity are supplied by the user. Subroutines COORDN, PROFILE, CLRNCE and SHAPE2 are called to determine the initial cushion and trunk geometry. Then the initial values of the cushion pressure, trunk pressure and plenum pressure are calculated from the static characteristics, computed as described in (c) above.

(e) Integration of State Equations

The dynamic simulation is coordinated by subroutine DYSYS. DYSYS calls subroutine RKDIF at each time step - RKDIF starts with the values of the seven state variables (plenum, trunk and cushion pressure, CG height, sink rate, pitch angle and pitch velocity) at a given time (t), and calculates new values of these variables at time (t+dt) by numerical integration using the Runge-Kutta method. The new values are obtained from derivations of the state variables at time t, and at intermediate times between t and t+dt. The calculation of derivatives is carried out in subroutine STEQU. STEQU contains the basic differential equations of pressure and motion of the ACLS. In order to calculate the derivatives, STEQU requires values of flows, forces and torques for the given values of the state variables. This is accomplished by calling subroutines COORDN, PROFILE, CLRNCE, SHAPE2, FLOW2 and FORCE, in that order. The first four subroutines calculate the various trunk and cushion areas and volumes corresponding to the ACLS orientation at a particular instant of time. From this data, subroutine FLOW2 determines the various flows through the ACLS. Subroutine CMPCRV supplies FLOW2 with data on the pressure-flow fan characteristics. Finally, subroutine FORCE calculates the forces and torques acting on the aircraft cg using the values of the appropriate pressures and areas supplied by STEQU and SHAPE2 respectively.

The above procedure is repeated for each time increment, and output values of pressures, flows, motion, etc., are printed at appropriate (user specified) intervals. The program terminates when the simulation time equals the user supplied time limit.

A. 2 Program Use

A. 2. 1 Input Data Format

Input data is supplied to the program in three ways.

(a) By data cards that are read in after program compilation (i. e., through the READ statement).

(b) By data specifications that are included within the program (i. e., through DATA and other specification statements).

(c) Through Subroutine PROFILE which is used to specify ground profile information.

Method (a) is used primarily to specify the parameters that are design variables and/or are likely to be frequently changed (aircraft weight, initial sink rate, initial pitch angle, etc.). Method (b) is used primarily for parameters which are likely to be changed less frequently (discharge coefficients, polytropic exponent, etc.). The format for specifying these two types of input data are given below. The input data are in English units.

The profile description essentially consists of supplying values of ground elevation $Y_g(i)$ corresponding to segment i (Eq. (19), Appendix C). This can be accomplished in one of several ways, e.g., using function subprograms, data cards, etc., depending on user preference and form in which the data is available.

A. 2. 1. 1 Data Cards

The following data cards are required to execute the program. Most cards have an alphanumeric input format. The numerical values are placed within the 'F', 'I' or 'E' fields. The 'A' fields are used to provide parameter names and units, and other legends for user convenience.

Card No.	Contents	Format
1-7	Header cards	80A1
	(The user can print a heading using these cards)	
	Aircraft Parameters	
8	Aircraft weight (lbs)	30A1, F10.4, 10A1
9	Aircraft pitch inertia about CG (slug ft^2)	30A1, F10.4, 10A1
10	Horizontal distance of CG from geometric center of cushion, CC (ft)	30A1, F10.4, 10A1
11	Vertical distance of CG from geometric center of cushion, GG (ft)	30A1, F10.4, 10A1
12	Heave drag coefficient, C_D	30A1, F10.4, 10A1
13	Heave drag area, A_{ph} (ft^2)	30A1, F10.4, 10A1
	Trunk Parameters	
14	Header card	80A1
15	Straight section length of cushion, L_s (ft)	30A1, F10.4, 10A1
16	Distance between inner trunk attachment points, d (ft)	30A1, F10.4, 10A1
17	Horizontal distance between inner and outer trunk attachment points, a (ft)	30A1, F10.4, 10A1
18	Vertical distance between inner and outer trunk attachment points, b (ft)	30A1, F10.4, 10A1
19	Peripheral length of trunk cross section, ℓ (ft)	30A1, F10.4, 10A1
20	Inflated trunk height (no load), h_y (ft)	30A1, F10.4, 10A1
21	Number of trunk orifice rows, N_r	30A1, I5
22	Number of trunk orifices per row, N_h	30A1, I5

Card No.	Contents	Format
23	Area of each trunk orifice, A_h (in^2)	30A1, F10.4, 10A1
24	Spacing between trunk orifice rows, S_h (ft)	30A1, F10.4, 10A1
25	Header card	80A1
26	Peripheral distance between inner trunk attachment point and first row of holes, L_p (ft)	30A1, F10.4, 10A1
	Air Supply Parameters	
27-28	Header cards	80A1
29	Plenum-to-cushion orifice area, A_{plch} (ft^2)	30A1, F10.4, 10A1
30	Plenum-to-trunk orifice area, A_{pltk} (ft^2)	30A1, F10.4, 10A1
31	Plenum-to-atmosphere orifice area, A_{plat} (ft^2)	30A1, F10.4, 10A1
32	Fan inlet orifice area, A_{atfn} (ft^2) (See Note 1)	30A1, F10.4, 10A1
33	Plenum volume, V_{plm} (ft^3)	30A1, F10.4, 10A1
34	Dead cushion volume, V_{chd} (ft^3)	30A1, F10.4, 10A1
	Landing Approach Parameters	
35	Header card	80A1
36	Initial X coordinate of CG, XCGI (ft)	30A1, F10.4, 10A1
37	Initial Y coordinate of CG, YCGI (ft)	30A1, F10.4, 10A1
38	Initial pitch angle, PHII (degrees)	30A1, F10.4, 10A1
39	Initial horizontal velocity, VELXI (ft/sec)	30A1, F10.4, 10A1
40	Initial sink rate, SINKRT (ft/sec)	30A1, F10.4, 10A1
41	Initial pitch velocity, DPHI (degrees/sec)	30A1, F10.4, 10A1

Card No.	Contents		Format
	Environmental Conditions		
42	Header card		80A1
43	Absolute atmospheric pressure, P_{at} (psia)		30A1, F10.4, 10A1
44	Ambient temperature (^{o}F)		30A1, F10.4, 10A1
	Fan Characteristics		
45	Fan curve polynomial coefficient*	α_o	40A1, E10.3
46	"	α_1	40A1, E10.3
47	"	α_2	40A1, E10.3
48	"	α_3	40A1, E10.3
49	"	α_4	40A1, E10.3
50	"	β_o	40A1, E10.3
51	"	β_1	40A1, E10.3
52	"	β_2	40A1, E10.3
53	"	β_3	40A1, E10.3
54	"	β_4	40A1, E10.3
55	Maximum unstalled fan pressure rise, QP1		40A1, E10.3
56	Minimum stalled fan pressure rise, QP2		40A1, E10.3
57	Minimum unstalled flow, QP3		40A1, E10.3
58	Maximum unstalled flow, QP4		40A1, E10.3
59	Maximum stalled flow, QP5		40A1, E10.3
	Integration and Print Control Parameters		
60	Integration time step, DTIME (sec)		40A1, E10.3
61	Simulation time limit, FTIME (sec)		40A1, E10.3
62	Number of time steps between printing, MM		40A1, I5

*See Figure 7 for explanation of symbols on cards 45-59.

Card No.	Contents	Format
	Trunk Segment Parameters	
63	Number of straight sections in one-fourth of the periphery, M	40A1, I5
64	Number of curved sections in one-fourth of the periphery, N	40A1, I5

Note 1. Care must be taken to choose the proper area for the fan upstream orifice. When the orifice is far enough upstream so that it is not affected by the fan inlet flow field, the effective orifice area can be found from geometry. When the upstream orifice is close to the fan inlet (e.g., partial inlet blockage), the flow patterns in the fan inlet will affect the orifice characteristics, and the effective orifice area must be found from measurements of the flow and pressure drop. For values of A_{atfn} larger than 1 ft^2, the simulation is carried out with an unrestricted fan inlet (no upstream orifice). The value 1 ft^2 is chosen arbitrarily and it can be altered, if necessary, by changing Statement No. 76 in Subroutine FLOW2 on page 177.

A. 2. 1. 2 Internal Data

The internal data are specified at the beginning of the main program (see line marked 'DATA ACQUISITION', Page 149, Appendix E). They are as follows.

CPA	-	Discharge coefficient, plenum-to-atmosphere orifice
CAF	-	Discharge coefficient, fan inlet orifice
CPC	-	Discharge coefficient, plenum-to-cushion orifice
CPT	-	Discharge coefficient, plenum-to-trunk orifice
CTC	-	Discharge coefficient, trunk-to-cushion orifice
CGAP	-	Discharge coefficient of clearance gap

CTA	-	Discharge coefficient, trunk-to-atmosphere orifice
CKK	-	Polytropic expansion exponent
GEC	-	Ground effect coefficient (See Note 1)
ZETA	-	Trunk damping ratio (See Note 2)
PERTK	-	Trunk orifice blockage parameter (See Note 3)
PERCH	-	Cushion exit seal parameter (See Note 3)
U	-	Ground-trunk friction coefficient (See Note 4)
DECCL	-	Aircraft horizontal deceleration rate (ft/sec^2) (See Note 5)

Note 1. When the ACLS is high above the ground, the cushion pressure (gage) will be zero. Although simulation of the full dynamic model will predict this condition, significant computing economy can be achieved by simplifying the full model at large heights by assuming zero cushion pressure rather than obtaining this same result through solution of the differential equation of cushion pressure. The ground effect coefficient is the factor which determines the ground effect area (cushion-to-atmosphere gap) above which the cushion pressure is set equal to zero rather than computed from the full ACLS simulation. The ground effect gap area, A_{gapg}, is determined from the ground effect coefficient as follows

$$A_{gapg} = (GEC)\ A_{gap\ell}$$

where $A_{gap\ell}$ is the equilibrium gap area found from the static load-deflection characteristic. Initial simulations with GEC = 10 have given satisfactory results. Larger values will require smaller integration time steps, and involve more computation. Smaller values may allow larger time steps, but can lead to starting transients when the ACLS comes into ground effect.

Note 2. The trunk damping ratio zeta, ζ, is a nondimensional measure of trunk damping. The damping coefficient for each segment, $\overline{B}_z$, [Assumption (f) in Section 2.2] is obtained from the damping ratio as follows

$$\overline{B}_z = 2\zeta \sqrt{\text{Heave Stiffness x Mass}}/4(M+N)$$

This assumes that the damping force is equally divided amongst all trunk segments. Test data and dimensional analysis will provide the basis for estimating the trunk damping ratio. Initial data indicates that the damping ratio will be in the range of 0.05 - 0.1.

Note 3. During ground contact, the trunk orifices nominally covered by the ground will not be completely blocked, and the cushion will not be perfectly sealed, because of ground irregularities, trunk ribs and imperfections and brake pads. Therefore, some small flow will leak out the cushion to the atmosphere and through the covered trunk orifices even during ground contact. PERTK and PERCH are measures of the trunk and cushion leakage areas during ground contact. PERTK is the fraction of the trunk orifice area that is blocked during ground contact. For example, PERTK = .85 signifies that 85% of the area of the trunk orifices in ground contact is blocked, and the leakage flow occurs through the unblocked 15% of the orifice area. PERCH is the ratio of the cushion leakage area during ground contact to the equilibrium clearance gap area. For example, PERCH = .15 signifies that during ground contact, 15% of the equilibrium clearance gap area remains unblocked.

Typically, when the brake pads are not deployed, PERTK will be about .85 - .9 and PERCH will be about .1 - .15 (i.e., 85-90% blockage in both cases). When the brake pads are deployed, the blockage will be reduced, and appropriate values for PERTK and PERCH can be estimated from pad geometry.

Note 4. The trunk-ground friction coefficient is required to calculate the pitching torque due to friction force. It depends on many factors, including the brake pads and/or trunk material characteristics, ground surface characteristics, etc. For simulations carried out thus far, the friction coefficient has been assumed to lie in the range of 0.4 to 0.5.

Note 5. In this simulation, the aircraft is assumed to decelerate, in a horizontal direction, at a constant (user selected) rate.

A.2.2 Program Output

The output printout provides the following data. (See Appendix F.)

1. The Input Parameters

Aircraft weight and pitch inertia, location of cg, initial approach parameters (sink rate, etc.), ACLS configuration, etc.

2. Final Equilibrium Conditions

(These are the conditions that exist after the landing dynamics have damped out.)

Height of CG

Pitch Angle

Cushion Perimeter

Cushion Volume
Trunk Volume
Gap Area, Cushion-atmosphere
Cushion Area
Trunk Contact Area
Orifice Area, Trunk-atmosphere
Orifice Area, Trunk-cushion
Cushion Pressure (gage)
Trunk Pressure (gage)
Plenum Pressure (gage)
Total Volume Air Flow
Total Volume Cushion Flow
Volume Flow, Plenum to Cushion
Volume Flow, Plenum to Trunk
Volume Flow, Trunk to Cushion
Volume Flow, Trunk to Atmosphere
Volume Flow, Plenum to Atmosphere
Stall Margin (See Note 1)
Heave Stiffness
Pitch Stiffness
Theoretical Fan Power

3. Static Characteristics

The height of the center of gravity above the ground, pitch angle, air gap area, cushion and trunk pressures and total flow for various combinations of force and torque loads (i. e., for various weights and offset distances from the center of the cushion).

4. Dynamic Simulation

Evaluation of the following variables at successive intervals of time during aircraft approach, touchdown and taxi.

Acceleration (vertical)

Velocity (sink rate)

CG Height (Y coordinate of cg) (from reference X axis)

X coordinate of CG

Trunk Pressure (gage)

Cushion Pressure (gage)

Fan Volume Flow

Pitch Angle

Trunk-to-Cushion Volume Flow

Trunk-to-Atmosphere Volume Flow

Cushion-to-Atmosphere Volume Flow

Gap Area (clearance area between trunk and ground)

Note 1. The fan stall margin is the maximum percentage rise in fan pressure that can occur without fan stall. This parameter is a measure of the ability of the system to absorb dynamic impact without fan stall. When the stall margin is below 5% (i. e., impact stall likely), the statement 'FAN CRITICALLY STABLE' appears in the program output.

A. 2. 3 Premature Program Termination

Premature program termination can occur under the following conditions:

(a) When the input parameters do not allow feasible solutions to be obtained. For instance, when the aircraft weight cannot be supported due to insufficient output from the fan.

(b) When the integration time increment DTIME is chosen too large, and causes numerical instabilities during the solution of the differential equations.

A. 2. 3. 1 Diagnostic Messages

When input parameter values do not allow a feasible solution, one of the following diagnostic statements is printed prior to program termination.

1. 'INFEASIBLE TRUNK GEOMETRY'

   This message indicates that the geometrical trunk parameters a, b, ℓ and h_y are such that a feasible solution for the trunk shape cannot be obtained - i.e., a real curve joining the trunk attachment points, and having length ℓ and height h_y cannot be found.

2. 'INFEASIBLE CONFIGURATION'

   This message indicates that the ACLS configuration specified by the user is infeasible. The means to correct this situation include:

   (a) Reduced load
   (b) Increased fan output
   (c) Reduced plenum bleed area

3. 'CHANGE VALUE OF XTOL'

   In the rare case that this message appears, the situation is remedied by increasing the iteration tolerance value XTOL.

A. 2. 3. 2 Numerical Instability

When the user supplied integration time step DTIME is too large, the Runge Kutta integration scheme will not converge, and the program will terminate due to field overflow. In such cases, a smaller time step will eliminate the problem. Initial results indicate that for typical ACLS configurations and operating conditions, time steps less than about 5×10^{-4} sec give satisfactory results.

A. 2. 4 Heave Simulation

The heave-pitch simulation program can be adapted for simulating just the heave motion by assuming a very high value for aircraft pitch inertia (say, 10^{10} slug ft^2). The pitch inertia data are supplied by card No. 9, as described in Section A. 2. 1. 1. Initial pitch angle and pitch velocity (Card No. 38 and 41, respectively) should be zero, while simulating just the heave motion.

APPENDIX B - PRINCIPAL PROGRAM NOMENCLATURE*

The symbols used in the analysis and the corresponding computer program variable names are defined below. All program variables are computed in the appropriate ft-lb-sec units except where indicated to the contrary.

Symbol	Program Variable Name	Explanation
a	A	Horizontal distance between inner and outer trunk attachment points
A_1-A_9	A1-A9	Area of trunk sectors used in volume computations
A_{atfn}	AATFN	Fan inlet orifice area
-	ACCEL	Aircraft acceleration (positive upwards)
A_{ch}	ACH	Cushion area
$A_{chi}(i)$	ACHI(I)	I value of cushion area (i.e., with no ground contact) of ith segment
$A_{chr}(i)$	ACHR(I)	R value of cushion area (i.e., decrement due to ground contact) of ith segment
-	ADIF	Gap area above ground effect gap area
A_{gap}	AGAP	Clearance gap area
A_{gape}	AGAPE	Equilibrium gap area
$A_{gapi}(i)$	AGAPI(I)	I value of clearance gap area (i.e., with no ground contact) of ith segment
-	AGAPP(I)	Iterated gap area
$A_{gapr}(i)$	AGAPR(I)	R value of clearance gap area (i.e., decrement due to ground contact) of ith segment
-	AGAPS(I)	Static values of AGAP
A_h	AH	Area of trunk orifice

*Nomenclature is listed alphabetically by symbols. Therefore some program variable names do not appear alphabetically.

Symbol	Program Variable Name	Explanation
A_{leak}	ALEAK	Minimum clearance gap area (caused by brake pads, imperfections, etc.)
A_{ph}	PHA	Heave drag area of cushion
A_{plat}	APLAT	Plenum-to-atmosphere orifice area
A_{plch}	APLCH	Plenum-to-cushion orifice area
A_{pltk}	APLTK	Plenum-to-trunk orifice area
A_{tk}	ATK	Trunk cross sectional area
$A_{tki}(i)$	ATKI(I)	I value of trunk cross sectional area of ith segment
$A_{tkr}(i)$	ATKR(I)	R value of trunk cross sectional area of ith segment
A_{tkat}	ATKAT	Trunk-to-atmosphere orifice area
$A_{tkati}(i)$	ATKATI(I)	I value of trunk-to-atmosphere orifice area of ith segment
$A_{tkatr}(i)$	ATKATR(I)	R value of trunk-to-atmosphere orifice area of ith segment
A_{tkch}	ATKCH	Trunk-to-cushion orifice area
$A_{tkchi}(i)$	ATKCHI(I)	I value of trunk-to-cushion orifice area of ith segment
$A_{tkchr}(i)$	ATKCHR(I)	R value of trunk-to-cushion orifice area of ith segment
A_{tkcn}	ATKCN	Trunk-ground contact area
$A_{tkcni}(i)$	ATKCNI(I)	I value of trunk-ground contact area of ith segment
$A_{tkcnr}(i)$	ATKCNR(I)	R value of trunk-ground contact area of ith segment
-	ATOL	Tolerance for gap area iteration
b	B	Vertical distance between trunk attachment points

Symbol	Program Variable Name	Explanation
B_z	DAMPC	Trunk damping constant
$\bar{B}_z$	-	Damping constant for each trunk segment
C_{af}	CAF	Discharge coefficient of atmosphere-to-fan orifice
CC	CC	Horizontal distance of CG from center of cushion
-	CCI	User supplied value of CC
-	CCS(I)	Values of CC used in the static computations
C_D	HDC	Heave drag coefficient
C_{enf}	CENF	Distance of center of aerodynamic heave drag area from CG
C_{gap}	CGAP	Discharge coefficient of clearance gap
C_{pa}	CPA	Discharge coefficient of plenum-to-atmosphere orifice
C_{pc}	CPC	Discharge coefficient of plenum-to-cushion orifice
C_{pt}	CPT	Discharge coefficient of plenum-to-trunk orifice
C_{ta}	CTA	Discharge coefficient of trunk-to-atmosphere orifice
C_{tc}	CTC	Discharge coefficient of trunk-to-cushion orifice
d	D	Distance between trunk attachment points
-	DECCL	Braking deceleration
del_x	DELX	Width of straight trunk segment (along aircraft axis)
-	DER(I)	Derivatives of state variables

Symbol	Program Variable Name	Explanation
-	DPHI	Pitch (angular) velocity
-	DPHII	Initial pitch velocity
-	DTIME	Time step dt
-	DVCH	Time derivative of cushion volume
-	DVTK	Time derivative of trunk volume
-	DY(I)	Derivatives of state variables
-	FORCD	Aerodynamic drag force
Forcn	FORCN	Total vertical pressure force transmitted to aircraft
-	FORCNS(I)	Static values of FORCN
Forct	FORCT	Trunk damping force
-	FTIME	Simulation time limit
-	GEC	Ground effect coefficient
GG	GG	Vertical distance of CG from center of cushion
-	HP	Theoretical fan power
h_y	HY	Equilibrium height of trunk cross section
-	ICASE	Element number of iteration closest to the given gap area. ICASE = 0 if configuration infeasible.
-	ICLN	Used to suppress error message of CLRNCE during iteration of FLOW1
-	ICON	Controls storage of static characteristic values in FLOW1.
-	ICREST	ICREST = 2 if configuration load and position within tolerance to aircraft weight and CG position. ICREST = 1 otherwise

Symbol	Program Variable Name	Explanation
-	ID	ID = 0 after first entry in ground effect region. ID = 1, cushion out of ground effect (initially)
-	IDID	IDID = 0 if any configuration of iteration 1 in FLOW1 infeasible. IDID = 1 otherwise
-	IDIF	Same as ICASE
-	IFAN	IFAN = 0 for unstalled fan operation IFAN = 1 for stalled fan operation
-	IIT	Element number in static characteristic
Inert	INERT	Pitch moment of inertia of aircraft about CG
-	IODIN	Indicator of number of passes through iteration 1 of FLOW1
-	IPCT	IPCT = 0 if PCH > PTK IPCT = 1 if PCH ≤ PTK
-	IPHI	Y element number of two dimensional array of iteration 1 grid in FLOW1
-	IPN	Indicator of number of passes through iteration 2 of FLOW1
-	IPP	IPP = 0 for combined trunk, plenum dynamics, IPP = 1 separate trunk, plenum dynamics
-	IPREST	IPREST = 2 if actual gap area and iterated gap area within tolerance IPREST = 1 if parameters not within tolerance
-	IQ	Used to effect gradual change in cushion flow model after ground effect zone entry
-	IRST	Counter used to prevent endless iteration in FLOW1
-	IS	IS = IXCG of the best iteration grid point

Symbol	Program Variable Name	Explanation
-	ISAVE	Same as ICASE
-	ISHAPE	ISHAPE = 0 if trunk inflation impossible ISHAPE = 1 if trunk inflation possible
-	IYCG	X element number of two dimensional array of iteration 1 grid in FLOW1
-	JS	JS = IPHI of the best iteration grid point
ℓ	L	Peripheral trunk length
ℓ_1	L1	Trunk length, outer attachment to horizontal tangent
ℓ_2	L2	Trunk length, inner attachment to horizontal tangent
ℓ_p	LP	Peripheral distance from inner trunk attachment to first row of orifices
L_s	LS	Straight section length of cushion
M	M	Number of straight trunk segments in one quarter of trunk periphery
M_a	MASS	Mass supported by ACLS (slugs)
-	MM	Number of steps before printing
N	N	Number of curved trunk segments in one quarter of trunk periphery
N_h	NH	Number of trunk orifices per row
-	NQ	Determines number of steps in which gap model change takes place
N_r	NR	Number of rows of trunk orifices
P_{at}	PAT	Atmospheric pressure, absolute
P_{atfn}	PATFN	Fan inlet pressure, gage
P_{ch}	PCH	Cushion pressure, gage

Symbol	Program Variable Name	Explanation
-	PCHS(I)	Static values of PCH, gage
-	PEN(J)	Iteration value of PATFN
Per_{ch}	PERCH	Determines air gap seal imperfection
Per_{tk}	PERTK	Factor that determines flow area of trunk orifices in ground contact
P_{fan}	PFAN	Fan pressure rise
-	PFANS(J)	Iterative values of PFAN
-	PHIDELT	Increment in pitch angle
-	PHII	Initial value of pitch angle
-	PHIS(I)	Static values of pitch angle
-	PHISTRT	Initial value of pitch angle in iteration 1 of FLOW1
-	PHISTOP	Final value of pitch angle in iteration 1 of FLOW1
-	PINC	Increment in PFAN after first feasible configuration
-	PINC1	Increment in PFAN before first feasible configuration
P_{plm}	PPLM	Plenum pressure, gage
-	PPLMS(I)	Static values of PPLM, gage
-	PSTART	Starting value of PFAN for iteration
-	PSTOP	Last value of PFAN in iteration
P_{tk}	PTK	Trunk pressure, gage
-	PTKS(I)	Static values of PTK, gage
-	PTOL	Tolerance for pressure and force iteration
Q_{chat}	QCHAT	Cushion-to-atmosphere flow (cfs)

Symbol	Program Variable Name	Explanation
Q_{fan}	QFAN	Fan flow (cfs)
-	QFANS(I)	Static values of QFAN
Q_{fnpl}	QFNPL	Fan-to-plenum flow (cfs)
-	QP1-QP5	Stall, recovery and other points on fan characteristic
Q_{plat}	QPLAT	Bleed flow (cfs)
Q_{plch}	QPLCH	Plenum-to-cushion flow (cfs)
Q_{pltk}	QPLTK	Plenum-to-trunk flow (cfs)
Q_{tkat}	QTKAT	Trunk-to-atmosphere flow (cfs)
Q_{tkch}	QTKCH	Trunk-to-cushion flow (cfs)
-	RTOL	Tolerance for R_2 iteration
R_1	R1	Outer radius of curvature of trunk
R_2	R2	Inner radius of curvature of trunk
S	S	Peripheral length of cushion
-	SC	Stall margin
S_h	SH	Trunk orifice row spacing
-	SINKRT	Aircraft velocity (positive upward)
-	SINPH2	Sin ϕ_2
-	SINPHR	R_2 Sin ϕ_2
T_{cp}	-	Cushion pressure torque component
T_{df}	-	Torque due to drag force
-	TEMPAT	Ambient temperature
t	TIME	Time
T_{tp}	-	Trunk pressure torque component

Symbol	Program Variable Name	Explanation
Torf	TORF	Trunk-ground contact friction torque
Torn	TORN	Pressure torque
-	TORQ	= TORN + TORF
Torqt	TORQT	Trunk damping torque
V_{ch}	VCH	Total cushion volume
V_{chd}	VCHD	Cushion dead volume
$V_{chi}(i)$	VCHI(I)	I value of cushion volume of ith segment
$V_{chr}(i)$	VCHR(I)	R value of cushion volume of ith segment
-	VCHS	VCH at time t-dt
-	VELX	Forward velocity of the aircraft
-	VELXI	Initial forward velocity
V_{plm}	VPLM	Plenum volume
V_{tk}	VTK	Trunk volume
$V_{tki}(i)$	VTKI(I)	I value of trunk volume of ith segment
$V_{tkr}(i)$	VTKR(I)	R value of trunk volume of ith segment
-	VTKS	VTK at time t-dt
X	X	Variable used in trunk area calculations
X_1-X_9	X1-X9	X-coordinates of centroids of trunk cross sectional area components
X_{12}	X12	X coordinate of trunk area components (A1-A2)
X_{cc}	XCC	X-coordinate of center of cushion (CC)
X_{cg}	XCG	X-coordinate of CG

Symbol	Program Variable Name	Explanation
-	XCGI	Initial XCG
$X_{ch}(i)$	XCH(I)	Distance of center of cushion pressure of ith segment from CC
X_{cr}	XCR	X-coordinate of trunk area components (A6-A7)
$X_{cx}(i)$	XCX(I)	Distance of center of ith segment from CC
X_e	XE	X-coordinate of centroid of total trunk cross section area
X_{er}	XER	X-coordinate of centroid of area $A_{tkr}(i)$
$X_h(i)$	XH(I)	X-coordinate of center of ith segment
$X_{tk}(i)$	XTK(I)	Distance of center of trunk pressure of ith segment from CC
-	XTOL	Tolerance for iteration 1 of FLOW1
-	Y(I)	State variables (see below)
-	Y(1)	Plenum pressure, gage
-	Y(2)	Cushion pressure, gage
-	Y(3)	Trunk pressure, gage
-	Y(4)	Vertical aircraft velocity
-	Y(5)	Vertical aircraft displacement
-	Y(6)	Pitch (angular) velocity
-	Y(7)	Pitch angle
Y_{cc}	YCC	Y-coordinate of center of cushion (CG)
Y_{cg}	YCG	Y-coordinate of CG
-	YCGDELT	Increment in YCG

Symbol	Program Variable Name	Explanation
-	YCGI	Initial value of YCG
-	YCGS(I)	Static values of YCG
-	YCGSTOP	Final value of YCG in iteration 1 of FLOW1
-	YCGSTRT	Initial value of YCG in iteration 1 of FLOW1
-	YDIF	= ADIF/S
$Y_g(i)$	YG(I)	Ground elevation corresponding to ith segment
$Y_{gh}(i)$	YGH(I)	Hard surface clearance for ith segment
$Y_h(i)$	YH(I)	Y-coordinate of center of ith segment
-	ZCC(I, J)	Value of CC for point (I, J) in iteration 1 of FLOW1
-	ZWT(I, J)	Value of FORCN for point (I, J) in iteration 1 of FLOW1
α_0-α_4	AL0-AL4	Polynomial coefficients of fan curve
β	BETA	Angle subtended by curved segment of the trunk
β_0-β_4	B0-B4	Polynomial coefficients of fan curve
δ (i)	DELTA(I)	Angular position of ith curved segment
K	CKK	Polytropic expansion constant
ϕ	PHI	Pitch angle. Positive anticlockwise
ϕ_1	PHI1	Angle subtended by outer trunk segment (atmosphere side)
ϕ_2	PHI2	Angle subtended by inner trunk segment (cushion side)
ϕ_3	PHI3	Angle subtended by cushion side of trunk deformation (Figure 6)

Symbol	Program Variable Name	Explanation
ϕ_4	PHI4	Angle subtended by atmosphere side of trunk deformation (Figure 6)
ρ	RHO	Air density (slugs/ft^3)
μ	U	Coefficient of friction between the trunk and the ground
ζ	ZETA	Trunk damping ratio

APPENDIX C - DETAILED HEAVE-PITCH MODEL ANALYSIS

C. 1 Introduction

The heave-pitch model incorporated in the program is divided into two parts - the static relationships and the dynamic model.

The static relationships evaluate the geometric parameters, pressures and flows for the ACLS in equilibrium. They provide static design data, and also determine the initial conditions for the dynamic simulation.

The dynamic model predicts the time histories of ACLS pressures and flows and aircraft motion during approach, touchdown and taxi.

C. 2 The Static Model

The static relations can be divided into two categories:

(a) Geometric relations, summarized in C. 2. 1 and C. 2. 2.

(b) Pressure-flow-force-torque relations, summarized in C. 2. 3.

C. 2. 1 Trunk Crossectional Shape

From trunk geometry (Figure 6),

$$R_1 \phi_1 = \ell_1 \quad (1)$$

$$R_2 \phi_2 = \ell_2 \quad (2)$$

$$\ell_1 + \ell_2 = \ell \quad (3)$$

$$\cos \phi_2 = \frac{R_2 - h_y}{R_2} \quad (4)$$

$$R_1 Cos(\phi_1 - 90^o) + R_2 Sin\phi_2 = a \qquad (5)$$

$$R_1 Sin(\phi_1 - 90^o) - (h_y - R_1) = b \qquad (6)$$

The six unknown trunk configuration parameters ℓ_1, ℓ_2, R_1, R_2, ϕ_1 and ϕ_2 can be obtained by solving Equations (1) through (6) simultaneously, in terms of the known trunk parameters a, b, h_y and ℓ

C.2.2 Segmented Trunk Analysis

The orifice areas and cushion and trunk volumes, for a particular trunk orientation, are calculated as follows:

The trunk is divided into a number of segments. Then for a given trunk orientation, areas and volumes are calculated independently for each segment. The areas and volumes are divided into two components - the i component and the r component. The i values are calculated assuming that the trunk segment under consideration is out of ground contact. The r values represent the changes of the segment areas and volumes due to trunk-ground contact. The segment areas and volumes are found by subtracting the respective r values from the i values. The total areas and volumes are determined by combining the areas and volumes for each segment. For example

$$V_{tk} = \sum_{\substack{\text{each} \\ \text{segment}}} \left(V_{tki}(i) - V_{tkr}(i) \right)$$

where

V_{tk} = total trunk volume

$V_{tki}(i)$ = i value of trunk volume for ith segment

$V_{tkr}(i)$ = r value of trunk volume for ith segment

($V_{tkr}(i)$ = 0 if ith segment is not in ground contact.)

The trunk is symmetric about axes AA and BB (Fig. 2). Since roll motion is not considered and the ground profile is assumed to be two dimensional, only the right half of the trunk needs to be analyzed. The results of the left half will be similar. The right side of the trunk can be divided into four sections; two curved sections, each subtending 90° at the center of curvature and two straight sections, on each side of axis AA. The curved sections are divided into N segments each, and the straight sections are divided into M segments each. Thus the complete trunk is divided into 4(N+M) segments. (See Figure 2.)

The following assumption is made in deriving the areas and volumes for each segment:

> The ground under any particular segment is considered parallel to the hard surface, and at an elevation corresponding to the ground profile at the segment center projection (as shown in Figure 3). This assumption represents the ground surface and the hard structure of the cushion by a series of short, parallel sections which, when chosen sufficiently small, closely approximate the actual ground profile and hard surface orientation.

In order to find the elevation of the segment center and the ground, the following five quantities are required.

(a) The coordinates of the CG; Y_{cg}, X_{cg}

(b) The pitch angle, ϕ

(c) The position of the CG with respect to the cushion center.

(d) The distance of the segment center from the cushion center, $X_{cx}(i)$; $i = 1, 2(M+N)$

(e) The ground profile, $Y_g(i)$ as a function of $X_h(i)$.

C.2.2.1 <u>Hard Surface Clearance</u>

Figure 3 shows the various parameters involved in calculation of the hard surface clearance for each segment.

For a given trunk orientation, X_{cg}, Y_{cg} and ϕ are known. From Figure 3,

$$X_{cc} = X_{cg} + GG \operatorname{Sin}\phi - CC \operatorname{Cos}\phi \qquad (7)$$

$$Y_{cc} = Y_{cg} - GG \operatorname{Cos}\phi - CC \operatorname{Sin}\phi \qquad (8)$$

From Figure 2

$$X_{cx}(i) = -\left[\frac{L_s}{2} + \left(\frac{d}{2} + R_2 \operatorname{Sin}\phi_2\right) \operatorname{Cos}\delta(i)\right]$$

$$\text{for } 1 \leq i \leq N \qquad (9)$$

where $$\delta(i) = (i-1)\beta + \frac{\beta}{2} \qquad (10)$$

and $$\beta = \frac{90^\circ}{N} \qquad (11)$$

$$X_{cx}(i) = -\left[\frac{L_s}{2} - (i-1-N)\ del_x - del_x/2\right] \tag{12}$$

$$\text{for } N < i \leq M+N$$

where $$del_x = L_s/(2M) \tag{13}$$

$$X_{cx}(i) = (i-N-M-1)\ del_x + del_x/2 \tag{14}$$

$$\text{for } M+N < i \leq N+2M$$

and finally

$$X_{cx}(i) = \frac{L_s}{2} + \left(\frac{d}{2} + R_2 \operatorname{Sin}\phi_2\right) \operatorname{Sin}\delta\,(i-N-2M) \tag{15}$$

$$\text{for } N+2M < i \leq 2N+2M$$

and $\delta\,(i)$ is given by Eq. (10).

Knowing X_{cc}, Y_{cc} and $X_{cx}(i)$, $X_h(i)$ and $Y_h(i)$ can be calculated as follows.

$$X_h(i) = X_{cc} + X_{cx}(i) \operatorname{Cos}\phi \tag{16}$$

$$Y_h(i) = Y_{cc} + X_{cx}(i) \operatorname{Sin}\phi \tag{17}$$

$$i = 1,\ 2M+2N$$

Since the ground profile is available in the following form,

$$Y_g = f(X_g) \tag{18}$$

substitution of the coordinates gives

$$Y_g(i) = f\left(X_h(i) + Y_h(i) \tan\phi\right) \tag{19}$$

$$i = 1,\ 2M + 2N$$

Finally, the hard surface clearance for the ith segment is:

$$Y_{gh}(i) = Y_h(i)/\cos\phi - Y_g(i)\cos\phi \qquad (20)$$

$$i = 1,\ 2M+2N$$

C. 2. 2. 2 Areas and Volumes

C. 2. 2. 2. 1 Calculation of I Values

As explained in Section C. 2. 2, i values of areas and volumes for a segment are calculated assuming that the segment is out of ground contact. The trunk sectors are shown in Figure 6a. From geometry, the trunk cross sectional area $A_{tki}(i)$ is given by

$$A_{tki}(i) = A_1 - A_2 + A_3 - A_4 + A_5 \qquad (21)$$

where

$$A_1 = \frac{\phi_2}{2} R_2^2$$

$$A_2 = \frac{(R_2 - h_y)}{2} R_2 \sin\phi_2$$

$$A_3 = \frac{\phi_1 R_1^2}{2}$$

$$A_4 = \frac{Xb}{2}$$

$$A_5 = \frac{(a - R_2\sin\phi_2 - X)(h_y - R_1)}{2}$$

and $$X = \frac{b(a - R_2\sin\phi_2)}{b + h_y - R_1}$$

The trunk volume depends on the position of the segment.

$$V_{tki}(i) = del_x \, A_{tki}(i) \tag{22}$$

for $N < i \leq N+2M$

and

$$V_{tki}(i) = \beta \left(\frac{d}{2} + X_e\right) A_{tki}(i) \tag{23}$$

for $i \leq N$

or $i > N+2M$

where X_e is the horizontal distance of the centroid of the area A_{tki} from the inner trunk attachment point (X-coordinate of centroid). X_e is calculated as follows

$$X_e = \frac{A_1X_1 - A_2X_2 + A_3X_3 - A_4X_4 + A_5X_5}{A_{tki}(i)}$$

where X_1, X_2, etc., are the X coordinates of the centroids of the areas A_1, A_2, etc., respectively.

$$X_1 = R_2 \text{Sin}\phi_2 - 4\text{Sin}^2 (\phi_2/2) \, R_2/3\phi_2$$

$$X_2 = 0.6667 \, R_2 \text{Sin}\phi_2$$

$$X_3 = R_2 \text{Sin}\phi_2 + 4\text{Sin}^2 (\phi_1/2) \, R_1/3\phi_1$$

$$X_4 = a - 0.333X$$

$$X_5 = R_2 \text{Sin}\phi_2 + 0.333(a - R_2 \text{Sin}\phi_2 - X)$$

The cushion area $A_{chi}(i)$ is given by

$$A_{chi}(i) = (\frac{d}{2} + R_2 \text{Sin}\,\phi_2)\ del_x \tag{24}$$

for $N < i \leq N+2M$

$$A_{chi}(i) = (\frac{d}{2} + R_2 \text{Sin}\,\phi_2)^2\ \frac{\beta}{2} \tag{25}$$

for $i \leq N$

or $i > N+2M$

To calculate the trunk-to-cushion flow area, it is necessary to know the number of trunk holes inside the cushion. From Figures 1 and 6, the number of rows of holes communicating with the cushion is given by the integer value of $(\ell_2 - \ell_p / S_h) + 1$. The trunk-to-cushion flow area is thus given by

$$A_{tkchi}(i) = \text{integer}\left[\frac{\ell_2 - \ell_p}{S_h} + 1\right] N_h A_h \cdot \frac{del_x}{S} \tag{26}$$

for $N < i \leq N+2M$

where S = cushion periphery

$$= 2L_s + 2\pi(\frac{d}{2} + R_2 \text{Sin}\,\phi_2) \tag{27}$$

and

$$A_{tkchi}(i) = \text{integer}\left[\frac{\ell_2 - \ell_p}{S_h} + 1\right] N_h A_h$$

$$\times\ \frac{\beta(\frac{d}{2} + R_2 \text{Sin}\,\phi_2)}{S} \tag{28}$$

for $i \leq N$

or $i > N+2M$

The trunk-to-atmosphere flow area is given by

$$A_{tkati}(i) = N_r A_h N_h \cdot \frac{del_x}{S} - A_{tkchi}(i) \quad (29)$$

for $N < i \leq N+2M$

and

$$A_{tkati}(i) = N_r A_h N_h \cdot \frac{\beta(\frac{d}{2} + R_2 \mathrm{Sin}\,\phi_2)}{S} - A_{tkchi}(i) \quad (30)$$

for $i \leq N$

or $i > N+2M$

The cushion-to-atmosphere flow area is given by

$$A_{gapi}(i) = (Y_{gh}(i) - h_y)\, del_x \quad (31)$$

for $N < i \leq N+2M$

where $Y_{gh}(i)$ is calculated from Equation (20), and

$$A_{gapi}(i) = (Y_{gh}(i) - h_y)\, \beta(\frac{d}{2} + R_2 \mathrm{Sin}\,\phi_2) \quad (32)$$

for $i \leq N$

or $i > N+2M$

Finally, the cushion volume is given by

$$V_{chi}(i) = Y_{gh}(i)\, (\frac{d}{2} + R_2 \mathrm{Sin}\,\phi_2)\, del_x - (A_1 - A_2)\, del_x \quad (33)$$

for $N < i \leq N+2M$

and

$$V_{chi}(i) = Y_{gh}(i) \frac{\beta}{2} \left(\frac{d}{2} + R_2 \sin\phi_2\right)^2$$

$$- \beta \left(\frac{d}{2} + X_{12}\right)(A_1 - A_2) \tag{34}$$

where

$$X_{12} = \frac{X_1 A_1 - X_2 A_2}{A_1 - A_2}$$

for $i \leq N$

or $i > N+2M$.

C. 2. 2. 2. 2 Calculation of R Values

The r values represent the changes in areas and volumes due to trunk-ground contact. Ground contact occurs when $Y_{gh}(i) < h_y$ (see Figure 3). With ground contact, the r values are calculated as follows. The trunk cross sectional area $A_{tkr}(i)$ is given by

$$A_{tkr}(i) = A_6 - A_7 + A_8 - A_9 \tag{35}$$

where A_6, A_7, etc., are the areas of the sectors shown in Figure 6b.

$$A_6 = \frac{R_2^2}{2} \phi_3$$

$$A_7 = \frac{\left(R_2 - h_y + Y_{gh}(i)\right)}{2} R_2 \sin\phi_3$$

$$A_8 = \frac{R_1^2 \phi_4}{2}$$

$$A_9 = \frac{\left(R_1 - h_y + Y_{gh}(i)\right)}{2} R_1 \sin\phi_4$$

$$\phi_3 = \text{Cos}^{-1} \frac{R_2 - (h_y - Y_{gh}(i))}{R_2}$$

and

$$\phi_4 = \text{Cos}^{-1} \frac{R_1 - (h_y - Y_{gh}(i))}{R_1}$$

The r value of the trunk volume $V_{tkr}(i)$ is calculated as follows

$$V_{tkr}(i) = A_{tkr}(i)\ del_x \tag{36}$$

for $N < i \leq N+2M$

$$V_{tkr}(i) = \beta\left(\frac{d}{2} + X_{er}\right) A_{tkr}(i)$$

for $i \leq N$

or $i > N+2M$

where X_{er} is the X-coordinate of the centroid of area $A_{tkr}(i)$

$$X_{er} = \frac{A_6X_6 - A_7X_7 + A_8X_8 - A_9X_9}{A_{tkr}}$$

and X_6, X_7, etc., are X coordinates of the areas A_6, A_7, etc., respectively

$$X_6 = R_2 \text{Sin}\,\phi_2 - 4\text{Sin}^2(\phi_3/2)\ R_2/3\phi_3$$

$$X_7 = R_2 \text{Sin}\,\phi_2 - 0.333 R_2 \text{Sin}\,\phi_3$$

$$X_8 = R_2 \text{Sin}\,\phi_2 + 4\text{Sin}^2(\phi_4/2)\ R_1/3\phi_4$$

$$X_9 = R_2 \text{Sin}\,\phi_2 + 0.333 R_1 \text{Sin}\,\phi_4$$

The cushion area $A_{chr}(i)$ is given by

$$A_{chr}(i) = del_x \; R_2 Sin\phi_3 \tag{37}$$

for $N < i \leq N+2M$

and

$$A_{chr}(i) = \frac{\beta}{2}\left(\left(\frac{d}{2} + R_2 Sin\phi_2\right)^2 - \left(\frac{d}{2} + R_2 Sin\phi_2 - R_2 Sin\phi_3\right)^2\right) \tag{38}$$

for $i \leq N$

or $i > N+2M$

The number of trunk orifice rows communicating with the cushion is given by the integer value of

$$\left[\frac{\ell_2 - \ell_p - \phi_3 R_2}{S_h}\right] + 1$$

The r value of the area of the trunk orifices communicating with the cushion is given by

$$A_{tkchr}(i) = A_{tkchi}(i) - \text{integer}\left[\frac{\ell_2 - \ell_p - \phi_3 R_2}{S_h} + 1\right] N_h A_h \cdot \frac{del_x}{S} \tag{39}$$

for $N < i \leq N+2M$

and

$$A_{tkchr}(i) = A_{tkchi}(i) - \text{integer}\left[\frac{\ell_2 - \ell_p - \phi_3 R_2}{S_h} + 1\right] N_h A_h$$

$$\frac{\beta(\frac{d}{2} + R_2 \text{Sin}\phi_2)}{S} \qquad (40)$$

for $i \leq N$

$i > N+2M$

Similarly, the number of orifice rows communicating with the atmosphere is given by the integer value of

$$\left[\frac{\ell_1 - \left(\ell - \left(\ell_p + (N_r - 1)\ S_h\right)\right) - \phi_4 R_1}{S_h}\right] + 1$$

The r value of the trunk-to-atmosphere area is thus

$$A_{tkatr}(i) = A_{tkati}(i) - \text{integer}\left[\frac{\ell_1 - \left(\ell - \left(\ell_p + (N_r - 1)\ S_h\right)\right) - \phi_4 R_1}{S_h} + 1\right] N_h A_h$$

$$\cdot \frac{del_x}{S} \qquad (41)$$

for $N < i \leq N+2M$

and

$$A_{tkatr}(i) = A_{tkati}(i) - \text{integer}\left[\frac{\ell_1 - \left(\ell - \left(\ell_p + (N_r - 1)\ S_h\right)\right) - \phi_4 R_1}{S_h} + 1\right] N_h A_h$$

$$\cdot \frac{\beta(\frac{d}{2} + R_2 \text{Sin}\phi_2)}{S} \qquad (42)$$

for $i \leq N$

or $i > N+2M$

Equations (39) through (42) give the r values that correspond to a perfect seal during ground contact; i. e., when the trunk orifices and clearance gap are completely blocked. However, due to ground irregularities, trunk ribs and imperfections, brake pads, etc., the seal will not be perfect and the actual r values will thus be smaller than those found from Equations (39) through (42). These reduced r values are related to the perfect seal values through blockage factors as follows.

$$A_{tkchr}(i) = A_{tkchr}(i)\Big|_{\text{perfect seal}} \times Per_{tk} \tag{43}$$

$$A_{tkatr}(i) = A_{tkatr}(i)\Big|_{\text{perfect seal}} \times Per_{tk} \tag{44}$$

where Per_{tk} is the blockage factor (less than unity) that depends on the trunk orifice sealing characteristic during ground contact.

The cushion clearance gap area is given by

$$A_{gapr}(i) = A_{gapi}(i) \tag{45}$$

The cushion volume r value is given by

$$V_{chr}(i) = -\, del_x \; (A_6 - A_7) \tag{46}$$

$$\text{for} \quad N < i \leq N+2M$$

$$V_{chr}(i) = -\, \beta(\frac{d}{2} + X_{cr})(A_6 - A_7) \tag{47}$$

$$\text{for} \quad i \leq N$$

$$i > N+2M$$

where $$X_{cr} = \frac{A_6X_6 - A_7X_7}{A_6 - A_7}$$

Finally, the trunk-ground contact area is given by

$$A_{tkcn}(i) = (R_2 Sin\phi_3 + R_1 Sin\phi_4)\ del_x \tag{48}$$

$$\text{for} \quad N < i \leq N+2M$$

$$A_{tkcn}(i) = \frac{\beta}{2}\left((\frac{d}{2} + R_2 Sin\phi_2 + R_1 Sin\phi_4)^2 - (\frac{d}{2} + R_2 Sin\phi_2 - R_2 Sin\phi_3)^2\right) \tag{49}$$

$$\text{for} \quad i \leq N$$

$$\text{or} \quad i > N+2M$$

The values of V_{tk}, A_{ch}, A_{tkch}, A_{tkat}, V_{ch} and A_{gap} for the full trunk and cushion are obtained by subtracting the r values from the i values for each segment and summing them over all the segments.

$$V_{tk} = 2 \sum_{i=1}^{2(N+M)} \left[V_{tki}(i) - V_{tkr}(i)\right] \tag{50}$$

$$A_{ch} = 2 \sum_{i=1}^{2(N+M)} \left[A_{chi}(i) - A_{chr}(i)\right] \tag{51}$$

$$A_{tkch} = 2 \sum_{i=1}^{2(N+M)} \left[A_{tkchi}(i) - A_{tkchr}(i)\right] \tag{52}$$

$$A_{tkat} = 2 \sum_{i=1}^{2(N+M)} \left[A_{tkati}(i) - A_{tkatr}(i) \right] \quad (53)$$

$$V_{ch} = 2 \sum_{i=1}^{2(N+M)} \left[V_{chi}(i) - V_{chr}(i) \right] + V_{chd} \quad (54)$$

where V_{chd} is the dead (inactive) cushion volume and

$$A_{gap} = 2 \sum_{i=1}^{2(N+M)} \left[A_{gapi}(i) - A_{gapr}(i) \right] \quad (55)$$

The factor 2 in the above equations is included, because the expressions in brackets have been calculated for one-half of the (symmetrical) trunk. The r values are zero when ground contact does not occur, i.e., $Y_{gh}(i) > h_y$. Otherwise they are calculated from Equations (35) through (47).

Due to ground irregularities, trunk imperfections, brake pads, etc., the cushion seal during ground contact will not be perfect (i.e., $A_{gap} \neq 0$). Therefore, a minimum value of A_{gap} is defined such that in ground contact, $A_{gap} = A_{leak}$. A_{leak} is related to the equilibrium gap area through the cushion blockage factor, as shown below.

$$A_{leak} = Per_{ch} A_{gape} \quad (56)$$

where A_{gape} is the equilibrium gap area and Per_{ch} is the cushion blockage factor.

C.2.2.3 Center of Pressure

The distances of the centers of pressure of each segment from the center of the cushion are required in order to estimate torques acting on the ACLS. The positions of the centers of pressure depend on whether the segment is in ground contact or not.

C.2.2.3.1 Segment Out of Ground Contact

Such a situation exists for the ith segment when $Y_{gh}(i) \geq h_y$. Since it is assumed that the pressures inside the trunk and the cushion are uniform, the pressure centers of a segment will coincide with respective centroids of the projected area.

As can be seen from Figures 2 and 4, the center of pressure for the ith segment of the cushion, $X_{ch}(i)$ is

$$X_{ch}(i) = -\frac{L_s}{2} - \frac{4}{3\beta}\left(\frac{d}{2} + R_2 \sin\phi_2\right) \cdot \cos\Big((i-1)\beta + \beta/2\Big)\sin(\beta/2) \quad (57)$$

for $i \leq N$

$$X_{ch}(i) = X_{cx}(i) \quad (58)$$

for $N < i \leq N+2M$

and

$$X_{ch}(i) = \frac{L_s}{2} + \frac{4}{3\beta}\left(\frac{d}{2} + R_2 \sin\phi_2\right) \cdot \sin\Big((i-N-2M-1)\beta + \beta/2\Big)\sin(\beta/2) \quad (59)$$

for $i > N+2M$

C.2.2.3.2 Segment in Ground Contact

Figure 4 shows the parameters needed to calculate the distances of the center of the cushion pressure $X_{ch}(i)$ and the center of trunk pressure $X_{tk}(i)$ for the ith segment in ground contact. From geometry, for $i \leq N$,

$$X_{ch}(i) = -\frac{L_s}{2} - \frac{4}{3\beta}\left(\frac{d}{2} + R_2 \mathrm{Sin}\phi_2 - R_2 \mathrm{Sin}\phi_3\right)$$

$$\mathrm{Cos}\left((i-1)\beta + \beta/2\right) \mathrm{Sin}(\beta/2) \tag{60}$$

$$X_{tk}(i) = -\frac{L_s}{2} - XX2 \; \mathrm{Cos}\left((i-1)\beta + \beta/2\right) \tag{61}$$

where

$$XX2 = \frac{4}{3}\frac{\mathrm{Sin}(\beta/2)}{\beta}\frac{(RR^3 - RR1^3)}{(RR^2 - RR1^2)}$$

$$RR = \frac{d}{2} + R_2 \mathrm{Sin}\phi_2 + R_1 \mathrm{Sin}\phi_4$$

and

$$RR1 = \frac{d}{2} + R_2 \mathrm{Sin}\phi_2 - R_2 \mathrm{Sin}\phi_3$$

For $N < i \leq N+2M$

$$X_{ch}(i) = X_{cx}(i) \tag{62}$$

$$X_{tk}(i) = X_{cx}(i) \tag{63}$$

Finally, for $i > N+2M$

$$X_{ch}(i) = \frac{L_s}{2} + \frac{4}{3\beta}\left(\frac{d}{2} + R_2 \mathrm{Sin}\phi_2 - R_2 \mathrm{Sin}\phi_3\right)$$

$$\mathrm{Sin}\left((i-N-2M-1)\beta + \beta/2\right) \mathrm{Sin}(\beta/2) \tag{64}$$

and

$$X_{tk}(i) = \frac{L_s}{2} + XX2 \; \mathrm{Sin}\left((i-N-2M-1)\beta + \beta/2\right) \tag{65}$$

where XX2 is obtained from Eq. (61).

C.2.3 Pressure-Flow-Force-Torque Relations

The flow diagram of the cushion is shown in Figure C.1.

The flow through the upstream fan orifice is given by

$$Q_{fan} = A_{atfn} C_{af} \sqrt{\frac{-2 P_{atfn}}{\rho}} \tag{66}$$

where Q_{fan} = volume flow through the fan

A_{atfn} = orifice area, atmosphere to fan inlet

C_{af} = fan inlet orifice discharge coefficient

P_{atfn} = fan entrance pressure (negative, gage)

ρ = air density

The fan pressure rise, P_{fan}, is given by

$$P_{fan} = P_{plm} - P_{atfn} \tag{67}$$

where P_{plm} = plenum pressure (gage).

The fan flow is obtained from the fan characteristics, and is a function of the fan pressure rise.

$$Q_{fan} = f(P_{fan}) \tag{68}$$

The remaining flows are found as follows.

$$Q_{plat} = A_{plat} C_{pa} \sqrt{\frac{2 P_{plm}}{\rho}} \tag{69}$$

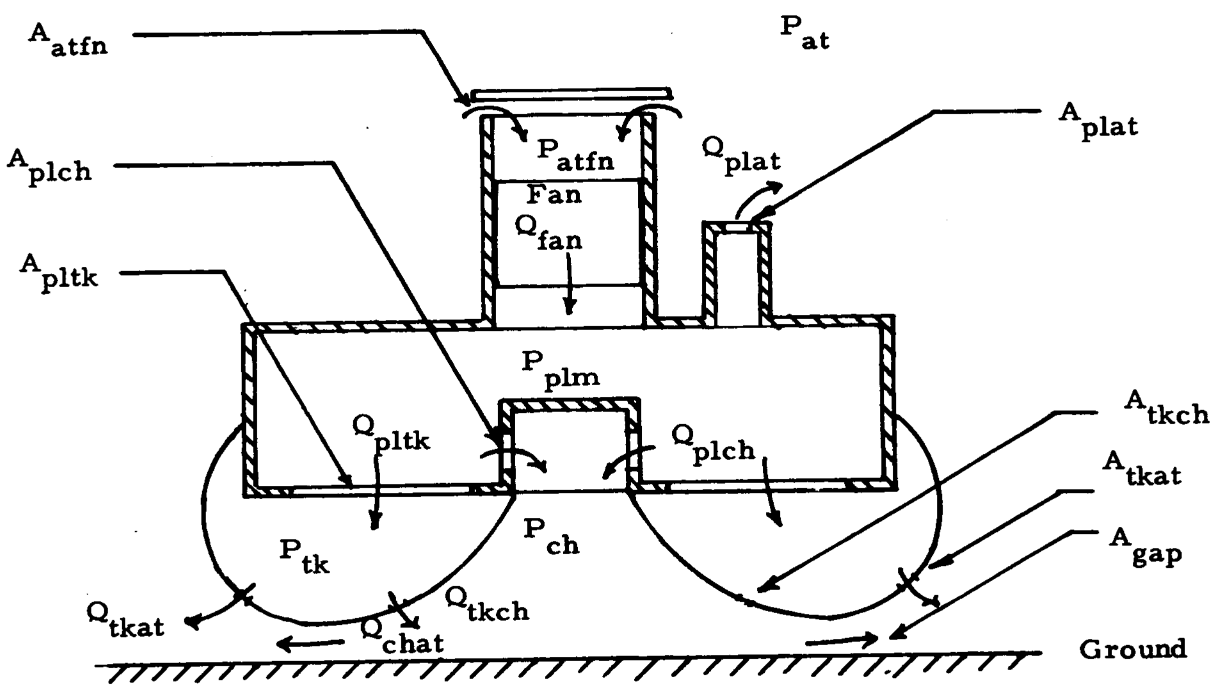


Figure C.1. Fluid Flow Through ACLS

where Q_{plat} - bleed flow rate

A_{plat} - bleed area

C_{pa} - bleed discharge coefficient

$$Q_{fnpl} = Q_{fan} - Q_{plat} \qquad (70)$$

where Q_{fnpl} - fan-to-plenum flow rate

$$Q_{fnpl} = Q_{plch} + Q_{pltk} \qquad (71)$$

where Q_{plch} - plenum-to-cushion flow rate

Q_{pltk} - plenum-to-trunk flow rate

$$Q_{plch} = A_{plch}\, C_{pc} \sqrt{\frac{2(P_{plm} - P_{ch})}{\rho}} \qquad (72)$$

where P_{ch} - cushion pressure (gage)

A_{plch} - plenum-to-cushion orifice area

$$Q_{pltk} = A_{pltk}\, C_{pt} \sqrt{\frac{2(P_{plm} - P_{tk})}{\rho}} \qquad (73)$$

where P_{tk} - trunk pressure (gage)

A_{pltk} - plenum-to-trunk orifice area

$$Q_{pltk} = Q_{tkch} + Q_{tkat} \tag{74}$$

where Q_{tkch} - trunk-to-cushion flow rate

Q_{tkat} - trunk-to-atmosphere flow rate

$$Q_{tkch} = A_{tkch}\, C_{tc} \sqrt{\frac{2(P_{tk} - P_{ch})}{\rho}} \tag{75}$$

$$Q_{tkat} = A_{tkat}\, C_{ta} \sqrt{\frac{2\ P_{tk}}{\rho}} \tag{76}$$

$$Q_{chat} = Q_{plch} + Q_{tkch} \tag{77}$$

where Q_{chat} - cushion-to-atmosphere flow rate

$$Q_{chat} = A_{gap}\, C_{gap} \sqrt{\frac{2\ P_{ch}}{\rho}} \tag{78}$$

The static (vertical) force developed by the cushion is determined from a force balance.

$$Forcn = (P_{ch}\ A_{ch} + P_{tk}\ A_{tkcn})\ Cos\phi \tag{79}$$

where P_{ch} - cushion pressure, gage

A_{ch} - cushion area $= 2 \sum_{i=1}^{2(M+N)} \left(A_{chi}(i) - A_{chr}(i) \right)$

P_{tk} - trunk pressure, gage

A_{tkcn} - trunk-ground contact area $= 2 \sum_{i=1}^{2(M+N)} A_{tkcn}(i)$

ϕ - pitch angle

From Figure 4, Torn, the torque developed by the cushion and trunk pressure, is given by

$$\text{Torn} = \sum_{i=1}^{2(M+N)} 2P_{ch}\left(A_{chi}(i) - A_{chr}(i)\right)\left(X_{ch}(i) - CC\right)$$

$$+ 2P_{tk}\left(A_{tkcn}(i)\right)\left(X_{tk}(i) - CC\right) \qquad (80)$$

where the i values of the areas, and the center of pressure distances are given by Equations (24), (25), (37), (38), (48), (49), and (57) through (65).

Under equilibrium conditions, the total cushion force equals the aircraft weight, and the torque is given by the product of the weight and the distance between the CG and the geometric center of the cushion. Under this equilibrium loading, the aircraft orients itself at a particular X_{cg}, Y_{cg} and ϕ. If ground profile and X_{cg} are known, variables Y_{cg} and ϕ uniquely define the aircraft and ACLS position, and define the variables $A_{chi}(i)$, $A_{chr}(i)$, $A_{tkcn}(i)$, $X_{ch}(i)$ and $X_{tk}(i)$. Thus,

$$A_{chi}(i) = f_{1i}(Y_{cg}, \phi) \qquad (81)$$

$$A_{chr}(i) = f_{2i}(Y_{cg}, \phi) \qquad (82)$$

$$A_{tkcn}(i) = f_{3i}(Y_{cg}, \phi) \qquad (83)$$

$$X_{ch}(i) = f_{4i}(Y_{cg}, \phi) \qquad (84)$$

and

$$X_{tk}(i) = f_{5i}(Y_{cg}, \phi) \qquad (85)$$

Thus, for the static solution, Equations (66) through (85) can be solved to determine the pressures, flows, areas, etc., Q_{fan}, Q_{plat}, Q_{fnpl}, Q_{plch}, Q_{pltk}, Q_{tkat}, Q_{tkch}, Q_{chat}, P_{atfn}, P_{fan}, P_{plm}, P_{tk}, P_{ch}, Y_{cg}, ϕ, $A_{chi}(i)$, $A_{chr}(i)$, $A_{tkcn}(i)$, $X_{ch}(i)$, $X_{tk}(i)$.

The heave stiffness can be found from the slope of the load-deflection characteristic,

$$Stif_{ycg} = - \frac{\Delta Forcn}{\Delta Y_{cg}} \tag{86}$$

where ΔForcn - change in normal force

ΔY_{cg} - change in CG elevation

Similarly, the pitch stiffness is found from the torque-rotation characteristic,

$$Stif_{phi} = - \frac{\Delta Torn}{\Delta \phi} \tag{87}$$

where ΔTorn - change in torque due to change in location of load with respect to CG

and $\Delta\phi$ - change in pitch angle.

C. 3 The Dynamic Model

The dynamic behavior of the ACLS is determined from the simultaneous solution of the equations describing the body dynamics and fluid mechanics of the cushion.

C. 3. 1 Body Dynamics

C. 3. 1. 1 Force Balance

During dynamic motion, the forces acting on the ACLS consist of:

(a) The cushion pressure force $(P_{ch}\ A_{ch})$ Cosϕ

(b) The trunk pressure force during trunk-ground contact $(P_{tk}\ A_{tkcn})$ Cosϕ

(c) The aircraft weight $(M_a g)$

(d) The aerodynamic drag ($1/2\ C_D \cdot A_{ph} \cdot \rho v^2$), where C_D is the heave drag coefficient, A_{ph} is the projected heave area and v is the heave velocity, dY_{cg}/dt.

(e) The trunk damping force during trunk-ground contact, Forct, given by

$$\text{Forct} = 2 \sum_{i=1}^{2(M+N)} \text{Forct(i)}$$

where

$$\text{Forct(i)} = \frac{B_z}{4(M+N)} \left(\frac{dY_{cg}}{dt} + \frac{d\phi}{dt} \left(X_{cx}(i) - CC \right) \right)$$

if segment is in ground contact.

Forct(i) = 0, if segment is out of ground contact

The basic equation of motion is then found from Newton's law as follows.

$$M_a \frac{dY_{cg}^2}{dt^2} = (P_{ch}\ A_{ch} + P_{tk}\ A_{tkcn}) \cos\phi - M_a g$$

$$- 1/2\ C_D\ A_{ph}\, \rho \left(\frac{dY_{cg}}{dt} \right)^2 - \text{Forct} \qquad (88)$$

C. 3. 1. 2 Torque Balance

The torques acting about the CG of the aircraft consist of

(a) The cushion pressure torque

$$T_{cp} = 2 \sum_{i=1}^{2(M+N)} P_{ch} \left(A_{chi}(i) - A_{chr}(i) \right) \left(X_{ch}(i) - CC \right)$$

(b) The trunk pressure torque

$$T_{tp} = 2 \sum_{i=1}^{2(M+N)} P_{tk} \left(A_{tkcn}(i)\right) \left(X_{tk}(i) - CC\right)$$

(c) The torque due to ground friction

$$Torf = -2 \sum_{i=1}^{2(M+N)} P_{tk} \left(A_{tkcn}(i)\right) \mu \left(Y_{gh}(i) + GG\right)$$

where μ is the coefficient of friction between the trunk and the ground.

(d) The torque due to aerodynamic drag force

$$T_{df} = 1/2\ C_D\ A_{ph} \rho \left(\frac{dY_{cg}}{dt}\right)^2 C_{enf}$$

where C_{enf} is the horizontal distance of the center of the aerodynamic drag force from the CG.

(e) The torque due to trunk damping, Torqt

$$Torqt = 2 \sum_{i=1}^{2(M+N)} Torqt(i)$$

where

$$Torqt(i) = \frac{B_z}{4(M+N)} \left(\frac{dY_{cg}}{dt} + \frac{d\phi}{dt}\left(X_{cx}(i) - CC\right)\right)\left(X_{tk}(i) - CC\right)$$

if the segment is in ground contact

$= 0$, if the segment is not in ground contact

A torque balance about the CG then gives

$$Inert \cdot \frac{d^2\phi}{dt^2} = T_{cp} + T_{tp} + Torf + T_{df} - Torqt \qquad (89)$$

where Inert is the pitch moment of inertia about the CG.

C. 3. 2 Fluid Mechanics

(a) Plenum

The fluid system consists of three interconnected chambers; plenum, trunk and cushion; fluid resistances and a fan. From the polytropic pressure-density relation,

$$\frac{(P_{plm}+P_{at})}{\rho_{plm}^{K}} = \text{constant} \tag{90}$$

Taking time derivatives,

$$\frac{dP_{plm}}{dt} = \frac{K\,(P_{plm}+P_{at})}{\rho_{plm}} \frac{d\,\rho_{plm}}{dt} \tag{91}$$

Conservation of mass in the plenum requires that

$$\frac{d}{dt}(\rho_{plm} V_{plm}) = \rho_{fnpl}\, Q_{fnpl} - \rho_{plm}\, Q_{plch} - \rho_{plm}\, Q_{pltk} \tag{92}$$

From Equations (91) and (92)

$$\frac{d\,P_{plm}}{dt} = \frac{K\,(P_{plm}+P_{at})}{\rho_{plm} V_{plm}} \left[\rho_{fnpl} Q_{fnpl} - \rho_{plm} Q_{plch} - \rho_{plm} Q_{pltk}\right] \tag{93}$$

Substituting $\rho_{plm} \simeq \rho_{fnpl} = \rho$ (mean density), the dynamic flow continuity equation for the plenum is as follows.

$$\frac{d\,P_{plm}}{dt} = \frac{K(P_{plm}+P_{at})}{V_{plm}} \left[Q_{fnpl} - Q_{plch} - Q_{pltk}\right] \tag{94}$$

(b) Cushion

The continuity equation for the cushion is similar to Equation (94), with an additional term to include the rate of change of cushion volume due to motion.

$$\frac{d\,P_{ch}}{dt} = \frac{K\,(P_{ch}+P_{at})}{V_{ch}} \left[Q_{plch} + Q_{tkch} - Q_{chat} - \frac{d\,V_{ch}}{dt} \right] \tag{95}$$

where $\frac{d\,V_{ch}}{dt}$ - rate of change of cushion volume.

(c) Trunk

$$\frac{d\,P_{tk}}{dt} = \frac{K\,(P_{tk}+P_{at})}{V_{tk}} \left[Q_{pltk} - Q_{tkch} - Q_{tkat} - \frac{d\,V_{tk}}{dt} \right] \tag{96}$$

Equations (88), (89), (94), (95) and (96) define the dynamic heave model of the ACLS. The flows, areas, volumes and lengths needed to evaluate these equations are found from the relationships derived in Section C.2.

C.4 Analytical Simplifications

The analysis described above has been developed for a general ACLS configuration. In using this analysis, several situations exist when the general relationsips can be simplified without loss of accuracy. These exist, for example, when some of the (user supplied) orifice areas are so large that the pressure drop across them is negligible, and need not be included in the computations. The program automatically determines the cases when such simplifications are possible, and modifies the basic analytical model accordingly to eliminate unnecessary computation. The modifications to the basic analysis are described below.

(a) When the cushion is high above the ground, the cushion pressure is equal to the atmospheric pressure. Although this result can be obtained from computation of Equation (78), significant computing reductions are achieved by assuming $P_{ch} = 0$ and $dP_{ch}/dt = 0$ (without computation) when the height is very large (i.e., prior to the landing impact). Thus, at the beginning of the simulation, when the cushion-to-atmosphere gap is more than the ground effect gap*, the right-hand side of Equation (78) is not computed, but is set equal to zero. When the cushion enters the ground effect region (i.e., gap less than ground effect gap), the above constraint on Equation (78) is removed.

(b) When the trunk-to-plenum orifice is large - i.e., the pressure drop is less than 2% of the upstream pressure - the plenum and trunk are treated as a single chamber, and Equations (94) and (96) are combined into a single equation.

$$\frac{d}{dt} P_{plm} = \frac{d}{dt} P_{tk} = \frac{K (P_{plm} + P_{at})}{(V_{plm} + V_{tk})} \left(Q_{fnpl} - Q_{plch} - Q_{tkch} - Q_{tkat} - \frac{d\, V_{tk}}{dt} \right) \tag{97}$$

(c) During dynamic operation, when the sharp peaks in cushion pressure occur, the force on the trunk membrane at the cushion-trunk interface will reverse (i.e., the computations of Equations (95) and (96) will indicate $P_{ch} > P_{tk}$. In such cases, trunk motion will tend to equalize the pressure difference, and this is included in the analysis by treating the trunk and cushion as a single chamber,

*Gap at which the cushion pressure begins to increase above atmospheric pressure. This gap is specified by the user.

with $P_{ch} = P_{tk}$, and combining Equations (95) and (96) into a single equation.

$$\frac{d}{dt} P_{tk} = \frac{d}{dt} P_{ch} = \frac{K(P_{tk}+P_{at})}{V_{tk}+V_{ch}} \left(Q_{pltk} + Q_{plch} - Q_{tkat} - Q_{chat} - \frac{d}{dt} V_{ch} - \frac{d}{dt} V_{tk} \right) \tag{98}$$

(d) For the duration of time when situations (b) and (c) above exist simultaneously, the plenum, trunk and cushion are treated as a single chamber ($P_{ch} = P_{tk} = P_{plm}$) and Equations (94), (95) and (96) are combined into a single equation.

$$\frac{d}{dt} P_{plm} = \frac{d}{dt} P_{tk} = \frac{d}{dt} P_{ch} = \frac{K(P_{plm}+P_{at})}{(V_{plm}+V_{ch}+V_{tk})} \left(Q_{fnpl} - Q_{tkat} - Q_{chat} - \frac{d}{dt} V_{ch} - \frac{d}{dt} V_{tk} \right) \tag{99}$$

APPENDIX D - SUBROUTINE DESCRIPTIONS

A flow chart of the overall program is shown in Figure A. 1 and discussed in Appendix A. Detailed descriptions of the main program and subroutines are given below.

D. 1 Main Program

The main program coordinates the static and dynamic simulation, carries out the data conversion, prints the static characteristics and determines the initial conditions. Internally supplied data (discharge coefficients, etc.) are read in directly. Other data are read in through subroutine PROGIO, which also prints out the data.

The data conversion section of the program converts trunk orifice area (AH) from in^2 to ft^2, mass from lbs to slugs, initial pitch angle (PHII) from degrees to radians, initial angular velocity (DPHII) from degrees per second to radians per second, and atmospheric pressure (PAT) from psi to psf. Density (RHO) is calculated from the atmospheric temperature. IFAN is set equal to zero to start the program with unstalled fan operation.

Subroutine TRUNK is called next to calculate the equilibrium shape of the trunk. ISHAPE is set equal to zero if the trunk configuration is infeasible and the program is terminated. Subroutine SEGMT divides the trunk into segments. Calculation of the distance of each segment center from the cushion center and assessment of the trunk and cushion areas and volumes (i values) associated with each segment is accomplished by calling subroutine SHAPE1.

The static characteristics of the ACLS are determined by calling subroutine FLOW1. ISAVE is set to zero if the configuration is considered infeasible (i. e., the static flow equations do not have feasible solutions). The equilibrium values of the variables (pressures, flows, etc.) for the given ACLS loading, along with the values at different load levels and load positions are printed.

The variable IPP is set to zero if the difference between the equilibrium trunk and plenum pressure is less than 2%. In such a situation, the computations are carried out by modeling the plenum and trunk as a single chamber with uniform pressure.

Initial conditions for the given landing configuration are either:

(a) Supplied by the user, i. e., XCGI, YCGI, PHII, VELXI, SINKRT and DPHI; or

(b) Calculated by calling subroutines COORDN, PROFILE, CLRNCE and SHAPE2, e. g., AGAP, VCH, VTK, etc.; or

(c) Estimated by interpretation from the static characteristics, i. e., PCH, PTK and PPLM.

The initial PCH is assumed to be 0 (psfg) if the initial gap area is more than the ground effect gap area. The parameter NQ, used in subroutine STEQU, controls the transition from the zero cushion pressure constraint as the ACLS moves into ground effect.

Finally, the dynamic simulation, Subroutine DYSYS, is called to carry out the numerical integration for the state equations, and determine the pressures, flows, motion, etc. of the ACLS as a function of time.

D. 2 SEGMNT

Subroutine SEGMNT divides the trunk into 4(M+N) segments. The values of M and N are specified by the user. The straight section of the trunk is divided into 4M segments (see Figure 2), and the circular part of the trunk is divided into 4N segments. Since the trunk is symmetrical about axis BB, and since roll motion is not considered in this model, only the right half of the trunk is analyzed. The results for the left half of the trunk are found from a mirror image of the right half.

The distance of the center of each segment from the cushion center is calculated, using Equations (9) through (15), and stored in array XCX(I).

D.3 TRUNK

Subroutine TRUNK calculates the trunk shape parameters R1, R2, L1, L2, PHI1 and PHI2 from the user supplied parameters A, B, L and HY, as shown in Figure D.1.

Calculation of R1, R2, L1, L2, PHI1 and PHI2 requires iteration. The iteration procedure is as follows:

(i) Initial guess, $R2 = \sqrt{\left(\frac{A}{2}\right)^2 + HY^2}$

(ii) $PHI2 = Cos^{-1} \frac{R2-HY}{R2}$

(iii) $R1 = \frac{(A-R2\ Sin(PHI2))^2 + (B+HY)^2}{2(B+HY)}$

(iv) $PHI1 = Cos^{-1} \frac{R1-B-HY}{R1}$

(v) $L2 = L - PHI1*R1$

(vi) $R2S = L2/PHI2$

R2S is compared with R2. If the difference is more than the tolerance RTOL, a new value of R2 ($R2 = \frac{R2+R2S}{2}$) is assumed and the procedure repeated until ABS(R2-R2S) < RTOL. For infeasible configurations, the iteration is stopped after 50 steps and the program is terminated.

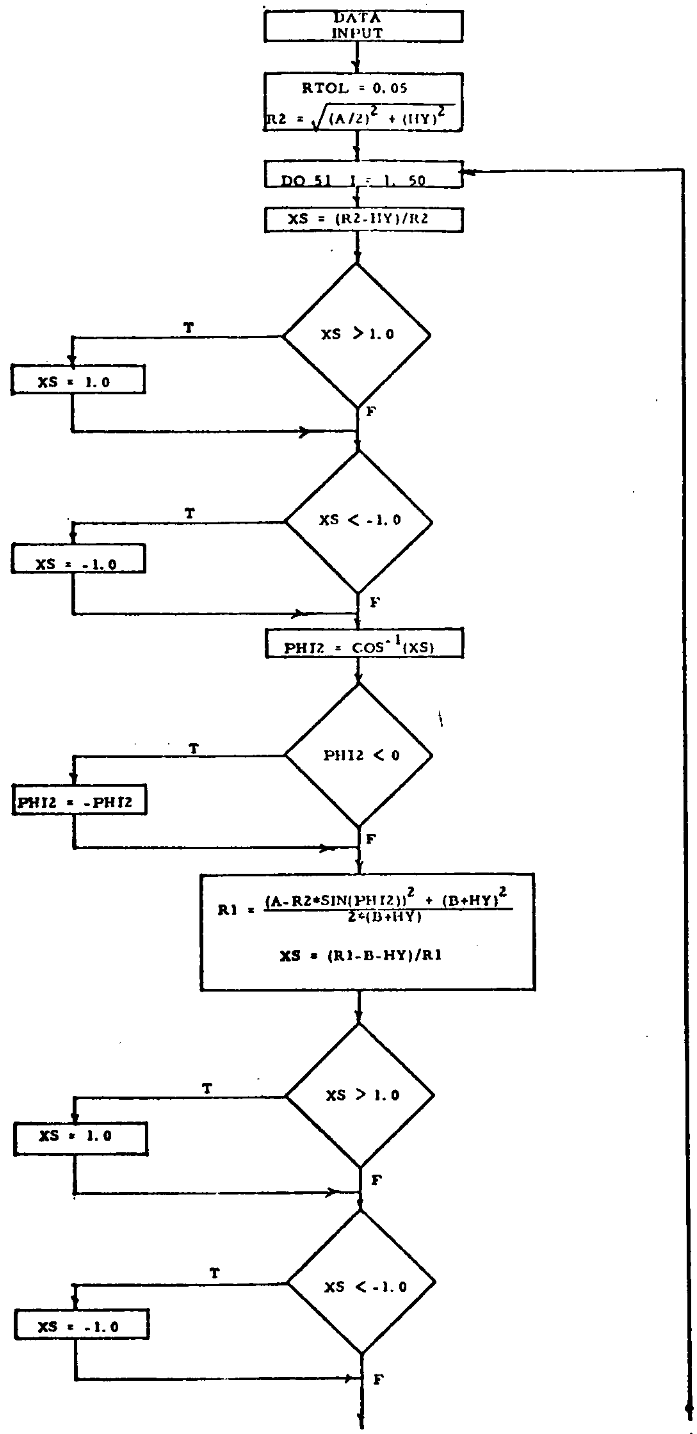


Figure D. 1. Flow Diagram of TRUNK

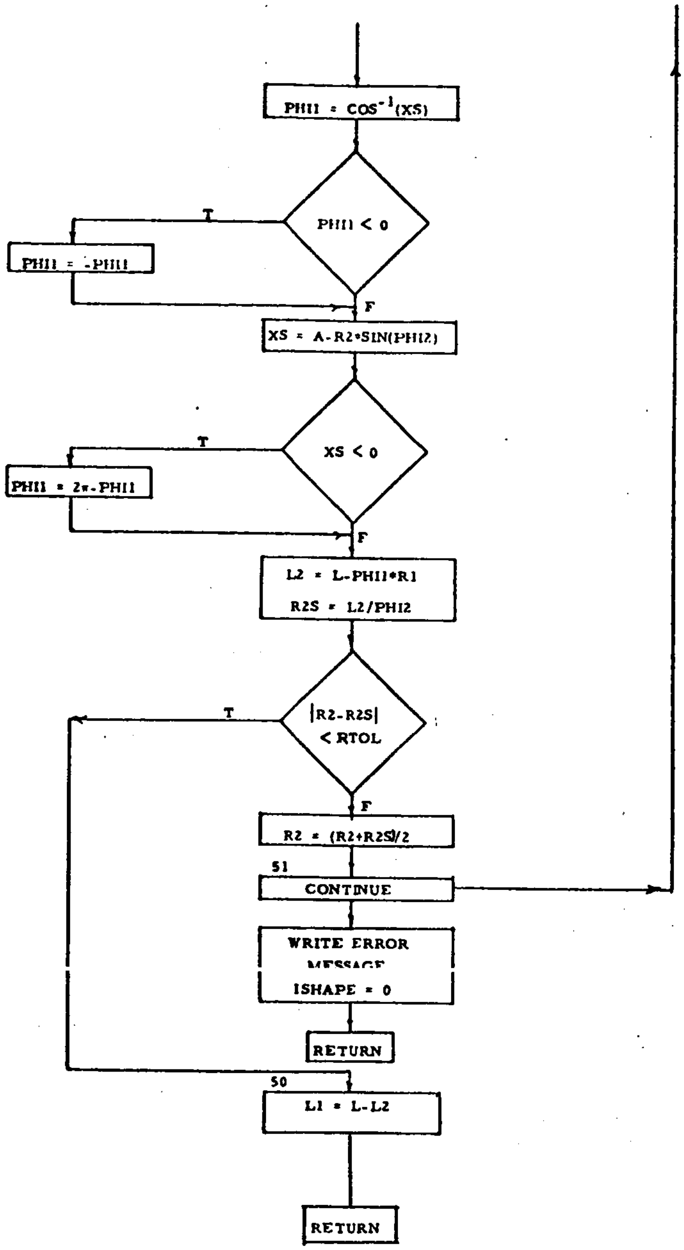


Figure D. 1 (Concluded). Flow Diagram of TRUNK

D.4 SHAPE1

The flow diagram for the subroutine SHAPE1 is shown in Figure D.2. SHAPE1 calculates the peripheral length S and i-values of the areas and volumes (per segment) listed below.

Trunk cross section area (ATKI(I))
Trunk volume (VTKI(I))
Cushion area (ACHI(I))
Trunk-to-cushion flow area (ATKCHI(I))
Trunk-to-atmosphere flow area (ATKATI(I)).

The above parameters are calculated from Equations (21) through (30) of Appendix C. The contact area ATKCNI(I) is set equal to zero since ground contact is not considered in SHAPE1.

D.5 COORDN

Subroutine COORDN calculates coordinates of the center of the cushion (XCC, YCC) from the coordinates of the CG (XCG, YCG) and the pitch angle (PHI) using Equations (7) and (8). The X and Y coordinates of the center of each segment are then calculated using Equations (16) and (17).

D.6 PROFILE

Subroutine PROFILE contains the user supplied ground elevation coordinates. The subroutine then calculates the elevation of the ground at the projection of the segment center for each segment and stores it in the array YG(I).

D.7 CLRNCE

Subroutine CLRNCE obtains the values of the Y coordinates of the segment centers, YH(I), from subroutine COORDN and the ground elevation

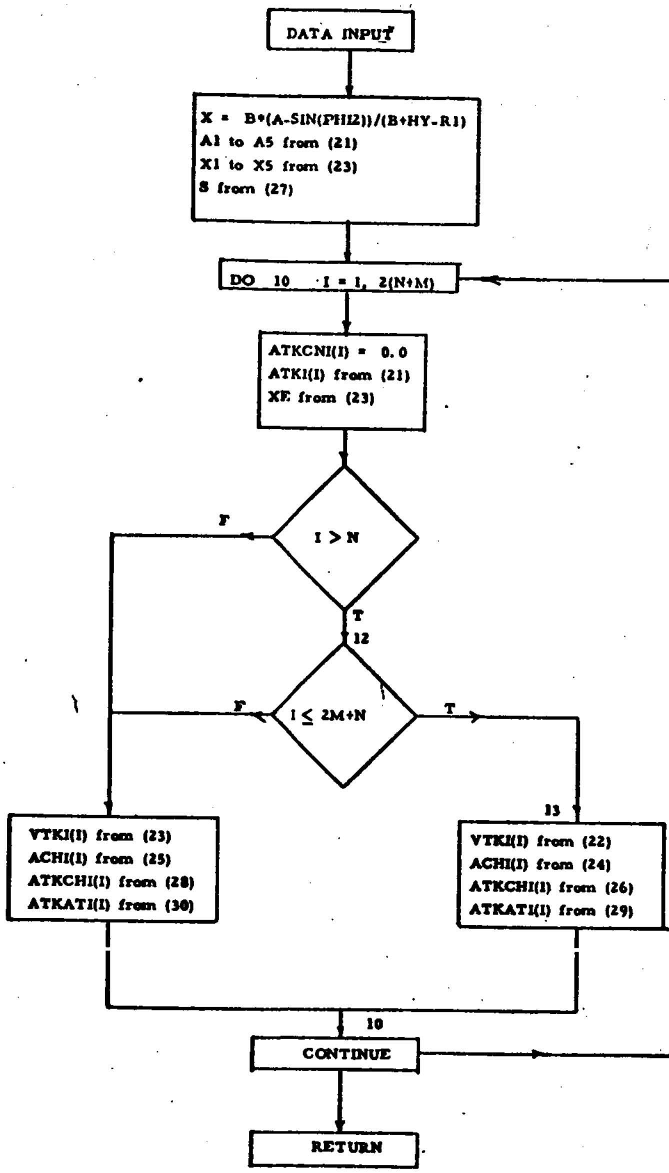


Figure D. 2. Flow Diagram of SHAPE1

corresponding to each segment, YG(I), from subroutine PROFILE, and calculates the hard surface clearance for each segment, YGH(I), using Equation (20).

D. 8 SHAPE2

Subroutine SHAPE2 determines various areas, volumes and center of pressure locations for each trunk segment from the hard surface clearance YGH(I). Those areas and volumes that have already been calculated in SHAPE1 are not recalculated.

The subroutine is divided into three parts, as shown in Figure D. 3.

Part 1: In Part 1, i values of cushion volume VCHI(I) and cushion-to-atmosphere gap area AGAPI(I) are determined from Equations (31) through (34). These values have not been calculated in SHAPE1, since they depend on trunk orientation, which varies with hard surface height.

Part 2: In Part 2, initially it is determined whether ground-trunk contact for a particular segment has been made, i. e., whether YGH(I) $<$ HY. If ground contact has occurred, r-values of the areas and volumes are calculated, which account for the decrements in the area and volume parameters due to the contact. Equations (35) through (49) are used to calculate the r-values. If a segment is not in ground contact, the r-values are set equal to zero. In either case, the location of the centers of pressure (cushion and trunk) for a segment with respect to the cushion center, XCH(I) and XTK(I) respectively, are calculated from Equations (60) through (65).

Part 3: In Part 3, the r-values of different areas and volumes of the segments are combined, and subtracted from the i-values, as shown in Equations (50) through (55).

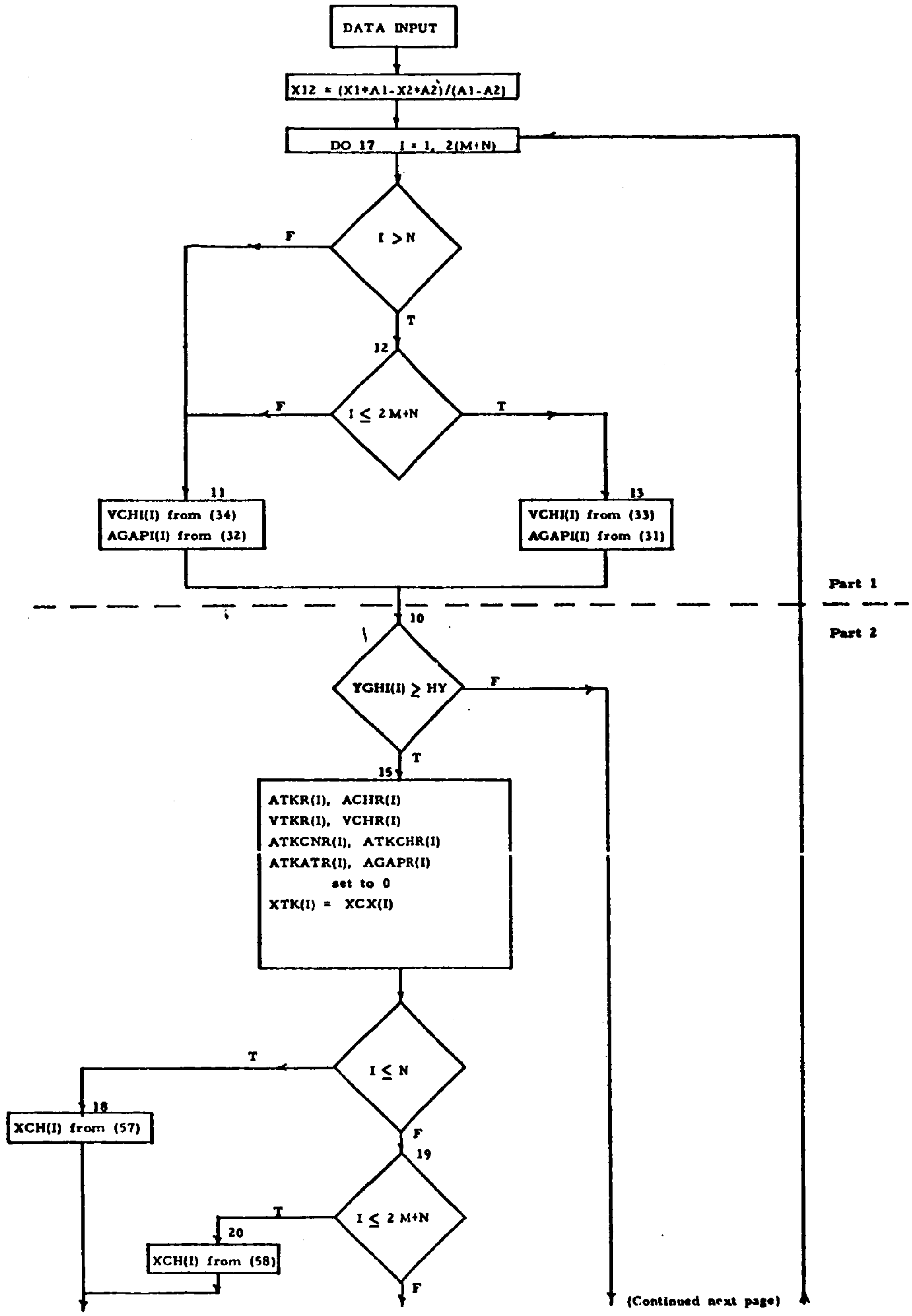


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Figure D. 3. Flow Diagram of SHAPE2

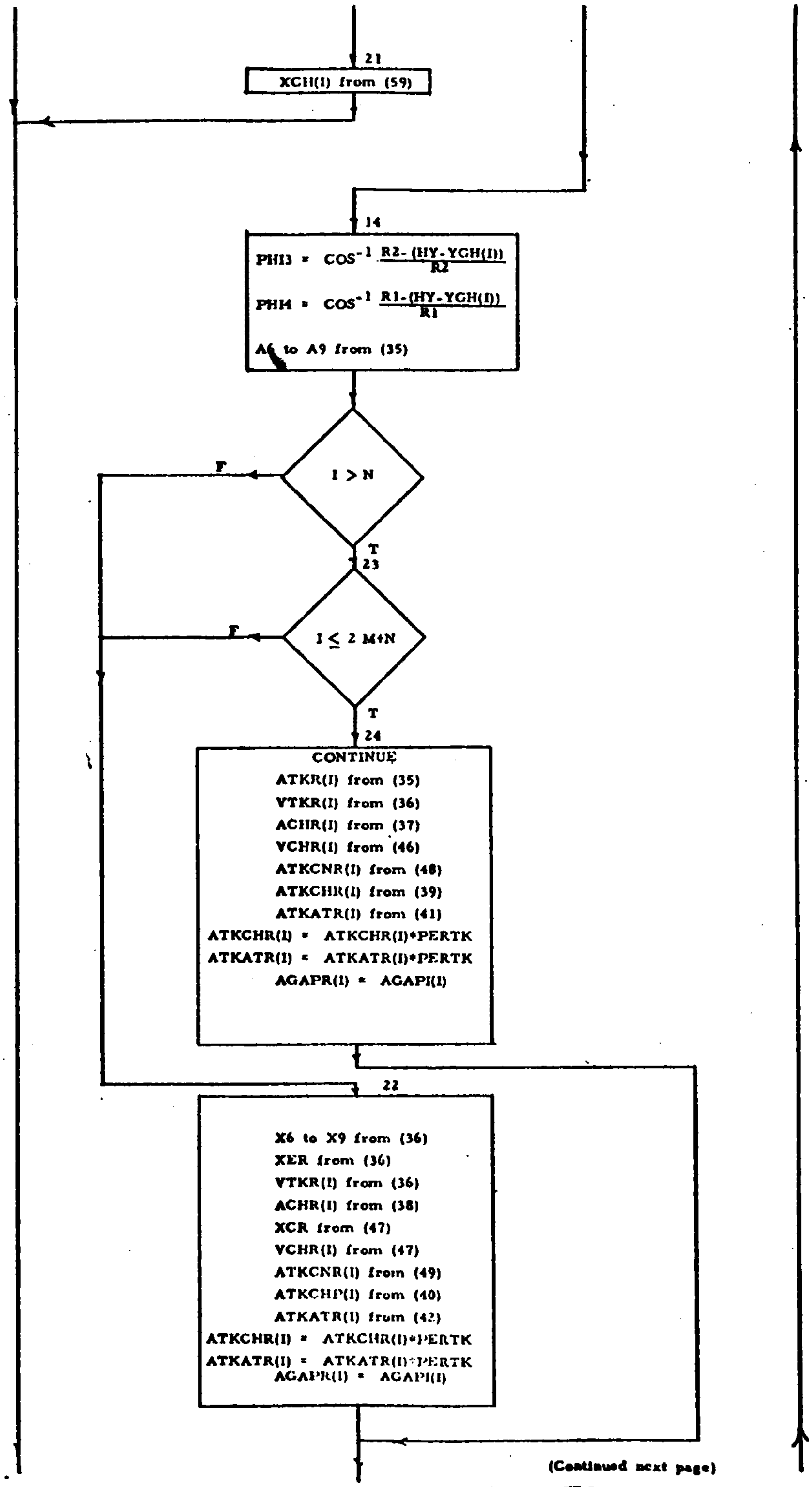

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Figure D. 3 (Continued). Flow Diagram of SHAPE2

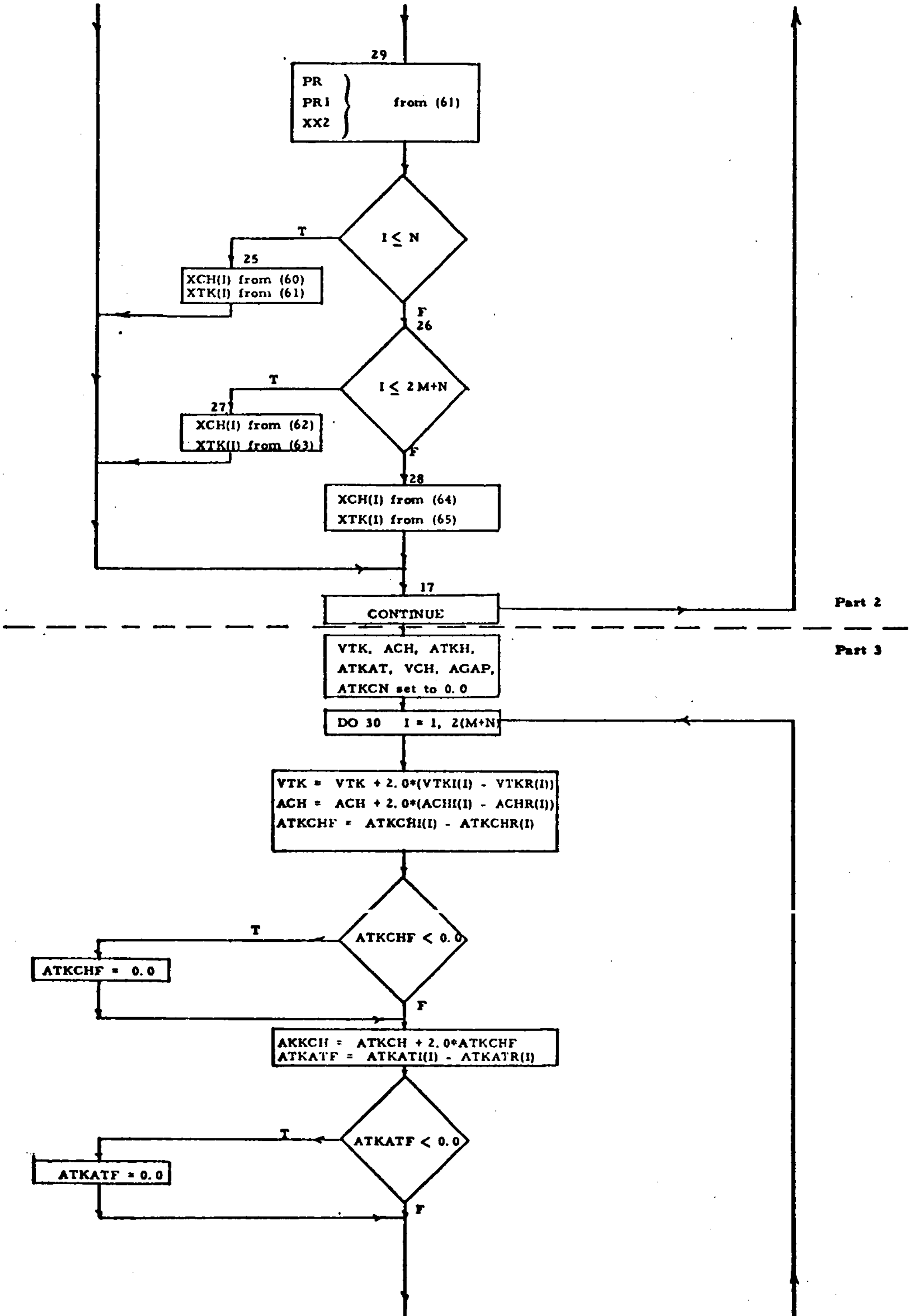

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Figure D.3 (Continued) Flow Diagram of SHAPE2

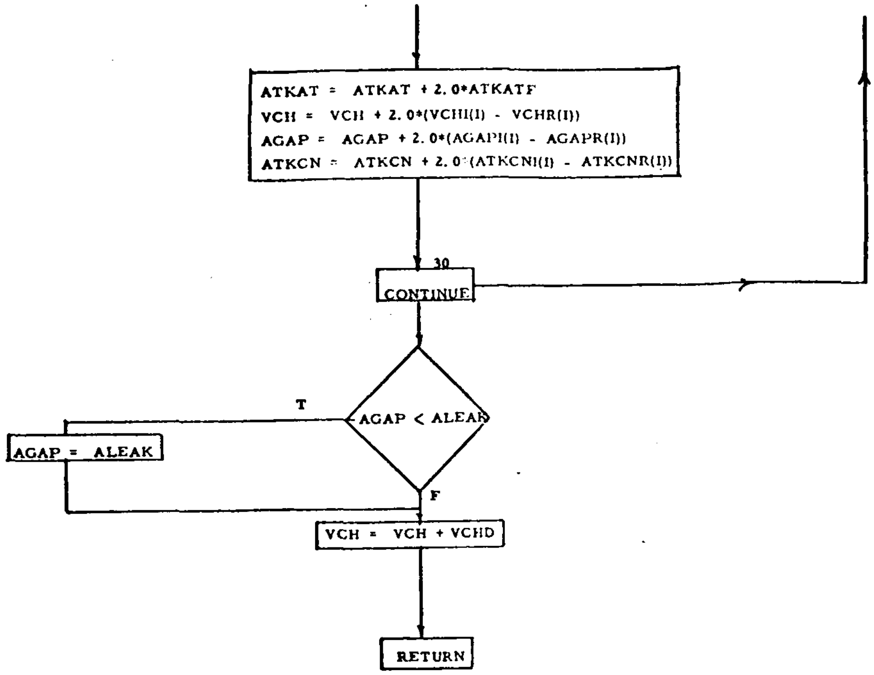

Figure D. 3 (Concluded). Flow Diagram of SHAPE2

D. 9 FORCE

The flow diagram of subroutine FORCE is shown in Figure D. 4. The following forces and torques are calculated in this subroutine.

(a) FORCN: The normal pressure force is obtained by multiplying the cushion pressure and the trunk pressure by the respective areas and taking the vertical component.

(b) TORN: The pressure force calculated for each segment is multiplied by the moment arm (i. e., the distance between the centers of pressure and the CG).

(c) FORCT: The r value of the contact area ATKCNR(I) is used to check whether ground contact for a particular segment has occurred. The trunk damping force is assumed to be equally divided amongst the trunk segments in contact. The damping force for each segment is calculated as shown in C. 3. 1. 1 (e).

(d) TORQT: Torque generated by FORCT is calculated by multiplying the individual segment damping force by the center of pressure moment arm.

(e) TORF: The contact friction torque is calculated by taking the product of the normal trunk pressure force, coefficient of trunk-ground friction, and vertical distance of the trunk contact zone from the CG. The variable TORQ is set equal to the sum of the torques TORN and TORF.

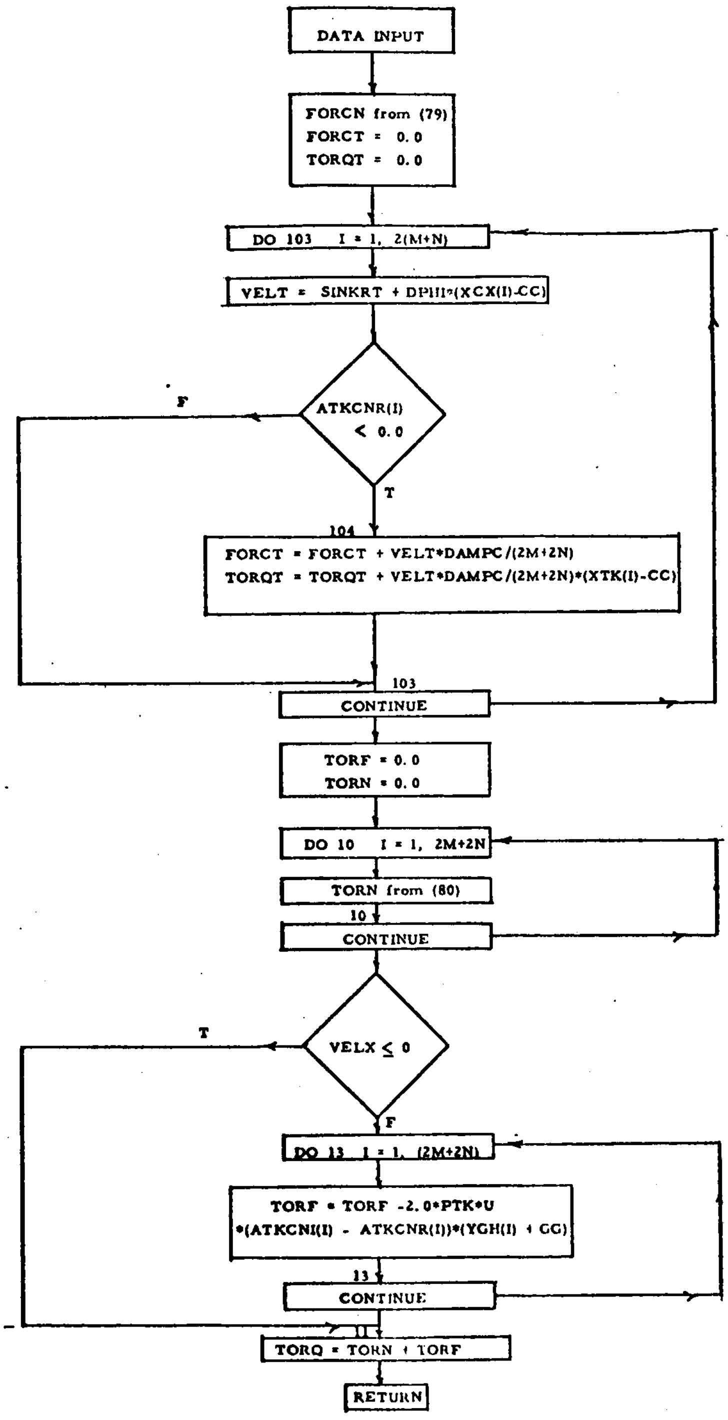

Figure D. 4. Flow Diagram of FORCE

D. 10 FLOW1

Subroutine FLOW1 calculates the static performance characteristics of the ACLS. The height of the CG above the ground (YCG), pitch angle (PHI), cushion-to-atmosphere gap area (AGAP), and plenum, trunk and cushion pressures and flows are calculated for a range of loads and load CG positions including specifically the user supplied aircraft weight and CG position.

D. 10. 1 Summary

The subroutine essentially consists of three nested iteration loops, as shown in Figure D. 5.

(i) Iteration 1: In Iteration 1, values of YCG and PHI are iterated until the ACLS load and torque equal (within a given tolerance) the aircraft weight and the static torque due to CG offset.

(ii) Iteration 2: This iteration determines the various pressures and flows associated with the fan, plenum, trunk and cushion. It iterates the value of PFAN until the air gap required to satisfy the orifice pressure-flow relations is within a given tolerance of the air gap calculated by geometry.

(iii) Iteration 3: This iteration is required (within Iteration 2) to determine the values of cushion pressure which satisfy the orifice pressure-flow relations.

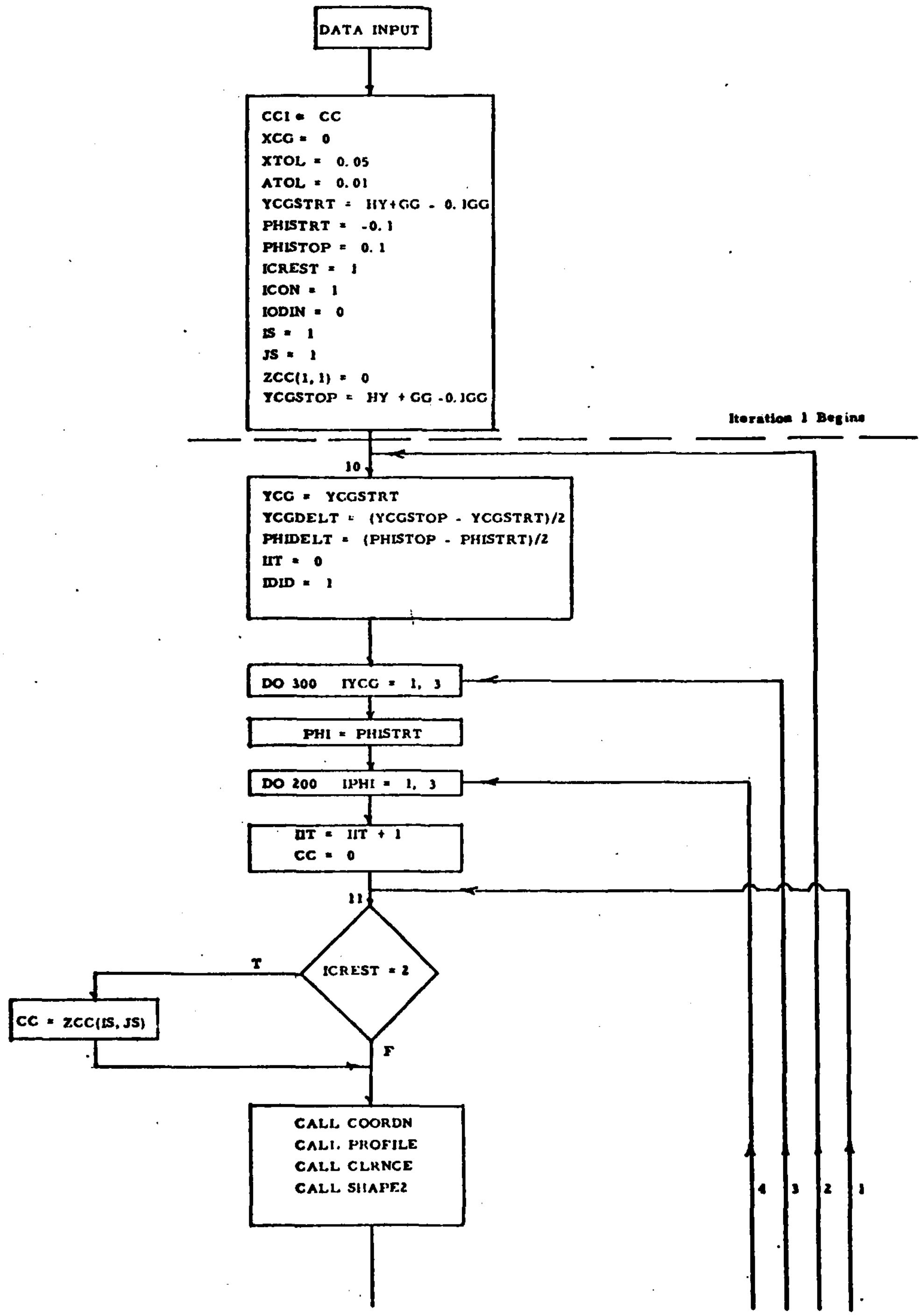

Figure D.5. Flow Diagram of FLOW1 (Continued next page)

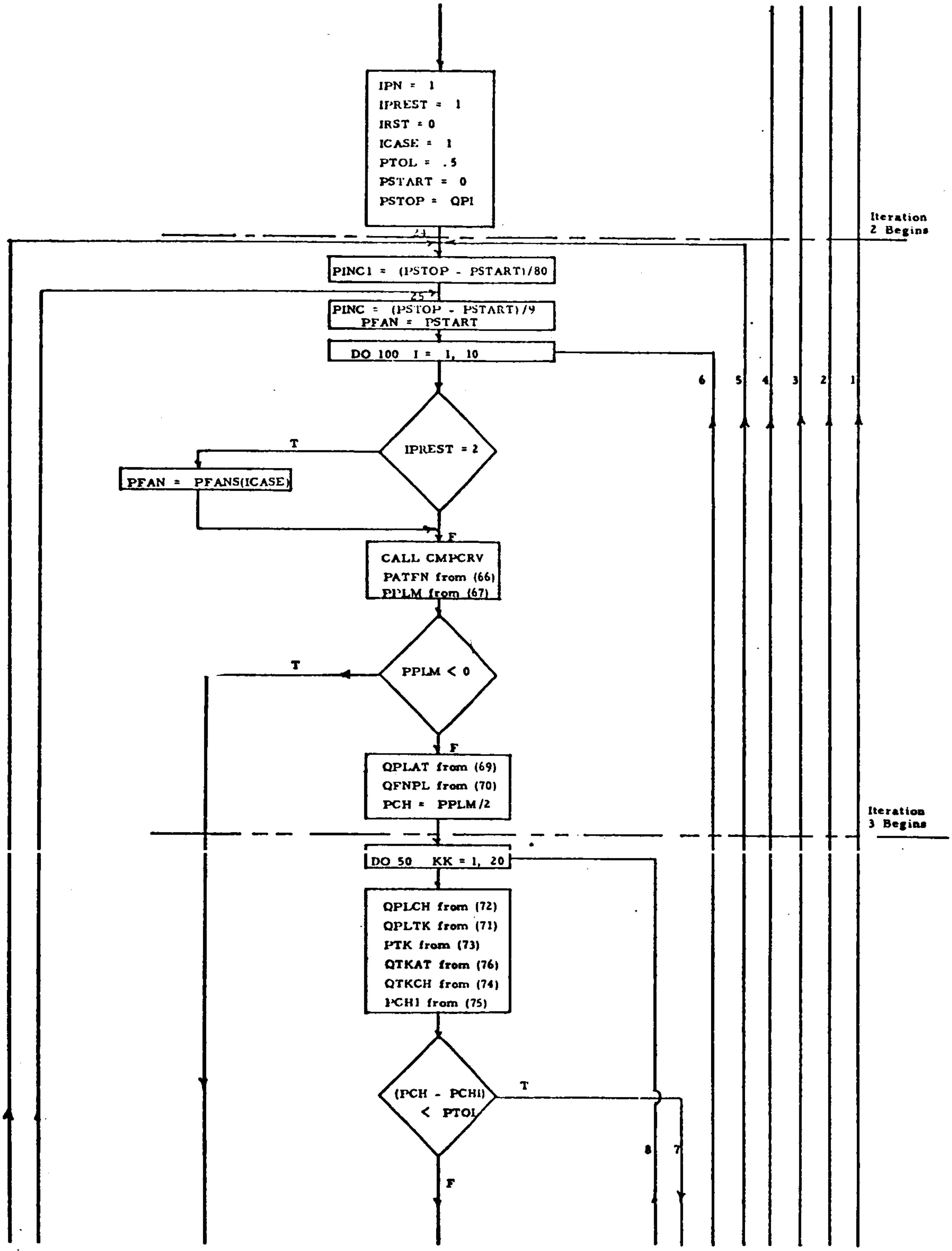

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Figure D.5 (Continued). Flow Diagram of FLOW1

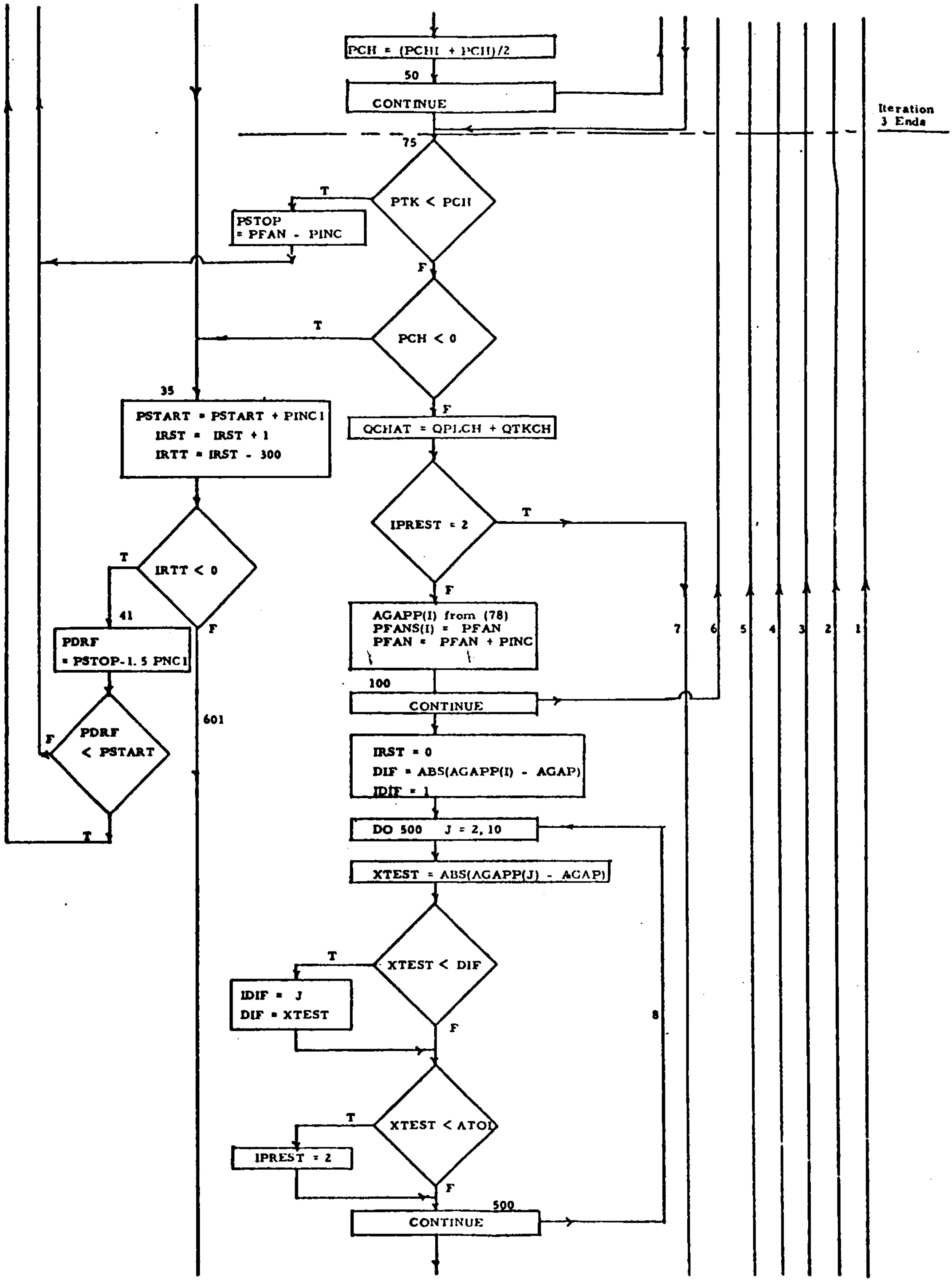

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Figure D. 5 (Continued). Flow Diagram of FLOW1

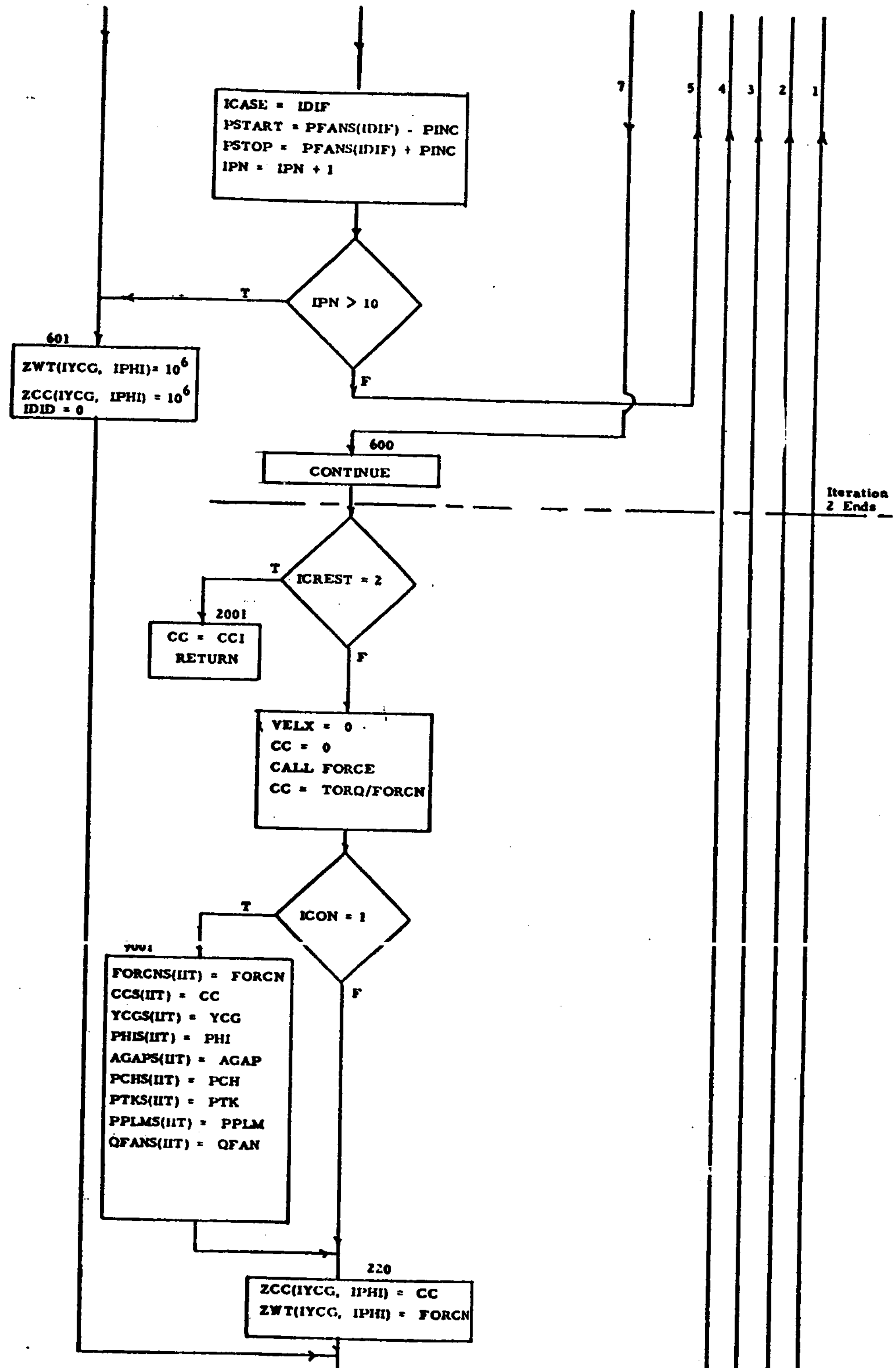

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Figure D.5 (Continued). Flow Diagram of FLOW1

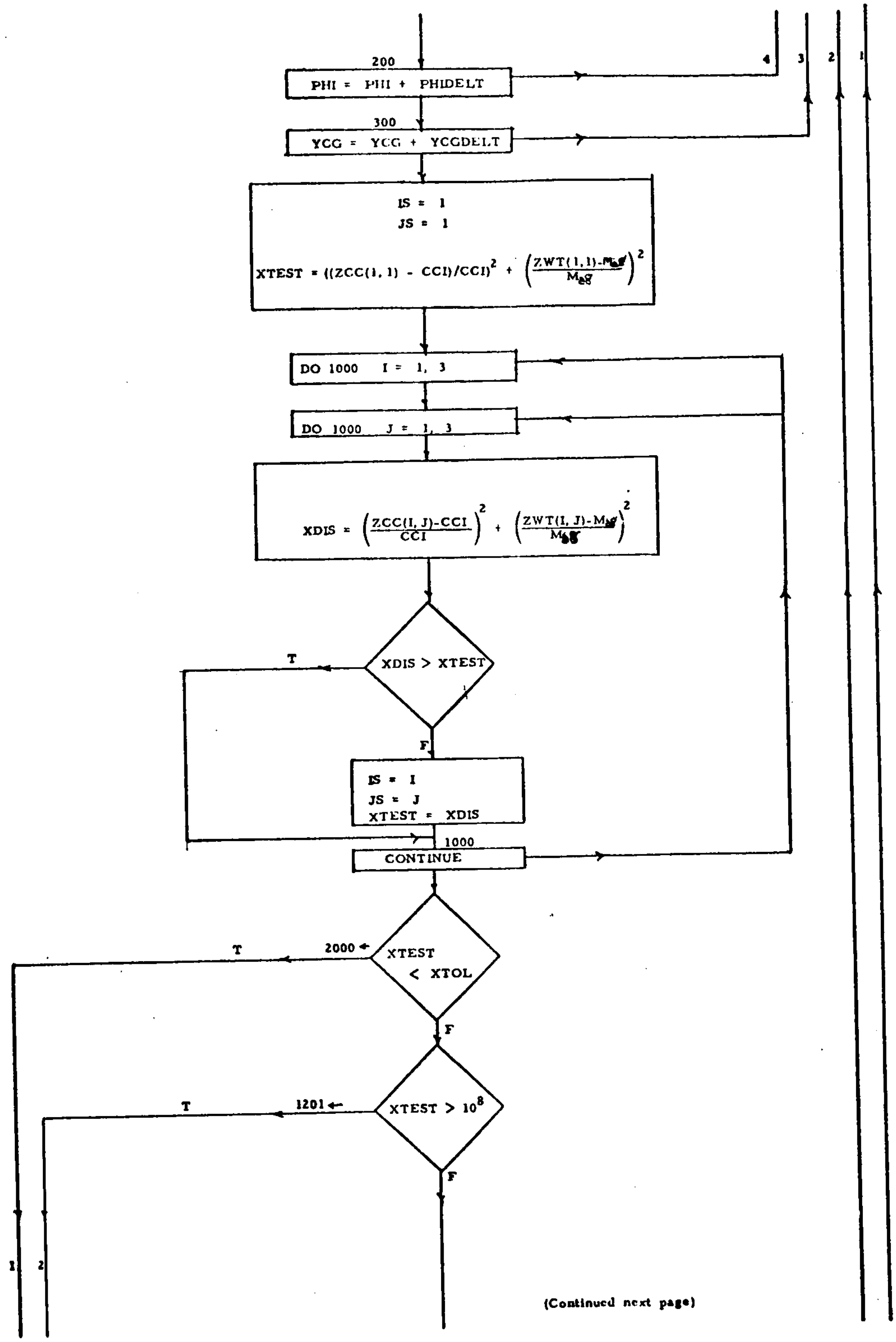

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Figure D. 5 (Continued). Flow Diagram of FLOW1

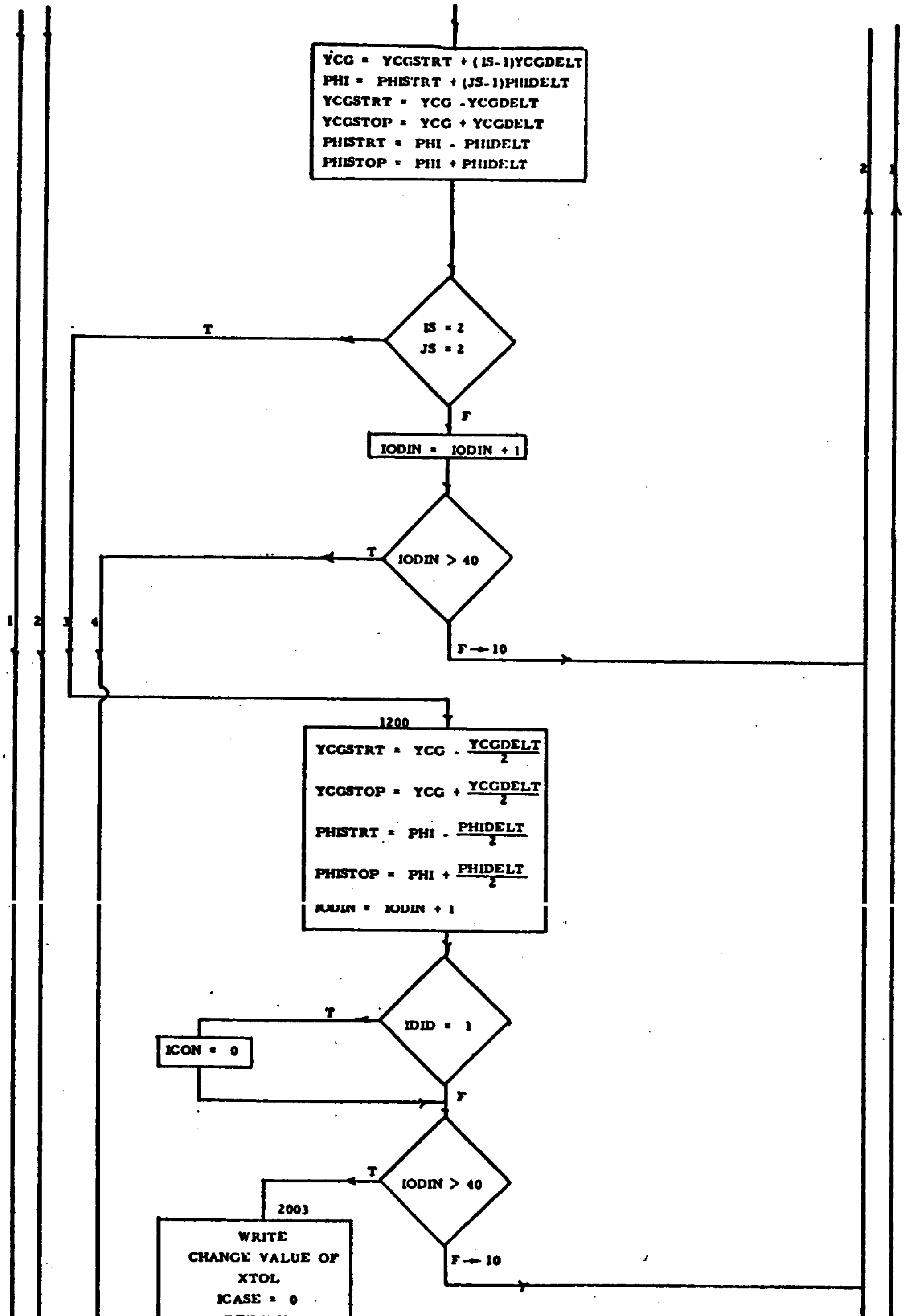

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Figure D. 5 (Continued). Flow Diagram of FLOW1

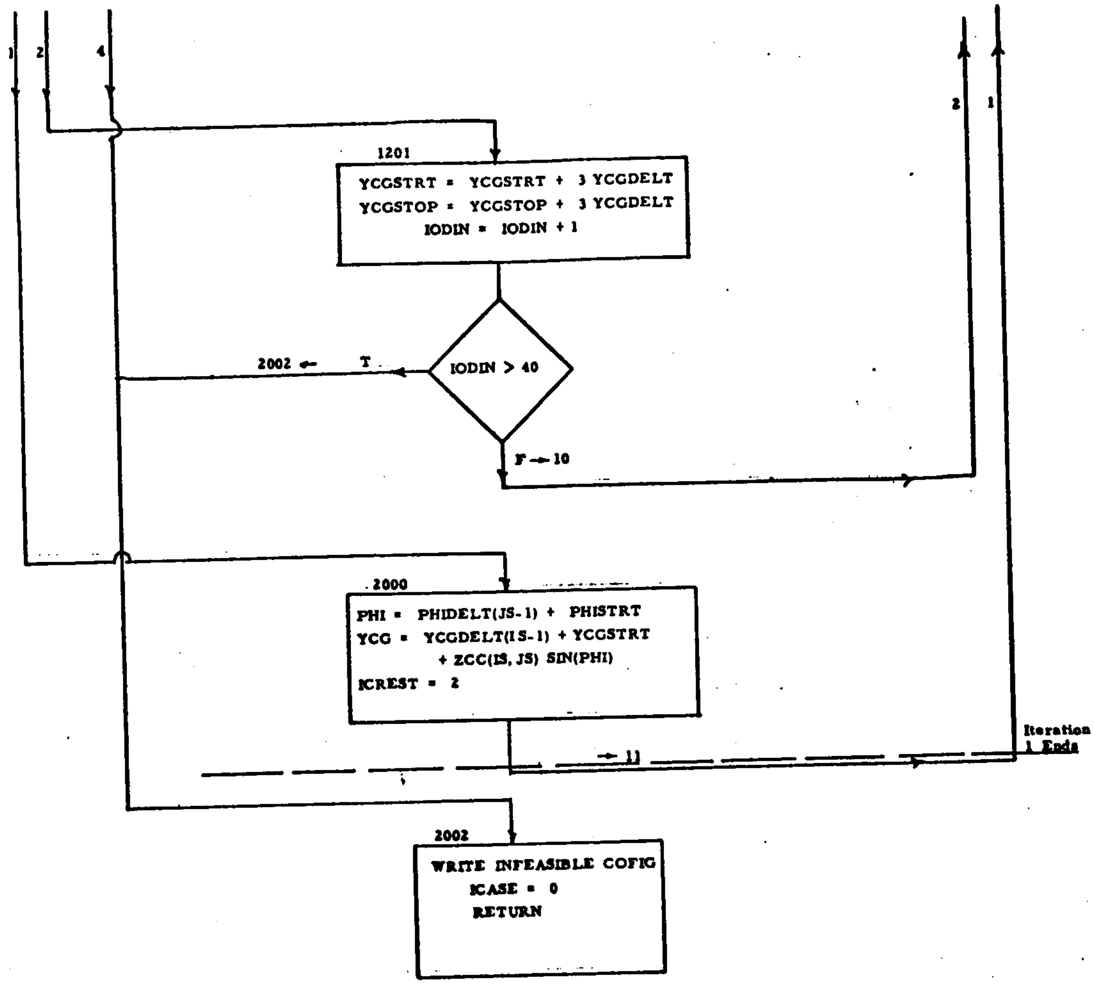


Figure D.5 (Concluded). Flow Diagram of FLOW1

The subroutine begins by assuming a grid of YCG, PHI values to initialize Iteration 1. The values of pressures and contact areas are calculated for the assumed values of YCG and PHI using Iterations 2 and 3. Subroutine FORCE is called next to determine the force and torque developed by the configuration under consideration. The CG offset corresponding to this torque is determined, and from this, a quadratic index of the difference between the ACLS force and aircraft weight, and the assumed and actual CG offset is formed. If the smallest quadratic index in the previous grid is larger than the acceptable tolerance value, a new grid of YCG and PHI is formed and the procedure is repeated. Otherwise, the iteration is terminated after the calculations are repeated once more to obtain the final equilibrium values. The values of the performance variables for an acceptable grid are stored along with the final equilibrium values and transferred to the Main Program for printout.

D. 10. 2 Details

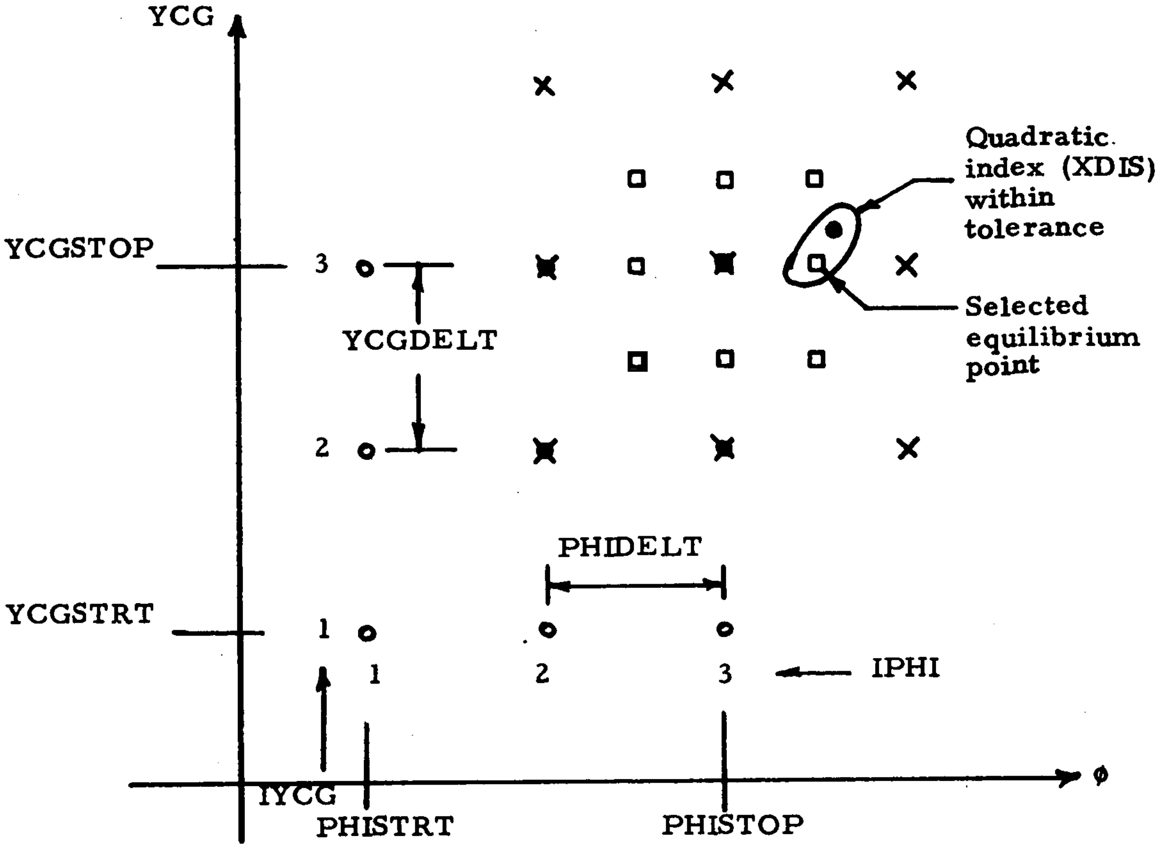
D. 10. 2. 1 Iteration 1

D. 10. 2. 1. 1 Initialization

The initial YCG, PHI grid is formed as shown in Figure D. 6. The first value of YCG in this grid (YCGSTRT) is chosen equal to (HY+GG-0. 1). The last value (YCGSTOP) is chosen equal to (HY+GG+0. 1). Similarly, PHISTRT = -0. 1 (radians) and PHISTOP = 0. 1. An initial grid of nine points is thus formed, as shown in Figure D. 6.

D. 10. 2. 1. 2 Calculations

Subroutines COORDN, PROFILE, CLRNCE and SHAPE2 are called to determine the various areas and volumes associated with a particular grid point. Iterations 2 and 3 are then used to determine the various pressures and flows through the ACLS. If the configuration under consideration does not generate a positive value of



o 1st grid

x 2nd grid

□ 3rd grid

● Equilibrium value

XDIS minimum for (3, 3) in 1st grid

XDIS minimum for (2, 2) in 2nd grid

XDIS minimum for (2, 3) in 3rd grid and < XTOL.

Figure D. 6.   Grid Generation for FLOW1 Iteration plenum or cushion pressure for any feasible point on the fan curve, it is considered infeasible and the computations are carried out for the next grid point. For all feasible grid points, the normal force FORCN and torque about the center of the cushion, TORQ, are determined. The distance of the CG from the center of the cushion, CC, is also calculated by dividing the torque by the force. FORCN and CC for a particular grid point are stored in two dimensional arrays, ZWT(IYCG, IPHI) and ZCC(IYCG, IPHI) respectively. For infeasible configurations, ZWT and ZCC are assigned a high value (= 10^6) for subsequent detection and elimination. The values of load, CC, YCG, PHI, AGAP, PCH, PTK and QFAN are also stored in arrays (static characteristics).

D. 10. 2. 1. 3 Grid Point Evaluation

After the arrays ZCC and ZWT are formed for all nine points of the grid, the points are tested to determine which point comes closest to the actual values of ACLS load and CG location (stored as CCI).

A quadratic index is formed to determine the proximity of the calculated grid point from the physical value.

$$XDIS = \left(\frac{ZWT(I, J) - MASS*32.2}{MASS*32.2}\right)^2 + \left(\frac{ZCC(I, J) - CCI}{CCI}\right)^2$$

Calculation of XDIS is carried out for all the feasible grid points. From this, the minimum value of XDIS, corresponding to a particular grid point, designated (IS, JS), is set equal to XTEST. If XTEST is within the iteration tolerance limit XTOL, the grid point (IS, JS) is taken as the equilibrium solution, and ICREST is assigned a value 2. The calculations are then repeated once more to determine updated values of YCG and PHI corresponding to the grid point (IS, JS), and the iteration is terminated. The values of YCG and PHI so found are returned to the Main Program.

If, however, XTEST > XTOL, a new grid is formed by observing the following rules.

(a) If grid point (IS, JS) is not the midpoint, as in Grid 1 (Fig. D.6), the grid is moved such that it does become a midpoint, as shown in Grid 2.

(b) If the grid point (IS, JS) is the midpoint, the new grid is shrunk in size, so that each side is half that of the original grid and the midpoint remains unchanged. The transfer from Grid 2 to Grid 3 in Figure D.6 illustrates this situation.

(c) If none of the points in the original grid is feasible, a new grid is formed with higher values of YCGSTRT and YCGSTOP, but without changing the values of PHI.

The procedure is then repeated as before until XDIS < XTOL. If after 40 iterations a solution cannot be found, the program terminates with an error message.

D.10.2.2 Iterations 2 and 3

Iterations 2 and 3 find the value of PFAN such that the cushion-to-atmosphere gap area satisfying the orifice pressure-flow relations is equal (within a given tolerance) to the gap area generated by SHAPE2 in Iteration 1.

The procedure is as follows.

(a) Initially, two fan pressure rise increment values PINC and PINC1 are defined. PINC1 is used to converge rapidly to the first feasible configuration, starting from PFAN = 0. Thereafter, PINC is used to determine the static characteristics for 10 values of PFAN.

(b) QFAN is found from PFAN by calling subroutine CMPCRV (fan characteristics).

(c) PATFN is determined from Equation (66).

(d) PPLM is found from Equation (67). The value of PPLM is checked. If it is negative, the configuration is infeasible, PSTART is assumed to be PSTART + PINC1 and the process is restarted.

(e) QPLAT is found using Equation (69).

(f) QFNPL is found using Equation (70).

Iteration 3 is set up next to evaluate PCH. This is summarized in steps (g) through (n).

(g) Initially PCH is assumed to be equal to PPLM/2.

(h) QPLCH is found using Equation (72).

(i) QPLTK is found using Equation (71).

(j) PTK is found using Equation (73).

(k) QTKAT is found using Equation (76).

(l) QTKCH is found from Equation (74).

(m) PCHI is determined from Equation (75).

(n) PCHI found in (m) is compared with initially guessed PCH. If the difference is less than PTOL, the iteration is assumed to be complete. Otherwise, a new value of $PCH = \frac{PCH+PCHI}{2}$ is assumed and the process repeated from step (h).

(o) If PCH is found to be negative, PSTART is assumed to be equal to PSTART + PINC1 and the process repeated from the beginning (Step (a)).

(i) In case the new value of PSTART is just one step from PSTOP, a new value of PINC1 is defined as $\frac{\text{PSTOP-PSTART (final)}}{80}$, so that the search for feasible configurations can be continued all the way to PSTOP.

(ii) If a feasible configuration is not found within the full flow range of the fan, the calculations are performed for the next grid point.

(p) If PCH > PTK, a new value of PSTOP is found, PSTOP = PFAN-PINC, and the procedure is repeated from the beginning (Step (a)).

(q) QCHAT is found using Equation (77).

(r) AGAPP(I) is found using Equation (78).

(s) PFAN is stored as PFANS(I).

The above procedure is repeated until 10 values of AGAPP(I) corresponding to 10 values of PFAN are found. Then the iteration value of AGAPP closest to the value of AGAP generated by SHAPE2 is found. This value is designated as AGAPP(IDIF). If the difference between these values is less than ATOL, the iteration is complete; and updated values for the pressures, flows, and areas are calculated for the fan pressure value, PFAN(IDIF). If, however, |AGAPP(IDIF)-AGAP| > ATOL, new values of PFAN are chosen and the iteration is repeated from Step (a). The new initial value is set equal to PFANS(IDIF-1), and the new final value is set equal to PFANS(IDIF+1). If, after 10 attempts, the iteration has not converged, the grid point in question is considered infeasible, and the calculations are then carried out for the next grid point.

D.11 DYSYS

Subroutine DYSYS, shown in Figure D.7, coordinates the dynamic simulation and calls the various subroutines. Initially, DYSYS calls STEQU to set up initial values of the derivatives of the state variables. Then it calls RKDIF to get new values of the variables at the next time step. The values are printed after every MM (user supplied) time steps.

DYSYS also carries out the following steps:

(a) It determines the values of DVCH, DVTK, VELX and XCG.

(b) It sets the value of the fan control parameter IFAN. This parameter is used by the fan subroutine CMPCRV to select the appropriate fan characteristic (IFAN = 0, unstalled operation; IFAN = 1, stalled operation). IFAN is set as follows

$$QFAN < QP5 \quad ; \quad IFAN = 1$$
$$QFAN > QP3 \quad ; \quad IFAN = 0$$

(c) It sets the trunk inflation parameter IPCT, which determines whether the cushion and trunk behave as two connected chambers or as a single independent chamber (See Appendix C). When PCH > PTK, the trunk membrane moves to equalize the trunk and cushion pressures. Thus for PCH > PTK, IPCT is set equal to zero and the computation is carried out (in STEQU) by considering a single chamber for the (combined) trunk and cushion. When PCH $\leq$ PTK, the trunk remains in its normal inflated shape. In this case, IPCT = 1.

D.12 RKDIF

RKDIF is the numerical integration subroutine which calculates the values of the state variables at time t+dt, given the values at time t, using a 4th order Runge Kutta method. The integration scheme is summarized below.

(a) The iteration procedure starts with the values of the state variables y_1, y_2, etc., at time t.

$y_i(t) \qquad i = 1, n$

(b) The slopes $Dy_i(t)$ are then determined from $y_i(t)$ by calling STEQU.

$Dy_i(t) = dy_i(t)/dt$

(c) The values y_{i1} at time $t + \frac{dt}{2}$ are then determined,

$y_{i1} = y_i + Dy_i \cdot dt/2$

(d) The slopes $Dy_{i1}(t + dt/2)$ are then determined by calling STEQU and using the values of y_{i1} found in (c) above.

(e) The values y_{i2} at time $t + dt/2$ are then determined

$y_{i2} = y_i + Dy_{i1} \cdot dt/2$

(f) The slopes Dy_{i2} $(t + dt/2)$ are then determined from STEQU using the values of y_{i2} found in (e) above.

(g) The values y_{i3} at time $t + dt$ are then determined

$y_{i3} = y_i + D_{yi2} \cdot dt$

(h) The slopes Dy_{i3} at time t + dt are then determined from STEQU using the values of y_{i3} found in (g) above.

(i) Finally, the values of the state variables at time t + dt are found as follows

$$y_i(t+dt) = y_i(t) + (Dy_i + 2Dy_{i1} + 2Dy_{i2} + Dy_{i3})\ dt/6$$

During each integration step (i.e., to advance from t to t + dt), STEQU is needed four times to determine the slopes (b, d, f, g above). The fifth call for STEQU in DYSYS is to check whether PCH exceeds PTK.

D. 13 STEQU

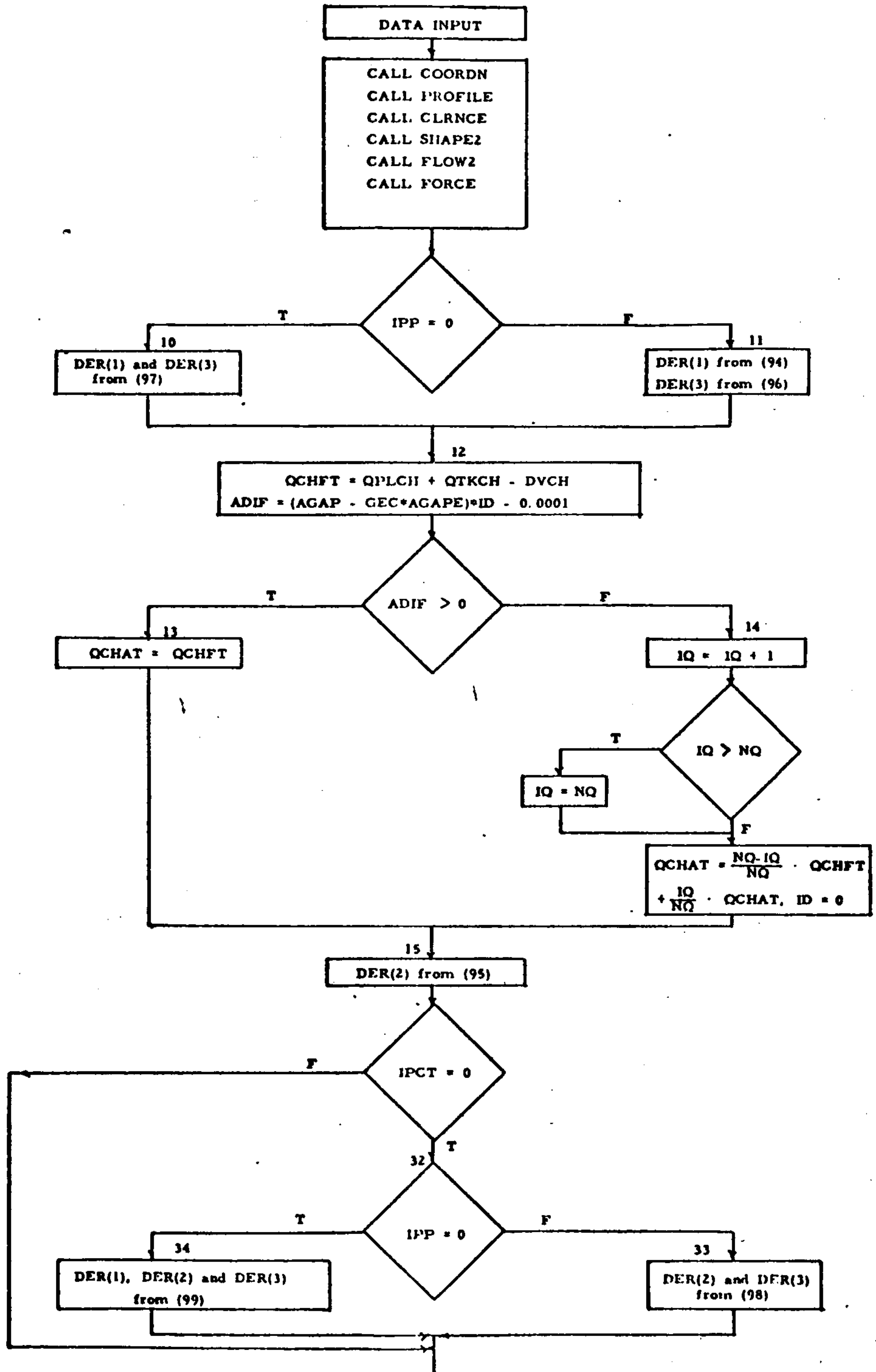
The flow diagram for subroutine STEQU is shown in Figure D. 8. STEQU determines the values of the derivatives of the state variables by substituting the state variables in the state equations. Besides the seven state variables, PPLM, PCH, PTK, YCG, SINKRT, PHI and DPHI, the state equations need values of other variables (such as flows, forces, torques, areas and volumes) which are determined from the state variables.

The areas and volumes for the given state variables are obtained by calling subroutines COORDN, PROFILE, CLRNCE and SHAPE2. The flows are obtained from subroutine FLOW2 and the forces and torques from subroutine FORCE.

The appropriate dynamic equations are chosen depending on which one of the five conditions below prevails.

(a) Normal operation, Equations (94), (95) and (96).

(b) When the pressure drop across the trunk orifice is negligible ($< 2\%$), Equations (94) and (96) are replaced by Equation (97).



(Continued next page)

Figure D. 8. Flow Diagram of STEQU

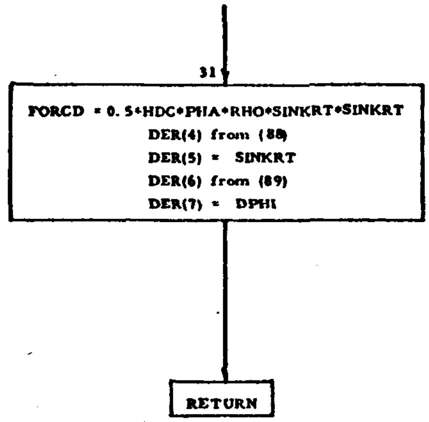


Figure D.8 (Concluded). Flow Diagram of STEQU

(c) ACLS above ground effect zone - i.e., PCH = 0, and DER(2) = $dP_{ch}/dt = 0$. (Right hand side of Equation (95) set equal to zero.) When the cushion enters the ground effect zone, the above constraints on cushion pressure are removed, and dP_{ch}/dt is changed in NQ steps from zero to the value found from Equation (95).

(d) When PCH > PTK, the cushion and trunk are combined, and the value of IPCT is set to 0 in DYSYS. For IPCT = 0, Equations (95) and (96) are replaced by Equation (98).

(e) If both conditions (b) and (d) exist simultaneously, the plenum, trunk and cushion are combined and Equations (94), (95) and (96) are replaced by (99).

Forces and torques due to aerodynamic drag are also calculated in STEQU and included in the respective state equations.

D. 14 FLOW2

Subroutine FLOW2 calculates the flows through the various orifices from the pressures (PCH, PTK, PPLM) and the cushion-to-atmosphere gap area (AGAP), as shown in Figure D. 9. The subroutine solves the 10 pressure-flow equations, Equations (66) through (70), (72), (73), (75), (76) and (78) for the 10 unknowns, QFAN, QPLAT, QFNPL, QPLCH, QPLTK, QTKAT, QTKCH, QCHAT, PATFN and PFAN. The solution procedure is as follows:

(a) QPLTK is calculated from Equation (73).

(b) QPLCH is calculated from Equation (72).

(c) QTKCH is calculated from Equation (75).

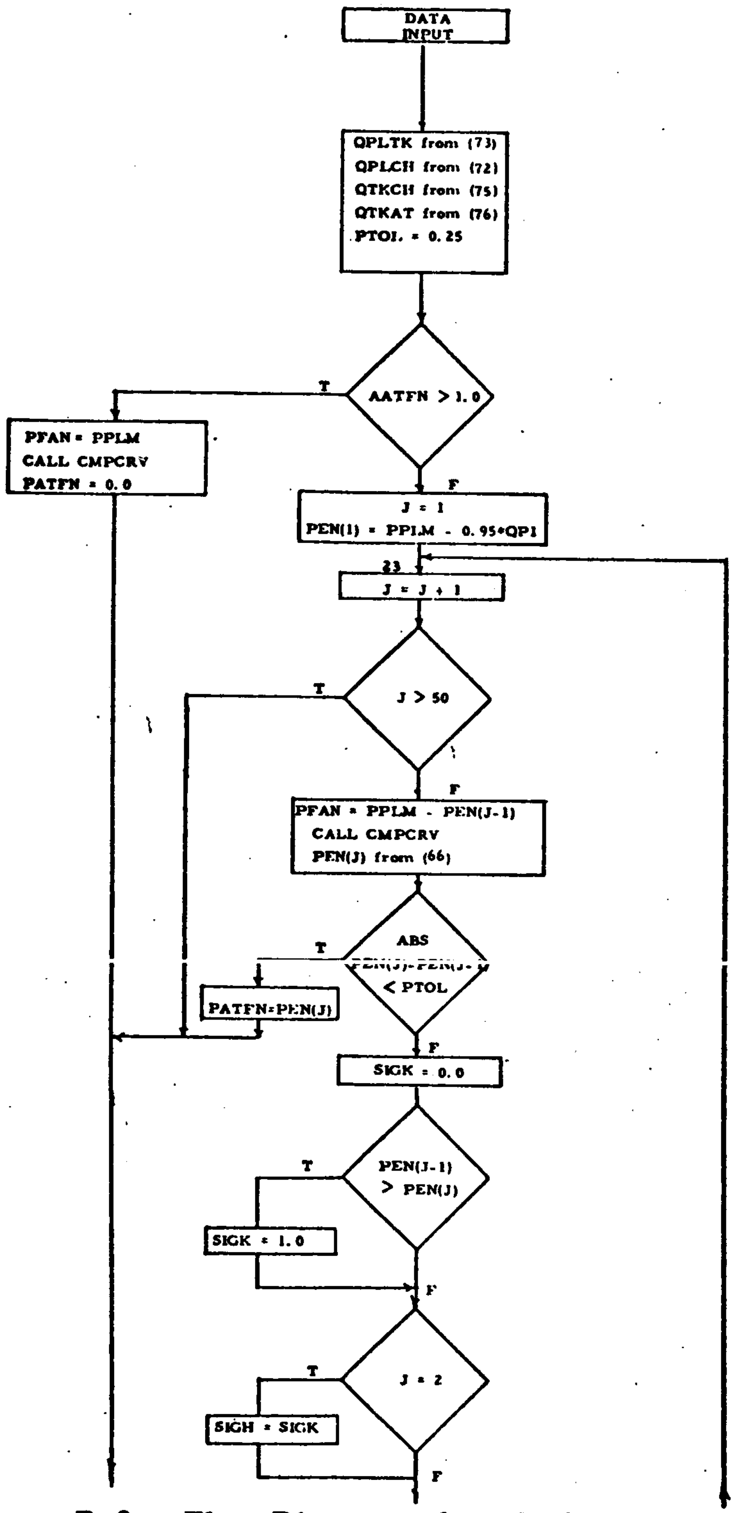


Figure D. 9. Flow Diagram of FLOW2

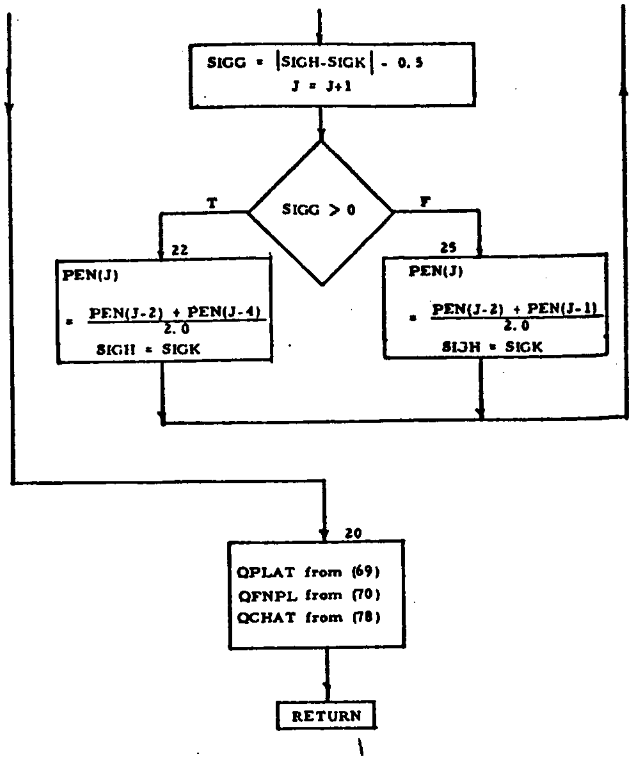


Figure D.9 (Concluded). Flow Diagram of FLOW2

(d) QTKAT is calculated from Equation (76).

(e) If the upstream orifice drop is not included in the model (i.e., AATFN > 1 sq ft), PATFN = 0, PFAN = PPLM, and QFAN is determined from the fan subroutine CMPCPV. If the upstream resistance is included (AATFN $\leq$ 1 ft^2), an iteration is carried out to determine PATFN, as described in steps (f) through (i) below.

(f) An initial value of PFAN is chosen and represented by the variable PEN(J).

(g) PFAN is determined from Equation (67).

(h) QFAN is determined from the fan subroutine CMPCRV.

(i) A new value of PEN, PEN(J+1), is found using Equation (66). If the difference between PEN(J) and PEN(J+1) is less than PTOL, PATFN is set equal to PEN(J+1). Otherwise a new value, PEN(J+2) is determined and the procedure repeated from step (h). The new value PEN(J+2) is selected as $\frac{PEN(J)+PEN(J+1)}{2}$, if the sign of PEN(J)-PEN(J+1) is the same as the sign of PEN(J-2)-PEN(J-1). Otherwise PEN(J+2) is selected as $\frac{PEN(J)+PEN(J-2)}{2}$. This iteration scheme was chosen to bring about rapid convergence.

(j) QPLAT is determined from Equation (69).

(k) QFNPL is determined from Equation (70).

(l) QCHAT is determined from Equation (78).

D. 15 CMPCRV

Subroutine CMPCRV determines the fan flow (QFAN) for a given fan pressure rise (PFAN).

The fan characteristics (see Figure 7) consist of two curves - the unstalled characteristic and a stalled characteristic. Both curves have been expressed in terms of 4th order polynomials. The polynomial coefficients and the pressures and flows indicating the curve limits of Figure 7 are supplied by the user.

The region of operation is determined by QFAN. If QFAN is calculated to be less than QP5, IFAN is set equal to 1 and the fan operates in stall. If QFAN is more than QP3, IFAN is set to 0 and the fan operates in the unstalled region. If QFAN lies between QP3 and QP5, IFAN is set equal to its previous value, and the fan continues to operate in the stall or unstalled region, depending on the region in which it was operating previously. IFAN is determined in DYSYS and is transferred to CMPCRV through COMMON.

APPENDIX E - PROGRAM LISTING

RUN VERSION 2.3 --PSRL LEVEL 373--   08/05/74

```
              PROGRAM FMA2 (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
        C
        C ****************************************************************
        C
        C  ACLS  VARIABLE NAME (SYMBOL) NOMENCLATURE
        C
        C COMPRESSOR (FAN) CURVE COEFFIC
        C AL0 AL1 AL2 AL3 AL4 B0 B1 B2 B3 B4 QP1 QP2 QP3 QP4
        C
        C PRESSURE AND FLOW VARIABLES
        C  QFAN  - TOTAL FAN FLOW CF/S           PFAN - FAN PRESSURE RISE PSF
        C  QPLTK - FLOW PLENUM TO TRUNK CF/S     PPLM - PLENUM PRESSURE  PSFG
        C  QPLCM - FLOW PLENUM TO CUSHION CF/S   PTK - TRUNK PRESSURE  PSFG
        C  QTKCM - FLOW TRUNK TO CUSHION CF/S    PCM - CUSHION PRESSURE  PSFG
        C  QTKAT - FLOW TRUNK-ATMOS CF/S         PAT - ATMOS PRESSURE  PSF
        C  QCMAT - FLOW CUSHION - ATMOS CF/S     PAIFN - FAN INLET PRESSURE
        C  QPLAT - FLOW PLENUM - ATMOS CF/S
        C
        C GEOMETRIC VARIABLES
        C  YGH(I) - ITH SEGMENT CLEARANCE FT     HY - TRUNK HEIGHT FT
        C  LS - STREIGHT PART OF ACLS FT         D - DIST BETWN TRUNK ATT PNTS FT
        C  A - X CORD OF OUTER ATT PNT FT        B - Y CORD OF OUTER ATT PNT FT
        C  L - LENGTH OF TRUNK PERIMETER FT      LP - DIST TO FIRST ROW HOLES  FT
        C  SH - SEPARATION OF HOLE ROWS  FT      AH - AREA OF HOLES  SQ FT
        C  NR - NUMBER OF ROWS OF HOLES          NH - NUMBER OF HOLES PER ROW
        C
        C AREA AND VOLUME VARIABLES
        C  APLTK - AREA PLENUM -TRUNK  SQFT      VPLM - VOLUME OF PLENUM  CUFT
        C  APLCM - AREA PLENUM - CUSHION  SQFT   VCM - VOLUME OF CUSHION  CUFT
        C  ATKAT - AREA TRUNK TO ATMOS  SQFT     VTK - VOLUME OF TRUNK  CUFT
        C  ATKCM - AREA TRUNK-CUSHION  SQFT      DVCM,DVTK - DERIVATIVES OF ABOVE
        C  ACM - AREA OF CUSHION  SQ FT          ATKCN - AREA OF TRUNK-GRND CONTACT  SQ FT
        C  ATK - AREA OF TRUNK XSECT  SQ FT      AGAP - AREA OF CUSHION AIF GAP SQ FT
        C  APLAT - AREA PLENUM TO ATMOS SQ FT    AATFN - AREA FAN INLET SQ FT
        C
        C ORIENTATION VARIABLES
        C YCG - Y COORDN OF CG  FT              SINKRT - VERTICAL VELOCITY FT/SEC
        C  XCG - X COORDN OF CG FT               VELX - HORIZONTAL VELOCITY FT/SEC
        C  PHI - PITCH ANGLE RADIANS             DPHI - ROTATIONAL VELOCITY  RADIANS/SEC
        C
        C ****************************************************************
        C
000003        REAL L,L1,L2,LS,LP,MASS,INERT
        C
        C DIMENSION MAIN STORAGE ARRAYS
        C      COMMON SPECIFICATIONS
        C
000003        COMMON/PARA/PERIK,ALEAK,AGAPE
000003        COMMON/AREA/AATFN,APLAT,APLCM,APLTK,ATKAT,ATKCM,AGAP,ATK,ACM,
             1 ATKCN,VCH,VTK,VPLM,VCMD
000003        COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NH,AH,NR,PHI1,PHI2,S
             1,A1,A2,X1,X2,R1,R2,L1,L2
000003        COMMON/COMPRS/AL0,AL1,AL2,AL3,AL4,B0,B1,B2,B3,B4,QP1,QP2,QP3,QP4
             1,QP5,IFAN
```

```
000003      COMMON/SPACE/XCX(100),XH(100),YH(100),Y0(100),Y0H(100),XCH(100),
           2 XTK(100),XCC,YCC,CC,GG,BETA,XC3,DELX
000003      COMMON/SHAPE/VCHI(100),VCHR(100),AGAPI(100),AGAPR(100),ATKR(100),
           1 ATKI(100),ATKCHI(100),ATKATR(100),ATKATI(100),ATKCNI(100),
           2 ATKCNR(100),VTKI(100),VTKR(100),ACHI(100),ACHR(100),ATKCHR(100)
000003      COMMON/FLUID/QFAN,QPLAT,QPLCH,QPLTK,QTKAT,QTKCH,QCHAT,PATFN,PFAN,PAT
           1AT
      C STATE VARIABLES
000003      COMMON/STATE/PPLM,PCH,PTK,SINKHT,YCG,DPHI,PHI
      C DYNAMIC PARAMETERS
000003      COMMON/DYNAMIC/TIME,DTIME,PTIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
           1,IO,IN,NQ,IPCT,MDC,PHA,GEC
000003      COMMON/JUNK/INERT,     VELXI,YCGI,ACGI,PHII,VELX
000003      COMMON/ICLN/ICLN
      C FAN CHARACTERISTICS
      C STATIC CHARACTERISTICS ARRAY
000003      COMMON/LOADS/FORCNS(20),CCS(20),YCGS(20),PHIS(20),AGAPS(20),
           1PCHS(20),PTKS(20),QFANS(20),PFANS(20),PPLMS(20)
000003      COMMON/COEFFS/CPA,CAF,CPC,CPT,CTC,CGAP,CTA,CKK
000003      COMMON/BLOCK/RHO,MASS,DVCH,DVTK,TEMPAT,LABEL(80),TORQ,FORCN
           1,FORCT,TORQT
      C
      C ************************************************************
      C DATA ACQUISITION
      C
000003      DATA CPA,CAF,CPC,CPT,CTC,CGAP,CTA/0.6,1.,.6,.9,.9,1.,.9/
000003      CALL PROGIO
000004      U=6.4
000005      DECCL=15.0
000007      CKK=1.4
000010      GEC=10.
000012      PERCH=0.15
000013      PERTK=0.85
000015      ZETA=0.0555
000016      ICASE=1
000017      IFAN=0
000020      ISHAPE=1
      C ************************************************************
      C DATA CONVERSION SECTION
      C CONVERT DATA TO PROPER UNITS
000021      PHII=PHII*3.14159/180.
000023      DPHI=DPHI*3.14159/180.
000024       AH=AH/144.0
000026       MASS=MASS/32.2
000027       RHO=1.241/(460.0+TEMPAT)
000032      PAT=PAT*144.
      C ************************************************************
      C CLEAR STATIC OUTPUT ARRAYS TO 0.0
000034      DO 9 I=1,20
000036      FORCNS(I)=0.
000037      CCS(I)=0.
000040      YCGS(I)=0.
000041      PHIS(I)=0.
000042      AGAPS(I)=0.
000043      PCHS(I)=0.
```

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RUN VERSION 2.3 --MSRL LEVEL 373--                    FMA2                              08/05/70
000044          PTKS(I)=0.
000045          PPLMS(I)=0.
000046          OFANS(I)=0.
000047    9     CONTINUE
          C **************************************************************
          C INITIAL GEOMETRY CALCULATIONS
000051          CALL TRUNK(ISHAPE)
000052          IF(ISHAPE.EQ.0) GO TO 199
          C DIVISION OF TRUNK IN TO SEGMENTS
000053           CALL SEGMNT
          C INITIAL ASSESSMENT OF AREAS + VOLUMES
000054          CALL SHAPE1
          C
          C *****************************************************************************
          C                          STATIC PART OF THE PROGRAM
          C *****************************************************************************
          C *****************************************************************************
          C
          C
          C DETERMINE STATIC CHARACTERISTICS
          C
000055          ALEAK=0.
000056           ICON=1
000057          CALL FLOW1(ICASE)
000061           IF(ICASE.EQ.0) GO TO 199
          C
          C PARAMETER CALCULATION
          C
000062          HP=VFAN*PFAN/550.
000064          SC=ABS(PFAN    -QP1)/QP1*100.
000070          ALEAK=AGAP*PERCH
000072          STIFPHI=ABS(FORCNS(6)*CCS(6)-FORCNS(4)*CCS(4))/ABS(PHIS(6)-PHIS(4)
               1)*3.14159/18 .
000103          STIFYCG=ABS(FORCNS(8)-FORCNS(2))/ABS(YCGS(8)-YCGS(2))/12.
000113          DAMPC=2.*ZETA*SQRT(STIFYCG*12.*MASS)
          C
          C WRITE FINAL EQUILIBRIUM CONDITIONS AND STATIC CHARACTERISTICS
          C OBTAINED FROM SUBROUTINE FLOW1
          C
000122    6620   WRITE(6,9034)
000126    9034   FORMAT(45X,30H FINAL EQUILIBRIUM CONDITIONS  ,/)
000126          WRITE(6,9037)YCG
000134    9037    FORMAT(43X,27H HEIGHT OF CG              = ,F8.3,2X,3H FT )
000134          PHIC=PHI*180./3.14158
000136          WRITE(6,9080)PHIC
000144    9080  FORMAT(43X,27H PITCH ANGLE               =,F8.3,2X,8H DEGREES)
000144          WRITE(6,9060) S
000152    9060   FORMAT(43X,27H CUSHION PERIMETER         =,F8.3,2X,10H FT       )
000152          WRITE(6,9061)VCH
000160    9061  FORMAT(43X,27H CUSHION VOLUME            =,F8.3,2X,8H CU FT   )
000160          WRITE(6,9062)VTK
000166    9062  FORMAT(43X,27H TRUNK VOLUME              =,F8.3,2X,8H CU FT   )
000166          WRITE(6,9038)AGAP
000174    9038  FORMAT 43X,27H AIR GAP AREA              =,F8.3,2X,8H SQ FT   )
000174          WRITE(6,9063)ACH
```

```
000202   9063  FORMAT(43X,27H CUSHION AREA               =,F8.3,2X,8H SQ FT   )
000202         WRITE(6,9081)ATKCN
000210   9081  FORMAT(43X,27H CONTACT AREA               =,F8.3,2X,8H SQ FT  )
000216         WRITE(6,9064)ATKAT
000216   9064  FORMAT(43X,27H ORIFICE AREA TRUNK-AIMOS =,F8.3,2X,8H SQ FT    )
000216         WRITE(6,9065)ATKCH
000224   9065  FORMAT(43X,27H ORIFICE AREA TRUNK-CUSH  =,F8.3,2X,6H SQ FT ,/)
000224         WRITE(6,9039)PCH
000232   9039  FORMAT(43X,27H CUSHION PRESSURE           =,F8.3,2X,9H LB/SQ FT  )
000232         WRITE(6,9040) PTK
000240   9040  FORMAT(43X,27H TRUNK PRESSURE             =,F8.3,2X,9H LB/SQ FT  )
000240         WRITE(6,9041)PPLM
000246   9041  FORMAT(43X,27H PLENUM PRESSURE            =,F8.3,2X,9H LB/SQ FT )
000246         WRITE(6,9042)QFAN
000254   9042  FORMAT(43X,27H TOTAL AIR FLOW             = ,F8.3,2X,10H CU FT/SEC )
000254         WRITE(6,9043)QCMAT
000262   9043  FORMAT(43X,27H TOTAL CUSHION FLOW        =,F8.3,2X,10H CU FT/SEC)
000262         WRITE(6,9044)QPLCH
000270   9044  FORMAT(43X,27H FLOW PLENUM TO CUSHION    =,F8.3,2X,10H CU FT/SEC)
000270         WRITE(6,9045)QPLTK
000276   9045  FORMAT(43X,27H FLOW,PLENUM TO TRUNK      =,F8.3,2X,10H CU FT/SEC)
000276         WRITE(6,9046)QTKCH
000304   9046  FORMAT(43X,27H FLOW,TRUNK TO CUSHION     =,F8.3,2X,10H CU FT/SEC)
000304         WRITE(6,9047)QTKAT
000312   9047  FORMAT(43X,27H FLOW,TRUNK TO ATMOSPHERE =,F8.3,2X,10H CU FT/SEC)
000312         WRITE(6,9049) QPLAT
000320   9049  FORMAT(43X,27H FLOW,PLENUM TO ATMOSPHERE=,F8.3,2X,10H CU FT/SEC )
000320         WRITE(6,9070)SC
000324   9070  FORMAT(43X,27H STALL MARGIN              =,F8.3,2X,8H PERCENT)
000326         IF(SC.LT.0.0)WRITE(6,9071)
000334   9071  FORMAT(43X,*--WARNING-FAN CRITICALLY STABLE--*/)
000334         WRITE(6,8091)STIFYCG
000342   8091  FORMAT(43X,27H HEAVE STIFFNESS           =,F8.3,2X,11H LBS/INCHES)
000342         WRITE(6,8092)STIFPHI
000350   8092  FORMAT(43X,27H PITCH STIFFNESS           =,F8.3,2X,14H-FT LB/DEGREE
              1E)
000350   9004  FORMAT(1H1)
000350         WRITE(6,9066)HP
000356   9066  FORMAT(/,43X,27H THEORETICAL FAN POWER    =,F8.3,2X,4H HP
              1 ///////)
000356         WRITE(6,9067)
000362   9067  FORMAT(49X,*STATIC CHARACTERISTICS *,/)
000362         WRITE(6,9052)
000366   9052  FORMAT(1X,*      LOAD       HORIZ CG          CG ELEV
              1 PITCH           AIR GAP   CUSHION PRESSURE  TRUNK PRESSURE  TOTAL
              1FLOW*)
000366         WRITE(6,9053)
000372   9053  FORMAT(1X,*        (LBS)        DISTANCE(FT)        (FT)
              1(DEGREES)          (SQ FT)       (LBS/SQ FT)       (LBS/SQ FT)        (CU
              1 FT/SEC)    *)
000372         DO 9040 I=1,9
000374         PHIS(I)=PHIS(I)*180./3.14159
000376         WRITE(6,9055)FORCNS(I),CCS(I),YCBS(I),PHIS(I),AGAPS(I),PCHS(I),
              1PTKS(I),QFANS(I)
000422   9055  FORMAT(4X,F10.4,1X,2(3X,F10.4,3X) ,2X,6(3X,F10.4,3X))
```

```
RUN VERSION 2.3 --PSRL LEVEL 373--                         FMA2                              08/05/74

000422              PHIS(I)=PHIS(I)*3.14159/180.
000424       6640   CONTINUE
             C*****************************************************************************
             C                           DYNAMIC PART OF THE PROGRAM
             C*****************************************************************************
             C*****************************************************************************
             C
             C INITIAL CONDITION CALCULATIONS
             C
000426                ICLN=
000427              IPP=1
000430              PIP=ABS((PTK-PPLM)/PTK)-0.02
000434              IF(PIP.LE.0.)IPP=0
000437              AGAPE=AGAP
000440              XCG=XCGI
000442              YCG=YCGI
000443              PHI=PHII
000445              VELA=VELXI
000447              CALL COORDN
000450              CALL PROFILE
000451              CALL CLRNCE
000452              CALL SHAPE2
000453              IF(PHII.LE.PHIS(1))I=1
000457              IF(PHII.LE.PHIS(1))GO TO 3
000461              IF(PHII.LE.PHIS(2))I=2
000465              IF(PHII.LE.PHIS(2))GO TO 3
000467               IF(PHII.LE.PHIS(3))I=3
000473               IF(PHII.LE.PHIS(3))GO TO 3
000475              I=3
000476          3   IF(YCGI.GE.YCGS(7))I=I+6
000503              IF(YCGI.GE.YCGS(7))GO TO 4
000506              IF(YCGI.GE.YCGS(4))I=I+3
000512          4   PTK=PTKS(I)
000514              PCH=PCHS(I)
000515              PPLM=PPLMS(I)
000517              ADIF=AGAP-AGAPE*GEC
000522              IF(ADIF)20,20,21
000524         21   YDIF=ADIF/S
000526              TT=(SINKRT+SQRT(SINKRT*SINKRT+2.*32.2*YDIF))/32.2
000535              VEL=-SINKRT+32.2*TT
000540              NQ=IFIX(GEC*AGAPE/S/VEL/DTIME)
000545              PCH=0.
000546              GO TO 22
000546         20   NQ=1
000547         22   ID=0
000550              ID=1
             C
             C DYNAMIC SIMULATION
             C
000551              CALL DYSYS
000552        199   CONTINUE
000552               END
```

```
              SUBROUTINE PROGIO
        C DATA INPUT SUBROUTINE
000002        REAL L,L1,L2,LS,LP,MASS,INERT
000002        DIMENSION DUMMY(20)
000002        COMMON/COMPRS/AL0,AL1,AL2,AL3,AL4,B0,B1,B2,B3,B4,QP1,QP2,QP3,QP4
             1,QP5,IFAN
000002        COMMON/AREA/AATFN,APLAT,APLCH,APLTK,ATKAT,ATKCH,AGAP,ATK,ACH,
             1 ATHCN,VCH,VTK,VPLM,VCHD
000002        COMMON/FLUID/QFAN,QPLAT,QPLCH,QPLTK,QTKAT,QTKCH,QCHAT,PATFN,PFAN,PAT
             1AT
000002        COMMON/DYNAMIC/TIME,DTIME,ZTIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
             1,IQ,IO,NQ,IPCT,HDC,PHA,GEC
000002        COMMON/JUNK/INERT,   VELVI,YCGI,XCGI,PHII,VELX
000002        COMMON/BLOCK/RHO,MASS,DVCH,EVTH,TEMPAT,LABEL(80),TORQ,FORCN
             1,FORCT,TORQT
000002        COMMON/STATE/PPLM,PCH,PTK,SINPHT,YCG,DPHI,PHI
000002        COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NH,AH,NR,PHI1,PHI2,S
             1,A1,A2,X1,X2,R1,R2,L1,L2
000002        COMMON/COEFFS/CPA,CAF,CPC,CPT,CTC,CGAP,CTA,CKK
000002        COMMON/SPACE/XCA(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
             2 XTK(100),XCC,YCC,CC,GG,BETA,XCG,DELX
        C
        C READ INPUT DATA USING FOLLOWING SUBROUTINES
        C  IOLAB - HEADER CARD
        C  IOLABI- INTEGER DATA WITH PRINT
        C  IOLABD- REAL DATA WITH PRINT
        C  IOLAB2- PRINT WITH LINE SKIP
        C  IODAT - REAL DATA NO PRINT
        C
000002  9001  FORMAT(1X)
000002  9002   FORMAT(1X,/)
000002  9004 FORMAT(1X,//)
000002  9005   FORMAT(1H1)
000002        WRITE(6,9005)
000004         CALL IOLAB2(3)
000010        WRITE(6,9001)
000014         CALL IOLAB(3)
000016        WRITE(6,9004)
000022         CALL IOLAB(1)
000024        CALL IOLABD(MASS)
000026        CALL IOLABD(INERT)
000030        CALL IOLABD(CC)
000032         CALL IOLABD(GG)
000034        CALL IOLABD(PHA)
000036        CALL IOLABD(HDC)
000040        WRITE(6,9002)
000044         CALL IOLAB(1)
000046        CALL IOLABD(LS)
000050        CALL IOLABD(D)
000052        CALL IOLABD(A)
000054        CALL IOLABD(B)
000056        CALL IOLABD(L)
000060         CALL IOLABD(HY)
000062        WRITE(6,9001)
```

```
RUN VERSION 2.3 --PSRL LEVEL 373--                    PROBIO                          08/05/74

000066          CALL IOLABI(NR)
000070          CALL IOLABI(NM)
000072          CALL IOLABD(HM)
000074          CALL IOLABD(SM)
000076          CALL IOLAB(1)
000100          CALL IOLABD(LP)
000102          WRITE(6,9002)
000106          CALL IOLAB(2)
000110          CALL IOLABD(APLCH)
000112          CALL IOLABD(APLTK)
000114          CALL IOLABD(APLAT)
000116          CALL IOLABD(AATFN)
000120          CALL IOLABD(VPLM)
000122          CALL IOLABD(VCHU)
000124          WRITE(6,9002)
000130          CALL IOLAB(1)
000132          CALL IOLABD(XCGI)
000134          CALL IOLABD(YCGI)
000136          CALL IOLABD(PHII)
000140          CALL IOLABD(VELXI)
000142          CALL IOLABD(SINKRT)
000144          CALL IOLABD(DPHI)
000146          WRITE(6,9002)
000152          CALL IOLAB(1)
000154          CALL IOLABD(PAT)
000156          CALL IOLABD(TEMPAT)
000160          DO 1400 I=1,17
000162          CALL IODAT(DUMMY(I))
000164   1400   CONTINUE
000166          AL0=DUMMY(1)
000167          AL1=DUMMY(2)
000171          AL2=DUMMY(3)
000172          AL3=DUMMY(4)
000174          AL4=DUMMY(5)
000175          B0=DUMMY(6)
000177          B1=DUMMY(7)
000200          B2=DUMMY(8)
000202          B3=DUMMY(9)
000203          B4=DUMMY(10)
000205          OP1=DUMMY(11)
000206          OP2=DUMMY(12)
000210          OP3=DUMMY(13)
000211          OP4=DUMMY(14)
000213          OP5=DUMMY(15)
000214          DTIME=DUMMY(16)
000216          FTIME=DUMMY(17)
000217          TIME=0.0
000221          READ(5,9070)(LABEL(I),I=1,40),MM
000234          READ(5,9070)(LABEL(I),I=1,40),M
000250          READ(5,9070)(LABEL(I),I=1,40),N
000264   9070   FORMAT(40A1,I5)
000264          WRITE(6,9005)
000270          RETURN
000271          END
```

```
                    SUBROUTINE SEGMNT
              C DIVISION OF TRUNK IN TO SEGMENTS AND CALCULATION
              C OF DISTANCE OF CENTER OF SEGMENTS FROM CENTER OF CUSHION
000002              REAL L,L1,L2,LS,LP,MASS,INERT
000002              DIMENSION DELTA(100)
000002              COMMON/DYNAMIC/TIME,DTIME,ETIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
                  1,IQ,ID,NQ,IPCT,MDC,PHA,GEC
000002              COMMON/STATE/PPLM,PCH,PTK,EINKRT,YCG,DPHI,PHI
000002             COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NH,AH,VR,PHI1,PHI2,S
                  1,A1,A2,X1,X2,R1,R2,L1,L2
000002             COMMON/SPACE/XCX(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
                  2 XTR(100),XCC,YCC,CC,GG,BETA,XCG,DELX
000002             BETA=3.1415926/FLOAT(2*N)
000004             DELX=LS/FLOAT(2*M)
              C CURVED PART OF THUNK
000010             DO 10 I=1,N
000011             DELTA(I)=(FLOAT(I-1)+.5)*BETA
000015             YCX(I)=-(LS/2.0+(D/2.0+R2*SIN(PHI2))*COS(DELTA(I)))
000031        10    CONTINUE
              C STRAIGHT PART OF TRUNK
000033             DO 20 I=1,M
000035             XCX(N+I)=-(LS/2.0-(FLOAT(I-1)+.5)*DELX)
000045        20    CONTINUE
              C STRAIGHT PART OF TRUNK
000047             DO 30 I=1,M
000051             NMI=N+M+I
000053             YCX(NMI)=DELX*(FLOAT(I-1)+.5)
000060        30    CONTINUE
              C CURVED PART OF THUNK
000063             DO 40 I=1,N
000064             DELTA(I)=BETA*(FLOAT(I-1)+.5)
000070             NMI2=N+2*M+I
000073             YCX(NMI2)=LS/2.0+(D/2.0+R2*SIN(PHI2))*SIN(DELTA(I))
000106        40    CONTINUE
000110             RETURN
000111             END
```

```
RUN VERSION 2.3 --PSRL LEVEL 373--                                                   08/05/78

                        SUBROUTINE TRUNK(ISHAPE)
                    C TRUNK GEOMETRY CALCULATIONS
000003                  REAL L,L1,L2,LS,LP,MASS,INERT
000003                  COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NH,AH,NR,PHI1,PHI2,S
                       1,A1,A2,X1,X2,R1,R2,L1,L2
000003                  RTOL=0.05
                    C ITERATION FOR R2
000004                  R2=SQRT((A/2.)**2+HY**2)
000013                  DO 10 I=1,5
000015                  XS=(R2-HY)/R2
000017                  IF(XS.GT.1.0) XS=1.0
000023                  IF(XS.LT.-1.0) XS=-1.0
000026                  PHI2=ACOS(XS)
000030                  IF(PHI2.LE.0.0) PHI2=-PHI2
000034                  SINPH2=SIN(PHI2)
000036                  R1=((A-R2*SINPH2)**2+(B-HY)**2)/(2.*(B-HY))
000047                  XS=(R1-B-HY)/R1
000052                  IF(XS.GT.1.0) XS=1.0
000057                  IF(XS.LT.-1.0) XS=-1.0
000062                  PHI1=ACOS(XS)
000064                  IF(PHI1.LE.0.0) PHI1=-PHI1
000070                  XS=A-R2*SINPH2
000073                  IF (XS.LE.0.0) PHI1=6.2831852-PHI1
000077                  L2=L-PHI1*R1
000102                  R2S=L2/PHI2
000104                  IF(ABS(R2-R2S).LE.RTOL) GO TO 50
000111                  R2=(R2+R2S)/2.0
000113             10   CONTINUE
000115                  WRITE(6,9001)
000120           9001     FORMAT(10X,* INFEASABLE TRUNK GEOMETRY *//)
000120                  ISHAPE=0
000122                  RETURN
000122             50   L1=L-L2
000124                  RETURN
000125                  END
```

RUN VERSION 2.3 --PSRL LEVEL 373--   08/05/74

```
                      SUBROUTINE SHAPE1
               C INITIAL ASSESSMENT OF AREAS,VOLUMES ASSUMING
               C NO GROUND CONTACT
 000002                REAL L,L1,L2,LS,LP,MASS,INERT
 000002                COMMON/AREA/AATFN,APLAT,APLCH,AFLTK,ATKAT,ATKCH,AGAP,ATK,ACH,
                     1 ATKCN,VCH,VTK,VPLM,VCHD
 000002                COMMON/DYNAMIC/TIME,DTIME,FTIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
                     1,IW,IN,NO,IPCT,MDC,PHA,GEC
 000002                COMMON/JUNK/INERT,       VELVT,YCGI,XCGI,PHIT,VELY
 000002                COMMON/BLOCK/RHO,MASS,DVCH,DVTK,TEMPAT,LABEL(10),TORQ,FORCN
                     1,FORCT,TORQT
 000002                COMMON/STATE/PPLM,PCH,PTK,WINKHT,YCG,DPHI,PHI
 000002                COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NH,AH,NR,PHI1,PHI2,S
                     1,A1,A2,X1,X2,R1,R2,L1,L2
 000002                COMMON/SHAPE/VCHI(100),VCHR(100),AGAPI(100),AGAPR(100),ATKR(100),
                     1 ATKI(100),ATKCHI(100),ATKATR(100),ATKATI(100),ATKCNI(100),
                     2 ATKCNR(100),VTKI(100),VTKR(100),ACHI(100),ACHR(100),ATKCHR(100)
 000002                COMMON/SPACE/XCA(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
                     2 XTK(100),YCC,YCC,CC,GG,BETA,XCG,DELX
 000002                SINPH2=SIN(PHI2)
 000004                SINPHR=SINPH2*R2
 000006                D2=D/2.+SINPHR
 000011                X=B*(A-SINPHR)/(B+HY-R1)
 000016                A1=PHI2/2.0*R2**2
 000021                A2=(R2-HY)/2.0*SINPHR
 000024                A3=PHI1/2.0*R1**2
 000027                A4=A*B/2.0
 000031                A5=(A-SINPHR-X)/2.0*(HY-R1)
 000037                X1=SINPHR-4.0*(SIN(PHI2/2.0))**2*R2/(3.0*PHI2)
 000051                X2=0.66667*SINPHR
 000053                X3=SINPHR+4.0*(SIN(PHI1/2.0))**2*R1/(3.0*PHI1)
 000065                X4=-0.333333*X
 000070                X5=SINPHR+0.333333*(A-SINPHR-X)
 000075                S=2.0*LS+6.28318*(D/2.0+SINPHR)
 000102                NSTOP=2*(N+M)
 000105                DO 10 I=1,NSTOP
 000106                ATKCNI(I)=0.0
 000107                ATKI(I)=A1+A3+A5-A2-A4
 000114                XE=(A1*X1-A2*X2+A3*X3-A4*X4+A5*X5)/ATKI(I)
 000127                IF(I-N)11,11,12
 000131        12      IF(I-3*M-N)13,13,11
               C STRAIGHT PART OF TRUNK
 000135        13      VTKI(I)=DELX*ATKI(I)
 000140                ACHI(I)=DELX*(D+2.0*SINPHR)/2.
 000145                ATKCHI(I)=FLOAT(IFIX((L2-LP)/SH+1.0)*NH)*AH*DELX/S
 000157                ATKATI(I)=FLOAT(NR*NH)*AH*DELX/S-ATKCHI(I)
 000167                GO TO 10
               C CURVED PART OF TRUNK
 000167        11      VTKI(I)=BETA*(D/2.+XE)*ATKI(I)
 000174                ACHI(I)=BETA*D2*D2/2.
 000177                ATKCHI(I)=FLOAT(IFIX((L2-LP)/SH+1.0)*NH)*AH*BETA*D2/S
 000212                ATKATI(I)=FLOAT(NR*NH)*AH*(BETA*D2)/S-ATKCHI(I)
 000223        10      CONTINUE
 000224                RETURN
```

RUN VFRSION 2.3 --PSRL LEVEL 373--   SHAPE1   08/05/7

000224   FND

RUN VERSION 2.3 --MSRL LEVEL 373--   08/05/74

```
                    SUBROUTINE COORDN
              C CALCULATION OF CENTER OF SEGMENT COORDINATE FROM
              C CG COORDINATES AND PITCH ANGLE
000002              REAL L,L1,L2,LS,LP,MASS,INERT
000002              COMMON/DYNAMIC/TIME,DTIME,FTIME,DAMPC,UFR(7),IPP,MM,N,M,U,DECCL
                   1,IO,ID,NO,IPCT,MDC,PHA,GFC
000002              COMMON/STATE/PPLM,PCH,PTK,SINKRT,YCG,DPHI,PHI
000002             COMMON/GEOMET/A,B,HY,L,D,LS,LP,S1,NM,AM,NR,PHI1,PHI2,S
                   1,A1,A2,X1,X2,R1,R2,L1,L2
000002             COMMON/SPACE/XCX(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
                   2 XTK(100),XCC,YCC,CC,GG,RETA,XCG,DELA
000002             NSTOP=2*(N+M)
000004              XCC=XCG+GG*SIN(PHI)-CC*COS(PHI)
000015              YCC=YCG-GG*COS(PHI)-CC*SIN(PHI)
000027             DO 10 I=1,NSTOP
000030             XH(I)=XCC+XCX(I)*COS(PHI)
000035             YH(I)=YCC+XCX(I)*SIN(PHI)
000043        10    CONTINUE
000045              RETURN
000046             END
```

```
RUN VERSION 2.3 --MSRL LEVEL 373--                                          08/05/78

                    SUBROUTINE PROFILE
              C GROUND PROFILE SUBROUTINE
              C GROUND ELEVATION AS A FUNCTION OF X COORDINATE
000002              REAL L,L1,L2,LS,LP,MASS,INERT
000002              COMMON/DYNAMIC/TIME,DTIME,FTIME,DAMPC,VER(7),IPP,MM,N,M,U,DECCL
                  1,IQ,ID,NO,IPCT,MDC,PHA,GEC
000002              COMMON/SPACE/XCX(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
                  2 XTK(100),XCC,YCC,CC,GG,RETA,XCG,DELX
000002              NSTOP=2*(M+N)
000004              DO 10 I=1,NSTOP
000004                YG(I)=0.0
000007        10    CONTINUE
              C TO BE CONTINUED
000011              RETURN
000012              END
```

```
                    SUBROUTINE CLRNCE
               C CALCULATION OF TRUNK GROUND CLEARANCE FOR EACH SEGMENT
000002              COMMON/DYNAMIC/TIME,DTIME,FTIME,DAMGC,UER(7),IMP,MM,N,M,U,DECCL
                   1,TO,IO,NO,IPCT,MDC,PHA,GEC
000002              COMMON/STATE/PPLM,PCH,PTK,RINHMT,YCG,DPHI,PHI
000002              COMMON/SPACE/XCA(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
                   2 XTR(100),XCC,YCC,CC,GG,REIP,XCG,DELX
000002              COMMON/ICLN/ICLN
000002              NSTOP=2*(N+1)
000004              DO 16 I=1,NSTOP
000006              YGH(I)=YH(I)/COS(PHI)-YG(I)*COS(PHI)
000016              IF(YGH(I).LE.0.0) YGH(I)=0.0
000021      16      IF(YGH(I).LE.0.0.AND.ICLN.EQ.0) WRITE(6,9001) I
000044    9001      FORMAT(5X,*HARD SURFACE CONTACT AT SEGMENT*,I5)
000044              RETURN
000044              END
```

```
                  SUBROUTINE SHAPE2
              C CALCULATION OF AREAS AND VOLUMES ASSOCIATED WITH ACLS,KNOWING ITS
              C ORIENTATION
   000002         REAL L,L1,L2,LS,LP,MASS,INERT
   000002        COMMON/PARA/PERIK,ALEAK,AGABE
   000002        COMMON/AREA/AATFN,APLAT,APLCH,APLTK,ATKAT,ATKCH,AGAP,ATK,ACH,
                1 ATKCN,VCH,VTK,VPLM,VCMD
   000002         COMMON/DYNAMIC/TIME,DTIME,FTIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
                1,IO,ID,NO,IPCT,MDC,PMA,GEC
   000002         COMMON/JUNK/INERT,      VELVI,YCGI,XCGI,PHII,VELX
   000002        COMMON/BLOCK/RHO,MASS,DVCH,RVTK,TEMPAT,LABEL(10),TORQ,FORCN
                1,FORCT,TORQT
   000002         COMMON/STATE/PPLM,PCH,PTK,SINKHT,YCG,DPHI,PHI
   000002        COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NH,AH,NR,PHI1,PHI2,S
                1,A1,A2,X1,X2,R1,R2,L1,L2
   000002         COMMON/SHAPE/VCHI(100),VCHP(100),AGAPI(100),AGAPR(100),ATKR(100),
                1 ATKI(100),ATKCHI(100),ATKATR(100),ATKATI(100),ATKCNI(100),
                2 ATKCNR(100),VTKI(100),VTKR(100),ACHI(100),ACHR(100),ATKCHR(100)
   000002        COMMON/SPACE/XCX(100),XH(100),YH(100),VG(100),YGH(100),XCH(100),
                2 XTK(100),XCC,YCC,CC,GG,BETA,XCG,DELX
   000002         SINPH2=SIN(PHI2)
   000004        SINPHR=SINPH2*R2
   000006        D2=D/2.0+SINPHR
   000011        X12=(X1*A1-X2*A2)/(A1-A2)
   000017        NSTOP=2*(M+N)
              C*****************************************************************
              C PART 1                    I VALUE OF VCM AND AGAP
              C*****************************************************************
   000022        DO 17  I=1,NSTOP
   000023        IF(I-N)11,11,12
   000025     12 IF(I-2*M-N)13,13,11
              C STRAIGHT PART OF TRUNK
   000031     13 VCHI(I)=YGH(I)*D2*DELX-(A1-A2)*DELX
   000037        AGAPI(I)=(YGH(I)-HY)*DELX
   000041        GO TO 10
              C CURVED PART OF TRUNK
   000042     11 VCHI(I)=YGH(I)*BETA/2.*D2**2-BETA*(D/2.+X12)*(A1-A2)
   000056        AGAPI(I)=(YGH(I)-HY)*BETA*D2
              C*****************************************************************
              C PART 2                    R VALUE CALCULATIONS
              C*****************************************************************
              C
              C NO GROUND CONTACT
              C
   000062     10  IF(YGH(I)-HY)14,15,15
   000065     15  ATKR(I)=0.0
   000067        ACHR(I)=0.0
   000070        VTKR(I)=0.0
   000071        VCHR(I)=0.0
   000072        ATKCNR(I)=0.0
   000073        ATKCHR(I)=0.0
   000074        ATKATR(I)=0.0
   000075        AGAPR(I)=0.0
              C DISTANCE OF SEGMENT PRESSURE CENTERS FROM CUSHION CENTER
```

```
000076            YTK(I)=XCX(I)
000077            IF(I-N)18,18,19
000101     18      XCH(I)=-LS/2.0-1.333333/BETA*D2*COS(BETA*(FLOAT(I-1)+.5))
           1*SIN(BETA*0.5)
000123            GO TO 17
000123        19  IF(I-N-2*M)20,20,21
000127        20  XCH(I)=XCX(I)
000131            GO TO 17
000132     21      XCH(I)=LS/2.0+1.333333/BETA*D2*SIN(BETA*0.5)
           1*SIN((FLOAT(I-N-2*M-1)+0.5)*BETA)
000155            GO TO 17
           C
           C TRUNK GROUND CONTACT
           C
000156        14  PHI3=ACOS((R2-(HY-YGH(I)))/R2)
                  PHI4=ACOS((R1-(HY-YGH(I)))/R1
000172            A6=R2**2*PHI3/2.0
000175            A7=(R2-HY+YGH(I))/2.0*R2*SIN(PHI3)
000205            A8=R1**2*PHI4/2.0
000210            A9=(R1-HY+YGH(I))/2.0*R1*SIN(PHI4)
000220            IF(I-N)22,22,23
000223        23  IF(I-2*M-N)24,24,22
           C STRAIGHT PART OF TRUNK
000227     24      CONTINUE
000227            ATKR(I)=A6-A7+A8-A9
000234            VTKR(I)=ATKR(I)*DELX
000236            ACHR(I)=DELX*R2*SIN(PHI3)
000243            VCHR(I)=-DELX*(A6-A7)
000247            ATKCHR(I)=-(R2*SIN(PHI3)+R1*SIN(PHI4))*DELX
000261            ATKCHR(I)=ATKCHI(I)-FLOAT(NH*IFIX((L2-LP-PHI3*R2)/SH+1))*AH*DELX/S
000274            ATKATR(I)=ATKATI(I)-FLOAT(NG*IFIX((L1-(L-(LP+(NR-1)*SH))-PHI4*R1)
           1/SH+1))*AH*DELX/S
000320            ATKCHR(I)=ATKCHR(I)*PERTK
000322            ATKATR(I)=ATKATR(I)*PERTK
000324             AGAPR(I)=AGAPI(I)
000325            GO TO 29
000326     22      ATKR(I)=A6-A7+A8-A9
           C CURVED PART OF TRUNK
000333            X6=SINPHR-4.0*(SIN(PHI3/2.0)**2)*R2/3.0/PHI3
000344            X7=SINPHR-0.333333*R2*SIN(PHI3)
000352            X8=SINPHR+4.0*(SIN(PHI4/2.0)**2)*R1/3.0/PHI4
000364            X9=SINPHR+0.333333*R1*SIN(PHI4)
000372            XER=(A6*X6-A7*X7+A8*X8-A9*X9)/ATKR(I)
000403            VTKR(I)=BETA*(D/2.0+XER)*ATKR(I)
000410            ACHR(I)=BETA/2.0*((D2)**2-(D2-R2*SIN(PHI3))**2)
000422            XCR=(A6*X6-A7*X7)/(A6-A7)
000427            VCHR(I)=-BETA*(D/2.0+XCR)*(A6-A7)
000437            ATKCHR(I)=-BETA/2.0*((D2+R1*SIN(PHI4))**2-(D2-R2*SIN(PHI3))**2)
000455            ATKCHR(I)=ATKCHI(I)-FLOAT(NH*IFIX((L2-LP-PHI3*R2)/SH+1))*AH*BETA
           1*D2/S
000474            ATKATR(I)=ATKATI(I)-FLOAT(NH*IFIX((L1-(L-(LP+(NR-1)*SH))-PHI4*R1)
           1/SH+1))*AH*BETA*D2/S
000517            ATKCHR(I)=ATKCHR(I)*PERTK
000521            ATKATR(I)=ATKATR(I)*PERTK
000523             AGAPR(I)=AGAPI(I)
```

```
RUN VERSION 2.3 --PSRL LEVEL 373--                    SHAPE2                    08/05/74

                C DISTANCE OF SEGMENT PRESSURE CENTERS FROM CUSHION CENTER
000524      29 RR=D2-R1*SIN(PHI4)
000531         RR1=D2-R2*SIN(PHI3)
000534         XX2=1.33333*SIN(BETA/2.)/BETA*(RR**3-RR1**3)/(RR*RR-RR1*RR1)
000553         IF(I-N)25,25,26
000556      25 XCM(I)=-LS/2.0-1.333333/BETA*   COS((FLOAT(I-1)+.5)*BETA)
              1*(D4-R2*SIN(PHI3))*SIN(BETA*0.5)
000604         XTK(I)=-LS/2.-XX2*COS((FLOAT(I-1)+0.5)*BETA)
000617         GO IO 17
000617      26 IF(I-N-2*M)27,27,28
000623      27 XCM(I)=XCX(I)
000625         XTK(I)=XCX(I)
000627         GO IO 17
000627      28 XCM(I)=LS/2.0+1.333333/BETA*(D2-R2*SIN(PHI3))*SIN(BETA*0.5)
              1*SIN((FLOAT(I-N-2*M-1)+0.5)*BETA)
000657         XTK(I)=LS/2.0+XX2*SIN((FLOAT(I-N-2*M-1)*0.5)*BETA)
000673      17 CONTINUE
              C*****************************************************************************
              C PERT 3                    SUMMATION OF SEGMENT AREAS VOLUMES
              C*****************************************************************************
000674         VTK=0.0
000674         ACM=0.0
000677         ATKCM=0.0
000700         ATKAT=0.0
000701         VCM=0.0
000702         AGAP=0.0
000703         ATKCN=0.0
000705         DO 30 I=1,NSTOP
000706         VTK=VTK+2.0*(VTKI(I)-VTKR(I))
000712         ACM=ACM+2.0*(ACMI(I)-ACMR(I))
000714         ATKCMF=ATKCHI(I)-ATKCHR(I)
000720         IF(ATKCHF.LT.0.0)ATKCHF=0.0
000723         ATKCM=ATKCM+2.*ATKCHF
000726         ATKATF=ATKATI(I)-ATKATR(I)
000730         IF(ATKATF.LT.0.0)ATKATF=0.0
000732         ATKAT=ATKAT+2.*ATKATF
000735         VCM=VCM+2.0*(VCMI(I)-VCMR(I))
000741         AGAP=AGAP+2.  *(AGAPI(I)-AGAGR(I))
000745         ATKCN=ATKCN+2.0*(ATKCNI(I)-ATKCNR(I))
000751      30 CONTINUE
000753         IF(AGAP.LT.ALEAK)AGAP=ALEAK
000756         VCM=VCM+VCMD
000760         RETURN
000761         END
```

```
                    SUBROUTINE FORCE
              C CALCULATION OF FORCES AND TORQUES ACTING ON ACLS
000002              REAL L,L1,L2,LS,LP,MASS,INERT
000002             COMMON/AREA/AATFN,APLAT,APLCH,APLTK,ATKAT,ATKCH,AGAP,ATK,ACH,
                  1 ATKCN,VCH,VTK,VPLM,VCHO
000002             COMMON/FLUID/QFAN,QPLAT,QPLCH,QPLTK,QTKAT,QTKCH,QCHAT,PATFN,PFAN,PAT
                  1AT
000002              COMMON/DYNAMIC/TIME,DTIME,OTIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
                  1,IO,IN,NO,IPCT,MOC,PHA,GEC
000002              COMMON/JUNK/INERT,     VELXI,YCGI,ACGI,PHII,VELX
000002              COMMON/STATE/PPLM,PCH,PTK,SINKT,YCG,DPHI,PHI
000002              COMMON/SHAPE/VCHI(100),VCHR(100),AGAPI(100),AGAPR(100),ATKR(100),
                  1 ATKI(100),ATKCHI(100),ATKATR(100),ATKATI(100),ATKCNI(100),
                  2 ATKCNR(100),VTKI(100),VTKR(100),ACHI(100),ACHR(100),ATKCHR(100)
000002             COMMON/SPACE/XCX(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
                  2 XTK(100),XCC,YCC,CC,GG,BETA,XCG,DELX
000002             COMMON/BLOCK/RHO,MASS,DVCH,RVTK,TEMPAT,LABEL(80),TORQ,FORCN
                  1,FORCT,TORQT
              C THE FOLLOWING FORCES AND TORQUES ARE CALCULATED
              C 1...FORCE AND TORQUE DUE TO NORMAL PRESSURE FORCE
              C      FORCN AND TORN
              C 2...FORCE AND TORQUE DUE TO TRUNK DAMPING
              C      FORCT AND TORQT
              C 3...TORQUE DUE TO GROUND FRICTION
              C      TORF
000002             FORCN=(PCH*ACH+PTK*ATKCN)*COS(PHI)
000011             NSTOP=2*(M+N)
000013             FORCT=0.0
000014             TORQT=0.
000015             DO 103 I=1,NSTOP
000016             VELI=SINKRT+DPHI*(XCX(I)-CC)
000022             IF(ATKCNR(I).LT.0.0)GO TO  104
000024              GO TO 103
000025        104 FORCT=FORCT+VELI*DAMPC/FLOAT(NSTOP)
000032             TORQT=TORQT+VELI    *DAMPC/FLOAT(NSTOP)*(XTK(I)-CC)
000043        103 CONTINUE
000045              TORF=0.0
000046              TORN=0.0
000050              DO 10 I=1,NSTOP
000051              TORN=TORN+2.0*PCH*(ACHI(I)-ACHR(I))*(XCH(I)-CC)
                  1 + 2.0*PTK*(ATKCNI(I)-ATKCNR(I))*(XTK(I)-CC)
000071       10     CONTINUE
000074             IF(VELX) 11,11,12
000075       12    DO 13 I=1,NSTOP
000077             TORF=TORF-2.0*PTK*U*(ATKCNI(I)-ATKCNR(I))*(YGH(I)+GG)
000111       13    CONTINUE
000114       11     TORQ=TORN+TORF
000116             RETURN
000117             END
```

```
                 SUBROUTINE FLOW1 (ICASE)
               C STATIC CHARACTERISTICS SUBROUTINE
000003            REAL L,L1,L2,LS,LP,MASS,INERT
000003            COMMON/SPACE/XCA(100),XH(100),YH(100),YB(100),WGH(100),XCH(100),
                 2 XTK(100),XCC,YCC,CC,GG,BETA,XCG,DELX
000003            COMMON/AREA/AATFN,APLAT,APLCH,APLTK,ATKAT,ATKCH,AGAP,ATK,ACH,
                 1 ATKCN,VCH,VTK,VPLM,VCHD
000003            COMMON/FLUID/QFAN,QPLAT,QPLCH,QPLTK,QTKAT,QTKCH,QCHAT,PATFN,PFAN,PAT
                 1AT
000003            COMMON/DYNAMIC/TIME,DTIME,ETIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
                 1,IP,IR,NQ,IPCT,HDC,PHA,GEC
000003            COMMON/JUNK/INERT,     VELXI,YCGI,XCGI,PHII,VELX
000003            COMMON/BLOCK/RHO,MASS,DVCH,DVTK,TEMPAT,LABEL(40),TORQ,FORCN
                 1,FORCT,TCROT
000003            COMMON/LOADS/FORCNS(20),CCS(20),YCGS(20),PHIS(20),AGAPS(20),
                 1PCHS(20),PTKS(20),QFANS(20),PFANS(20),PPLMS(20)
000003            COMMON/STATE/PPLM,PCH,PTK,SINKHT,YCG,RPHI,PHI
000003            COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NH,AH,NR,PHI1,PHI2,S
                 1,A1,A2,X1,X2,R1,R2,L1,L2
000003            COMMON/COEFFS/CPA,CAF,CPC,CPT,CTC,CGAP,CTA,CKK
000003            COMMON/COMPRS/ALC,AL1,AL2,AL3,AL4,R0,R1,R2,R3,E4,QP1,QP2,QP3,QP4
                 1,QP5,IFAN
000003            DIMENSION ZCC(5,5),ZWT(5,5)
000003            DIMENSION AGAPP(20)
               C THIS SUBROUTINE ESSENTIALLY CONSISTS OF THREE NESTLED
               C ITERATION LOOPS
               C....ITERATION 1
               C    VALUE OF YCG AND PHI IS ITERATED UNTIL THE CONFIGURATION
               C    GENERATES ENOUGH FORCE AT CORRECT DISTANCE TO BALANCE THE
               C    WEIGHT OF THE SYSTEM
               C....ITERATION 2
               C    VALUE OF PFAN IS ITERATED SO THAT THE VALUE OF AGAP REQUIRED
               C    BY PRESSURE FLOW RELATIONS MATCH AGAP GENERATED BY YCG AND PHI
               C....ITERATION 3
               C    VALUE OF PCH IS ITERATED
               C ALL THREE ITERATIONS INVOLVE CHOOSING INITIAL VALUES,
               C TESTING THE GENERATED VARIABLE AND SELECTING NEXT ITERATIVE VALUES
000003            CCT=CC
000005            YCG=0.0
000006            XTOL=0.05
000007            ATOL=0.01
               C********************************************************************
               C INITIAL VALUE,ITERATION 1
000011            YCGSTRT=HY+GG-0.1*GG
000014            YCGSTOP=HY+GG+0.1*GG
               C
000017            PHISTRT=-0.1
000020            PHISTOP=0.1
000021            ICREST=1
000022            ICC=1
000023            IOJIN=0
000024            ZCC(1,1)=0.
000025            IS=1
000026            JS=1
```

```
              C****************************************************************
              C****************************************************************
              C ITERATION 1 BEGINS. YCG,PHI ITERATED
              C****************************************************************
              C****************************************************************
000027           10 YCG=YC STRT
000031              YCGDELT=(YCGSTOP-YCGSTRT)/2.
000034              PHIDELT=(PHISTOP-PHISTRT)/2.0
000036              IDIV=1
000037              III=0
              C A NINE POINT GRID OF YCG,PHI IS CHOSEN FOR TESTING
000040              DO 300 IYCG=1,3
000042              PHI=PHISTRT
000044              DO 200 IPHI=1,3
000045              III=III+1
000047              CC=0.
000050           11 IF(ICREST.EQ.2)CC=ZCC(IS,JS)
              C AGAP IS DETERMINED FOR GIVEN YCG,PHI
000054              CALL COORDN
000057              CALL PROFILE
000060              CALL CLRNCF
000061              CALL SHAPE2
000062              IPX=1
000063              IPR-ST=1
000064              IRSI=0
000065              ICASE=1
000067              PTOL=0.5
              C****************************************************************
              C INITIAL VALUE, ITERATION 2
000071              PSTART=0.0
000072              PSTOP=QP1
              C
              C****************************************************************
              C****************************************************************
              C ITERATION 2 BEGINS.PFAN ITERATED
              C****************************************************************
              C****************************************************************
000073        24     PINC1=(PSTOP-PSTART)/80.0
000074        25     PINC=(PSTOP-PSTART)/9.0
              C ITERATE PFAN TO MATCH VALUE OF AGAP
000101              PFAN=PSTART
000102              DO 100 I=1,10
000103               IF(IPHEST.EQ.2) PFAN=PFANS(ICASE)
              C
              C CALL FAN MODEL TO FIND QFAN
000107              CALL CMPCRV(QFAN,PFAN)
              C
000111              PATFN=-RHO/2.0*(QFAN/(AATFN*CAF))**2
000114              PPLM=PFAN+PATFN
000120               IF(PPLM.LT.0.0) GO TO 35
000122              SIGN=1.0
000124              QPLAT=APLAT*CPA*SQRT(2.0/RHO*ABS(PPLM))*SIGN
000134               QFMPL=QFAN-QPLAT
              C****************************************************************
              C INITIAL VALUE, ITERATION 3
```

```
000134          PCH=PPLM/2.
          C
          C**********************************************************************
          C**********************************************************************
          C ITERATION 3 BEGINS.PCH ITERATED
          C**********************************************************************
          C**********************************************************************
000140          DO 50 KK=1,20
          C ITERATION OF CUSHION PRESSURE
000142          SIGN=1.0
000144          IF(PCH.GT.PPLM)SIGN=-1.0
000150        QPLCH=APLCH*CPC*SQRT(2.0/RHO*ABS(PPLM-PCH))*SIGN
000162          QPLTK=QFNPL-QPLCH
000164          SIGN=1.0
000165          IF (QPLTK.LT.0.0) SIGN=-1.0
000171        PTK=PPLM-RHO/2.0*(QPLTK/(APLTK*CPT))**2  *SIGN
000201        SIGN=1.0
000202          IF(PTK.LT.0.0) SIGN=-1.0
000205          QTKAT=ATKAT*CTA*SQRT(2.0/RHO*ABS(PTK))*SIGN
000216        QTKCH=QPLTK-QTKAT
000220        SIGN=1.0
000221        IF(QTKCH.LT.0.0) SIGN=-1.0
000225          PCHI=PTK-RHO/2.0*(QTKCH/(ATKCH*CTC))**2  *SIGN
          C**********************************************************************
          C TESTING VARIABLE, ITERATION 3
000235          IF(ABS(PCH-PCHI).LE.PTOL)GO TO 75
          C
          C**********************************************************************
          C SELECTING NEW VALUE, ITERATION 3
000241          PCH=(PCHI+PCH)/2.0
          C
          C ITERATION CONTINUED
000243    50          CONTINUE
          C**********************************************************************
          C ITERATION 3 ENDS
          C**********************************************************************
000245          GO TO 75
          C INFEASIBLE CONFIGURATION. CHOOSE NEXT VALUE OF PFAN
000245    35          PSTART=PSTART+PINC1
000247          IRST=IRST+1
000251          IRIT=IRST-350
000253        IF(IRIT)41,41,601
000254      41 PDRF=PSTOP-1.5*PINC1
000257        IF(PDRF.LT.PSTART) GO TO 24
000262        GO TO 25
000262    75    IF(PTK.LT.PCH)PSTOP=PFAN-PINC
000267          IF(PTK.LT.PCH)GO TO 25
000272          IF(PCH.LT.0.0) GO TO 35
000273        QCHAT=QPLCH+QTKCH
000275        IF(IPREST.EQ.2)GO TO 600
000277        AGAPP(I)=QCHAT/(CGAP*SQRT(2./RHO*PCH))
000306        PFANS(I)=PFAN
000310        PFAN=PFAN+PINC
000312      100 CONTINUE
000314        IRST=0
```

```
                C*************************    ******************************************
                C TESTING VARIABLE, ITERATION 2
      000315          DIF=ABS(AGAPP(1)-AGAP)
      000320          IDIF=1
      000321          DO 500 J=2,10
      000323          XTEST=ABS(AGAPP(J)-AGAP)
      000324          IF(XTEST.LT.DIF)IDIF=J
      000332          IF(XTEST.LT.DIF)DIF=XTEST
      000335          IF(XTEST.LT.ATOL)IPREST=2
      000341      500 CONTINUE
                C
      000343          ICASE=IDIF
                C*************************************************************************
                C CHOOSING N W VALUES, ITERATION 2
      000344          PSTART=PFANS(IDIF)-PINC
      000344          PSTOP= PFANS(IDIF)+PINC
                C
      000350          IPN=IPN+1
      000351          IF(IPN.GE.10)GO TO 601
      000353          GO TO 24
      000354      601 ZWT(IYCG,IPHI)=10.**6
      000360          ZCC(IYCG,IPHI)=10.**6
      000363          IDIV=0
      000364          GO TO 200
                C*************************************************************************
                C ITERATION 2 ENDS
                C*************************************************************************
      000364      600 CONTINUE
      000364          IF(ICREST.EQ.2)GO TO 2001
      000366          VFLA=0.
      000367          CC=0.
      000370          CALL FORCE
      000371          CC=TORQ/FORCN*COS(PHI)
      000376          IF(ICON.EQ.1)GO TO 9001
      000401          GO TO 220
                C STORE VALUES OF PERFORMANCE VARIABLES, IF
                C     A) EQUILIBRIUM POINT IS NEAREST TO THE MID POINT
                C     B) ALL POINTS REPRESENT FEASIBLE CONFIGURATION
      000401     9001 FORCNS(IIT)=FORCN
      000403          CCS(IIT)=CC
      000405          YCGS(IIT)=YCG
      000406          PHIS(IIT)=PHI
      000410          AGAPS(IIT)=AGAP
      000411          PCHS(IIT)=PCH
      000413          PTKS(IIT)=PTK
      000414          PPLMS(IIT)=PPLM
      000416          PFANS(IIT)=PFAN
      000417      220 ZCC(IYCG,IPHI)=CC
      000423          ZWT(IYCG,IPHI)=FORCN
      000425      200 PHI=PHI+PHIDELT
      000431      300 YCG=YCG+YCGDELT
      000435          IS=1
      000436          JS=1
                C*************************************************************************
                C TESTING VARIABLE,ITERATION 3
```

```
000437          XTEST=((ZCC(1,1)-CCI)/CCI)**2+((ZWT(1,1)-MASS*32.2)/MASS/32.2)**2
000450          DO 1000 I=1,3
000452          DO 1000 J=1,3
000453          XDIS =((ZCC(I,J)-CCI)/CCI)**2+((ZWT(I,J)-MASS*32.2)/MASS/32.2)**2
000467          IF(XDIS.GT.XTEST)GO TO 1000
000473          IS=I
000474          JS=J
000475          XTEST=XDIS
000474    1000  CONTINUE
000502          IF(XTEST.LT.XTOL)GO TO 2000
          C
000505          IF(XTEST.GT.10.**8) GO TO 1201
          C**************************************************************************
          C SELECTING NEXT VALUES, ITERATION 3
          C SIDE POINT IS THE BEST, MOVE GRID SIDEWAYS
000512          YCG=YCGSTRT+FLOAT(IS-1)*YCGDELT
000516          PHI=PHISTRT+FLOAT(JS-1)*PHIDELT
000522          YCGSTRT=YCG-YCGDELT
000524          YCGSTOP=YCG+YCGDELT
000526          PHISTRT=PHI-PHIDELT
000527          PHISTOP=PHI+PHIDELT
000531          IF(IS.EQ.2.AND.JS.EQ.2)GO TO 1200
000540          IODIN=IODIN+1
000542          IF(IODIN.GE.40)GO TO 2002
000544          GO TO 10
          C MID POINT IS THE BEST, NARROW GRID
000545    1200  YCGSTRT=YCG-YCGDELT/2.
000550          YCGSTOP=YCG+YCGDELT/2.
000552          PHISTOP=PHI+PHIDELT/2.
000555          PHISTRT=PHI-PHIDELT/2.
000557          IODIN=IODIN+1
000561          IF(IOID.EQ.1)ICON=0
000563          IF(IODIN.GE.40)GO TO 2003
000565          GO TO 10
          C NO POINT IS FEASIBLE, LIFT UP THE GRID
000566    1201  YCGSTRT=YCGSTRT+3.*YCGDELT
000571          YCGSTOP=YCGSTOP+3.*YCGDELT
000573          IODIN=IODIN+1
000575          IF(IODIN.GE.40)GO TO 2002
000577          GO TO 10
000600    2000  PHI=FLOAT(JS-1)*PHIDELT+PHISTRT
000605          YCG=FLOAT(IS-1)*YCGDELT+YCGSTRT+ZCC(IS,JS)*SIN(PHI)
000620          ICREST=2
          C**************************************************************************
          C ITERATION 3 ENDS
          C**************************************************************************
000621          GO TO 11
000622    2002  WRITE(6,1202)
000626    1202  FORMAT(10X,*INFEASIBLE CONFIGURATION*//)
000626          ICASE=0
000630          RETURN
000630    2003  WRITE(6,1203)
000634    1203  FORMAT(10X,*CHANGE VALUE OF XTOL*//)
000634          ICASE=0
000636          RETURN
```

```
000636    2001 CC=CCI
000640         RETURN
000640         END
```

```
RUN VERSION 2.3 --PSRL LEVEL 373--                                                        08/05/74

                      SUBROUTINE DYSYS
                C DYNAMIC SIMULATION PROGRAM
000002                REAL L,L1,L2,LS,LP,MASS
000002                COMMON/COMPRS/AL0,AL1,AL2,AL3,AL4,B0,B1,B2,B3,B4,QP1,QP2,QP3,QP4
                     1,QP5,IFAN
000002                COMMON/AREA/AATFN,APLAT,APLCH,APLTK,ATKAT,ATKCH,AGAP,ATK,ACH,
                     1 ATKCN,VCH,VTK,VPLM,VCHD
000002                COMMON/FLUID/QFAN,QPLAT,QPLCH,QPLTK,QTKAT,QTKCH,QCHAT,PATFN,PFAN,PAT
                     1AT
                C STATE VARIABLES
000002                COMMON/STATE/PPLM,PCH,PTK,SINKRT,YCG,DPHI,PHI
                C DYNAMIC PARAMETERS
000002                COMMON/DYNAMIC/TIME,DTIME,FTIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
                     1,T0,I0,NO,IPCT,MDC,PHA,GEC
000002                COMMON/JUNK/INERT,     VELVI,YCGI,ACGI,PHII,VELX
000002                COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NH,AH,NR,PHI1,PHI2,S
                     1,A1,A2,X1,X2,R1,R2,L1,L2
000002                COMMON/BLOCK/RHO,MASS,DVCH,DVTK,TEMPAT,LABEL(80),TORQ,FORCN
                     1,FORCT,TOROT
000002                COMMON/SPACE/XCX(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
                     2 XTK(100),XCC,YCC,CC,GG,BETA,XCG,DELX
000002                DVTK=0.0
000003                DVCH=SINKPT*ACH
                C INITIALIZE DYNAMICS
000005                IPCT=1
000006                IFAN=0
000007                CALL STEQU
                C PRINT HEADER FOR DYNAMIC OUTPUT
                C PRINT HEADER AND 25 LINES PER PAGE
                C EACH LINE AFTER MM TIME STEPS
000010                J=1
000011                I=MM
000012                K=25
000014             15 IF(FTIME-TIME)14,11,11
000017             11 IK=K-25
000021                IF(IK)13,14,13
000022             14 WRITE(6,9004)
000026                WRITE(6,9006)
000032                WRITE(6,9001)
000034                WRITE(6,9002)
000042                WRITE(6,9003)
000046           9001 FORMAT(1X,*NO.  TIME     FAN       CG       TRUNK      CUSHION   PI
                     1TCH      FLOW      FLOW      FLOW      CG       GAP      ACCEL     SINK RA
                     2 SINK RATE*)
000046           9002 FORMAT(1X,*                  FLOW      X COORDN  PRESSURE  PRESSURE
                     1ANGLE    TRK-CUSH  TRK-ATM   CUSH-AIM  WEIGHT    AREA      *)
000046           9003 FORMAT(1X,*        SEC       CFS       FT        PSFG      PSFG      DE
                     1GREE      CFS       CFS       CFS       FT        SQFT      G
                     2    FPS       *)
000046           9004 FORMAT(1H1)
000046           9006 FORMAT(43X,* DYNAMIC SIMULATION*/)
000046                K=0
000047             13 VCH5=VCH
000050                VTK5=VTK
```

```
000052          IL=I-MM
000054          IF(IL)16,17,16
000055       17 ACCEL=DER(4)/32.2
000057          PHIC=PHI*180./3.14159
000061          WRITE(6,9000)J,TIME,QFAN,XCG ,PTK,PCH,PHIC,QTKCH,QIKAT,QCHAT,YCG,
               1AGAP,ACCEL,SINKRT
000121   9000   FORMAT(1X,I4,F6.3,1X,12(F9.4,1X)/)
000121          J=J+1
000123          K=K+1
000124          I=0
000125       16 IF(WFAN.LT.QP5) IFAN=1
000131          IF(WFAN.LT.QP5) GO TO 34
000134          IF(WFAN.GT.QP3) IFAN=0
000137          IF(WFAN.GT.QP3) GO TO 34
000142          IFAN=1-IFAN
000143       34 CONTINUE
        C
        C NUMERICALLY INTEGRATE USING RUNGE KUTTA METHOD
000143          PCHF=PCH
000144          PTKF=PTK
000146          PPLMF=PPLM
000147          YCF=YCG
000151          PHIF=PHI
000152          DPHIF=DPHI
000154          SINKRF=SINKRT
000155          IPC1=1
000157          CALL RKDIF
000160          PTEST=PCH-PTK
000162          IF(PTEST)52,52,51
        C REPEAT CALCULATIONS USING DIFFERENT MODEL
        C IF PCH IS GREATER THAN PTK
000164       51 IPC1=0
000165          PCH=PCHF
000166          PTK=PTKF
000170          PPLM=PPLMF
000171          YCG=YCF
000173          DPHI=DPHIF
000174          PHI=PHIF
000176          SINKRT=SINKRF
000177          TIME=TIME-DTIME
000201          PCH=PTK
000203          CALL RKDIF
000204       52 DVCM=(VCH-VCMS)/DTIME
000207          DVTK=(VTK-VTKS)/DTIME
000211          VELA=VELX-DECCL*DTIME
000215          IF(VELX.LE.0.0)VELX=0.
000217          XCG=XCG+VELX*DTIME
000221          I=I+1
000223          GO TO 15
000224       19 RETURN
000225          END
```

```
RUN VERSION 2.3 --PSRL LEVEL 373--                                          08/05/74

                  SUBROUTINE RKDIF
000002            REAL L,L1,L2,LS,LP,MASS,INERT
000002            DIMENSION Y(7),SY(7),Y0(7),Y1(7),Y2(7)
000002            COMMON/DYNAMIC/TIME,DTIME,ETIME,DAMPC,DY(7) ,IPP,MM,N,M,U,DECCL
                 1,TO,IO,NO,IPCT,MDC,PHA,GEC
000002            COMMON/STATE/Y
000002            CALL STEQU
000003            H=DTIME/2.0
000005            DO 10 I=1,7
000007            SY(I)=Y(I)
000011            Y0(I)=DY(I)
000012    10      Y(I)=H*DY(I)+Y(I)
000017            TIME=TIME+H
000021            CALL STEQU
000022            DO 20 I=1,7
000024            Y1(I)= Y(I)
000026    20      Y(I)=SY(I)+H*DY(I)
000033            CALL STEQU
000034            DO 30 I=1,7
000036            Y2(I)=DY(I)
000040    30      Y(I)=SY(I)+DTIME*DY(I)
000045            CALL STEQU
000046            TIME=TIME+H
000050            H=H/3.0
000052            DO 40 I=1,7
000053            PRT1=2.0*(Y1(I)+Y2(I))
000056            PRT2=Y0(I)+DY(I)
000060            Y(I)=SY(I)+H*PRT1+H*PRT2
000065    40      CONTINUE
000066            CALL STEQU
000067            RETURN
000070            END
```

RUN VERSION 2.3 --PSRL LEVEL 373-- 08/05/74

```
              SUBROUTINE STEQU
       C STATE EQUATIONS FOR THE DYNAMIC SYSTEM
000002        REAL L,L1,L2,LS,LP,MASS,INERT
000002        COMMON/PARA/PERIK,ALEAK,AGAPE
000002        COMMON/SPACE/XCX(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
             2 XTK(100),XCC,YCC,CC,GG,BETA,XCG,DELX
000002        COMMON/GEOMET/A,B,HY,L,D,LS,LP,SM,NM,AH,NR,PHI1,PHI2,S
             1,A1,A2,X1,X2,R1,R2,L1,L2
000002        COMMON/COEFFS/CPA,CAP,CPC,CPT,CTC,CGAP,CTA,CKK
000002        COMMON/AREA/AATFN,APLAT,APLCH,APLIK,ATKAT,ATKCH,AGAP,ATK,ACH,
             1 ATKCN,VCH,VTK,VPLM,VCHD
000002        COMMON/FLUID/QFAN,QPLAT,QPLCH,QPLTK,QTKAT,QTKCH,QCHAT,PATFN,PFAN,PAT
             1AT
000002         COMMON/DYNAMIC/TIME,DTIME,FTIME,DAMPC,DER(7),IPP,MM,N,M,U,DECCL
             1,IQ,IP,NQ,IPCT,MDC,PHA,GEC
000002        COMMON/LOADS/FORCNS(20),CCS(20),YCGS(20),PHIS(20),AGAPS(20),
             1PCHS(20),PTKS(20),QFANS(20),PFANS(20),PPLMS(20)
000002         COMMON/JUNK/INERT,     VELXI,YCGI,XCGI,PHII,VELX
000002        COMMON/BLOCK/RHO,MASS,DVCH,DVTK,TEMPAT,LABEL(20),TORQ,FORCN
             1,FORCT,TORQT
000002         COMMON/STATE/PPLM,PCH,PTK,SINKHT,YCG,DPHI,PHI
       C
       C FOLLOWING SURROUTINES ARE CALLED TO GENERATE VALUES OF
       C FLOWS,TORQUES AND FORCES, FROM STATE VARIABLES, FOR STATE EQUATIONS
000002         CALL COORDN
000003        CALL PROFILE
000004         CALL CLRNCE
000005         CALL SHAPE2
000006        CALL FLOW2
000007        CALL FORCE
       C
       C
       C
       C**********************************************************************
       C**********************************************************************
       C                           STATE EQUTIONS
       C**********************************************************************
       C**********************************************************************
       C
       C VARIATIONS IN THE EQUATIONS ARE MADE TO ACCOMODATE SPECIAL CONDITIONS
000010        IF(IPP)11,10,11
000011     10 DER(1)=CKK*(PPLM+PAT)/(VPLM-VTK)*(QFAN-QPLCH-QPLAT-QTKCH-QTKAT
             1-DVTK)
000024        DER(3)=DER(1)
000026        GO TO 12
000027     11 DER(1)=(CKK*(PPLM+PAT)/VPLM)*(QFAN-QPLCH-QPLTK-QPLAT)
000037        DER(3)=(CKK*(PTK+PAT)/VTK)*(QPLTK-QTKCH-QTKAT-DVTK)
000050     12 QCHFT=QPLCH+QTKCH-DVCH
000053        ADIF=(AGAP-GEC*AG PE)*FLOAT(IQ)-0.0001
000061        IF(ADIF)14,14,13
000063     13 QCHAT=QCHFT
000065        GO TO 15
000066     14 IQ=IQ+1
000067        IF(IQ.GE.NQ)IQ=NQ
```

```
RUN VERSION 2.3 --MSRL LEVEL 373--                   STEQU                          08/05/74

000072          QCHAT=FLOAT(NQ-IQ)/FLOAT(NQ)*QCHFT+FLOAT(IQ)/FLOAT(NQ)*QCHAT
000102          ID=0.
000103       15 DER(2)=(CKK*(PCH+PAT)/VCH)*(QPLCH+QIKCH-QCHAT-DVCH)
000113          IF(IPCT)31,32,31
000115       32 IF(IPP)33,34,33
000116       34 DER(1)=CKK*(PPLM+PAT)/(VPLM+VTK+VCH)*(QFAN-QPLAT-QTKAT-QCHAT
               1 -DVCH-DVTK)
000132          DER(2)=DER(1)
000134          DER(3)=DER(1)
000135          GO TO 31
000136       33 DER(3)=CKK*(PTK+PAT)/(VTK+VCH)*(QPLIK+QPLCH-QTKAT-QCHAT-DVTK-DVCH)
000151          DER(2)=DER(3)
000153       31 SIGN=1.
000154          IF(SINKRT.LT.0.0) SIGN=-1.0
000160          FORCD=-.5*HDC*PHA*RHO*SINKRT*SINKRT*SIGN
000165          DER(4)=(FORCN-FORCT-MASS*32.2-FORCD)/MASS
000172          DER(5)=SINKRT
000173          SIGN=1.
000175          IF(DPHI.LT.0.0)SIGN=-1.
          C     CENF IS DISTANCE OF CENTER OF AERODYNAMIC
          C FORCE FROM CG
000200          CENF=CC
000201          DER(6)=(TORQ-TORQT+FORCD*CENF)/INERT
000206          DER(7)=DPHI
000210          RETURN
000211          END
```

```
                SUBROUTINE FLOW2
        C SUBROUTINE TO FIND FLOW VALUES DURING DYNAMIC SIMULATION
000002      REAL L,L1,L2,LS,LP,MASS
000002      COMMON/AREA/AATFN,APLAT,APLCH,APLTK,ATKAT,ATKCH,AGAP,ATK,ACH,
           1 ATKCH VCH,VTK,VPLM,VCHD
000002      COMMON/FLUID/QFAN,QPLAT,QPLCH,QPLTK,QTKAT,QTKCH,QCHAT,PATFN,PFAN,PAT
           1AT
000002      COMMON/STATE/PPLM,PCH,PTK,SINKHT,YCG,DPHI,PHI
000002      COMMON/DYNAMIC/TIME,DTIME,YTIME,DAMPC,UFR(7),IPP,MM,N,M,U,DECCL
           1,IQ,ID,NQ,IPCT,HDC,PHA,GEC
000002      COMMON/JUNK/INERT,      VELYI,YCGI,XCGI,PHIT,VELX
000002      COMMON/GEOMET/A,B,HY,L,D,LS,LP,SH,NM,AU,UR,PHI1,PHI2,S
           1,A1,A2,X1,X2,R1,R2,L1,L2
000002      COMMON/COEFFS/CHA,CAF,CPC,CST,CTC,CGAP,CTA,CKK
000002      COMMON/BLOCK/RHO,MASS,DVCH,DVTK,TEMPAT,LABEL(80),TORQ,FORCN
           1,FORCT,TORQT
000002      COMMON/SPACE/XCX(100),XH(100),YH(100),YG(100),YGH(100),XCH(100),
           2 XTK(100),XCC,YCC,CC,GG,BETA,XCG,DELX
000002      DIMENSION PEN(60)
        C
        C DETERMINE UPDATED VALUES OF AREAS VOLUMES
        C
000002      SIGN=1.0
000003      IF((PPLM-PTK).LT.0.0) SIGN=-1.0
000010      QPLTK=SIGN*CPT*APLTK*SQRT(ABS(2.0/RHO*(PPLM-PTK)))
000021      SIGN= .0
000023      IF((PPLM-PCH).LT.0.0) SIGN=-1.0
000027      QPLCH=SIGN*CPC*APLCH*SQRT(ABS(2.0/RHO*(PPLM-PCH)))
000040      SIGN=1.0
000042      IF((PTK-PCH).LT.0.0) SIGN=-1.0
000046      QTKCH=SIGN*CTC*ATKCH*SQRT(ABS(2.0/RHO*(PTK-PCH)))
000057      SIGN=1.0
000061      IF(PTK.LT.0. )SIGN=-1.
000064      QTKAT=CTA*ATKAT*SQRT(2.0/RHO*ABS(PTK))*SIGN
        C ITERATION FOR FAN INLET PRESSURE
000074      PTOL=1.
000076      ATEST= ATFN-1.
000077      IF(ATEST)30,31,31
        C
        C NO ITERATION IF FAN INLET IS OPEN
000101   31 PFAN=PPLM
000103      CALL CMPCRV(QFAN,PFAN)
000105      PATFN=0.0
000106      GO TO 20
        C
000107   30 J=1
000110      PEN(1)=PPLM-0.95*QP1
000113   23 J=J+1
000115      IF(J.GT.50) GO TO 24
000120      PFAN=PPLM-PEN(J-1)
000122      CALL CMPCRV(QFAN,PFAN)
000124      SIGN=1.0
000125      IF(QFAN.LT.0.0)SIGN=-1.0
000131      PEN(J)=-SIGN*RHO/2.0*(QFAN/(AATFN*CAF))**2
```

RUN VERSION 2.3 --PSRL LEVEL 373-- FLOW2 08/05/76

```
000140          IF(ABS(PEN(J)-PEN(J-1)).LT.PTOL) PATFN=PEN(J)
000145          IF(ABS(PEN(J)-PEN(J-1)).LT.PTOL) GO TO 20
000151          SIGN=0.0
000153          IF(PEN(J-1).GT.PEN(J))SIGK=1.0
000160          IF(J.EQ.2)SIGM=SIGK
000163          SIGG=ABS(SIGM-SIGK)-0.5
000167          J=J+1
000171          IF(SIGG)25,25,22
000172       25 PEN(J)=(PEN(J-2)+PEN(J-1))/2.
000174          SIGM=SIGK
000177          GO TO 23
000200       22 PEN(J)=(PEN(J-2)+PEN(J-4))/2.
000204          SIGM=SIGK
000205          GO TO 23
000206       20 SIGN=1.
000207          IF(PPLM.LT.0.0) SIGN=-1.0
000213          OPLAT=APLAT*CPA*SQRT(2.0/RHO*ABS(PPLM     ))*SIGN
000223          OFNPL=QFAN-OPLAT
000225          SIGN=1.0
000227          IF(PCH.LT.0.0) SIGN=-1.0
000232          QCHAT=AGAP*CGAP*SQRT(2.0/RHO*ABS(PCH     ))*SIGN
000243          RETURN
000243          END
```

```
                  SUBROUTINE CMPCRV(QFAN,PFAN)
            C FAN MODEL SUBROUTINE
            C INPUT PRESSURE AND OUTPUT FLOW
000005             COMMON/COMPRS/AL0,AL1,AL2,AL3,AL4,B0,B1,B2,B3,B4,QP1,QP2,QP3,QP4
                  1,QP5,IFAN
000005             IF(IFAN)4,4,5
000006           4 QFAN=AL0+AL1*PFAN+AL2*PFAN**2+AL3*PFAN**3+AL4*PFAN**4
000022             RETURN
000023           5 QFAN=B0+B1*PFAN+B2*PFAN**2+B3*PFAN**3+B4*PFAN**4
000037             RETURN
000040             END
```

```
RUN VERSION 2.3 --PSRL LEVEL 373--                                                         08/05/74

                    SUBROUTINE IOLABI(IDATA)
                C READ AND PRINT DATA CARD
                      COMMON LABEL(80)
000003               READ(5,9012)(LABEL(K),K=1,30),IDATA,(LABEL(J),J=31,42)
000003               WRITE(6,9008)(LABEL(K),K=1,30),IDATA,(LABEL(J),J=31,42)
000025
000050      9012      FORMAT(30A1,I5,5X,12A1)
000050      9008      FORMAT(38X,30A1,3H = ,I5,2X,12A1)
000050               RETURN
000051               END
```

RUN VERSION 2.3 --PSRL LEVEL 373--   08/05/74

```
                         SUBROUTINE TOLAR(JS)
                C READ AND PRINT HEADER CARD
 000003                  COMMON LABEL(80)
 000003                  DO 100 I=1,JS
 000005                  READ(5,9011)(LABEL(K),K=1,80)
 000016                  WRITE(6,9006)(LABEL(K),K=1,80)
 000030     100          CONTINUE
 000034     9011         FORMAT(80A1)
 000034     9006         FORMAT(20X,80A1)
 000034                  RETURN
 000034                  END
```

RUN VERSION 2.3 --PSRL LEVEL 373--   08/05/7[illegible]

```
                SUBROUTINE IOLABD(DATA)
        C READ AND PRINT REAL DATA CARD
000003          COMMON LABEL(8v)
000003          READ(5,9010)(LABEL(K),K=1,30),DATA,(LABEL(J),J=31,42)
000025          WRITE(6,9000)(LABEL(K),K=1,30),DATA,(LABEL(J),J=31,42)
000050   9010   FORMAT(30A1,F10.4,12A1)
000050   9000   FORMAT(38X,30A1,3H = ,F8.3,2X,12A1)
000050          RETURN
000051          END
```

```
                      SUBROUTINE IOLAB2(JS)
                C READ AND PRINT WITH LINE SKIP
000003                COMMON LABEL(80)
000003                DO 100 KPL=1,JS
000005                READ(5,9011) (LABEL(I),I=1,80)
000014                WRITE(6,9007) (LABEL(I),I=1,80)
000030      100       CONTINUE
000034      9011      FORMAT(80A1)
000034      9007      FORMAT(20X,80A1,/)
000034                RETURN
000034                END
```

```
RUN VERSION 2.3 --PSRL LEVEL 373--                                                   08/05/70

                        SUBROUTINE IODAT(X)
                  C READ ONLY DATA CARD  E10.3 FORMAT
                  C I PUT OF COMPRESSOR DATA
 000003                 REAL X
 000003                 COMMON LABEL(80)
 000003                 READ(5,1000)(LABEL(I),I=1,40),X
 000017           1000  FORMAT(40A1,E10.3)
 000017                 RETURN
 000020                 END
```

APPENDIX F

ILLUSTRATIVE SIMULATION -

INPUT DATA AND SAMPLE PRINTOUT

Internal Data List

CPA	0.6
CAF	1.0
CPC	0.6
CPT	0.9
CTC	0.9
CGAP	1.0
CTA	0.9
CKK	1.4
GEC	10.0
ZETA	0.05
PERTK	0.85
PERCH	0.15
U	0.4
DECCL	15.0

Data Card List

IBM FORTRAN Coding Form — GX28-7327-6 U/M050 Printed in U.S.A.

```
                         AIR CUSHION LANDING SYSTEM
                                PRØGRAM FMA-2
                 DYNAMIC SIMULATIØN ØF HEAVE-PITCH MØTIØN
     THIS PRØGRAM CØMPUTES THE STATIC CHARACTERISTICS ØF THE ACLS
     AND SIMULATES THE HEAVE-PITCH MØTIØN ØF THE AIRCRAFT
     CAUSED BY LANDING AND TAXIING
                              AIRCRAFT PARAMETERS
TØTAL WEIGHT                  275.          LBS
PITCH INERTIA                 10.           SLUG SQ FT
HØRIZØNTAL DIST ØF CG         0.2           FT
VERT DIST ØF CG               0.6           FT
PRØJECTED HEAVE AREA          8.0           SQ FT
HEAVE DRAG CØEFFICIENT        1.0
                                TRUNK PARAMETERS
STRAIGHT SECTIØN LENGTH        3.083        FT
INNER ATTACHMENT DISTANCE     0.334         FT
HØRIZ DIST BET ATTACH PNTS     .611         FT
VERT DIST BET ATTACH PNTS      0.0          FT
PERIMETER ØF TRUNK CRØSSECTIØN1.920         FT
TRUNK HEIGHT                  .6110         FT
NUMBER ØF ØRIFICE RØWS        00009
NUMBER ØF ØRIFICES PER RØW    00178
AREA ØF EACH ØRIFICE          0.0123        SQ IN
SPACING BETWEEN ORIFICE ROWS  .0625         FT
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

IBM FORTRAN Coding Form

GX28-7327-6 U/M050
Printed in U.S.A.

PROGRAM | PUNCHING INSTRUCTIONS | GRAPHIC | PUNCH | PAGE OF | CARD ELECTRO NUMBER
PROGRAMMER | DATE

```
                  PERIPHERAL DISTANCE BETWEEN
INNER ATTACHMT PNT + FIRST RØW  .647      FT
                                 AIR SUPPLY PARAMETERS
                   AIR SØURCE                  - AXIAL FLØW FAN,JØY AVER 562D1779
ØRIFICE AREA PLENUM TØ CUSH     0.0            SQ FT
ØRIFICE AREA PLENUM TØ TRUNK     3.740         SQ FT
ØRIFICE AREA PLENUM TØ ATM.     0.076          SQ FT
EFFECTIVE AREA ATMØS. TØ FAN    1.5            SQ FT
PLENUM VØLUME                   3.12           CU FT
DEAD VØLUME ØF CUSHIØN           .745          CU FT
                                INITIAL CONDITIONS.
INITIAL X CØØRDN ØF CG          0.             FT
INITIAL Y CØØRDN ØF CG          1.711          FT
INITIAL PITCH ANGLE             5.0            DEGREES
INITIAL HØRIZØNTAL VELØCITY     73.3           FT/SEC
INITIAL SINK RATE               0.0            FT/SEC
INITIAL PITCH ANGULAR VEL       0.0            DEGREE/SEC
                             ENVIRØNMENTAL CØNDITIØNS
ATMØSPHERIC PRESSURE            14.7           LBS/SQ IN
AMBIENT TEMPERATURE             70.0           DEG F
CØMPRESSØR CØEFFIC AL0                         +4.330E+01
CØMPRESSØR CØEFFIC AL1                         +3.334E-02
CØMPRESSØR CØEFFIC AL2                         -4.260E-03
CØMPRESSØR CØEFFIC AL3                         +5.250E-05
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

IBM FORTRAN Coding Form

GX28-7327-6 U/M050
Printed in U.S.A.

PROGRAM		PUNCHING INSTRUCTIONS	GRAPHIC	PAGE OF
PROGRAMMER	DATE		PUNCH	CARD ELECTRO NUMBER

FORTRAN STATEMENT

```
CØMPRESSØR CØEFFIC AL4                    -2.040E-07
CØMPRESSØR CØEFFIC B0                     +3.846E+01
CØMPRESSØR CØEFFIC B1                     -9.057E-01
CØMPRESSØR CØEFFIC B2                     +6.350E-03
CØMPRESSØR CØEFFIC B3                     -2.010E-05
CØMPRESSØR CØEFFIC B4                     +2.340E-08
ØP1 MAXIMUM STABLE PRESSURE               +1.600E+02
ØP2 MINIMUM STALL PRESSURE                +5.720E+01
ØP3 MINIMUM STABLE FLOW                   +2.250E+01
ØP4 MAXIMUM STABLE FLOW                   +4.330E+01
ØP5 MAXIMUM STALL FLOW                     4.0
INTEGRATION TIME STEP                     0.0005    SEC
SIMULATION TIME LIMIT                     0.1       SEC
TIME STEPS BETWEEN PRINTING               00002
STRAIGHT PART SEGMENT NO. BY FOUR -M      00010
CURVED PART SEGMENT NO. BY FOUR -N        00010
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

```
AIR CUSHION LANDING SYSTEM

PROGRAM FMA-2

DYNMMIC SIMULATION OF HEAVE-PITCH MOTION

THIS PROGRAM COMPUTES THE STATIC CHARACTERISTICS OF THE ACLS
AND SIMULATES THE HEAVE-PITCH MOTION OF THE AIRCRAFT
CAUSED BY LANDING AND TAXIING

AIRCRAFT PARAMETERS
TOTAL WEIGHT                        =  275.000  LBS
PITCH INERTIA                       =   10.000  SLUG SQ FT
HORIZONTA DIST OF CG                =     .200  FT
VERT DIST OF CG                     =     .600  FT
PROJECTED HEAVE AREA                =    8.000  SQ FT
HEAVE DRAG COEFFICIENT              =    1.000

TRUNK PARAMETERS
STRAIGHT SECTION LENGTH             =    3.083  FT
INNER ATTACHMENT DISTANCE           =     .334  FT
HORIZ DIST BET ATTACH PNTS          =     .611  FT
VERT DIST BET ATTACH PNTS           =    0.000  FT
PERIMETER OF TRUNK CROSSECTION      =    1.920  FT
TRUNK HEIGHT                        =     .611  FT

NUMBER OF ORIFICE ROWS              =      9
NUMBER OF ORIFICES PER ROW          =    178
AREA OF EACH ORIFICE                =     .012  SQ IN
SPACING BETWEEN ORIFICE ROWS        =     .063  FT
PERIPHERAL DISTANCE BETWEEN
INNER ATTACHMT PNT + FIRST ROW      =     .6[illegible]7  FT

AIR SUPPLY PARAMETERS
AIR SOURCE                          - AXIAL FLOW FAN,JOY AVFR 56201779
ORIFICE AREA PLENUM TO CUSH         =    0.000  SQ FT
ORIFICE AREA PLENUM TO TRUNK        =    3.740  SQ FT
ORIFICE AREA PLENUM TO -TM.         =     .076  SQ FT
EFFECTIVE AREA ATMOS. TO FAN        =    1.500  SQ FT
PLENUM VOLUME                       =    3.120  CU FT
DEAD VOLUME OF CUSHION              =     .745  CU FT

INITIAL CONDITIONS
INITIAL X COORDN OF CG              =    0.000  FT
INITIAL Y COORDN OF CG              =    1.711  FT
INITIAL PITCH ANGLE                 =    5.000  DEGREES
INITIAL HORIZONTAL VELOCITY         =   73.300  FT/SEC
INITIAL SINK RATE                   =    0.000  FT/SEC
INITIAL PITCH ANGULAR VEL           =    0.000  DEGREE/SEC

ENVIRONMENTAL CONDITIONS
ATMOSPHERIC PRESSURE                =   14.700  LBS/SQ IN
AMBIENT TEMPERATURE                 =   70.000  DEG F
```

FINAL EQUILIBRIUM CONDITIONS

HEIGHT OF CG	=	1.213	FT
PITCH ANGLE	=	-.358	DEGREES
CUSHION PERIMETER	=	11.242	FT
CUSHION VOLUME	=	2.170	CU FT
TRUNK VOLUME	=	4.698	CU FT
AIR GAP AREA	=	.071	SQ FT
CUSHION AREA	=	6.670	SQ FT
CONTACT AREA	=	.633	SQ FT
ORIFICE AREA TRUNK-ATMOS	=	.056	SQ FT
ORIFICE AREA TRUNK-CUSH	=	.069	SQ FT
CUSHION PRESSURE	=	41.306	LB/SQ FT
TRUNK PRESSURE	=	82.548	LB/SQ FT
PLENUM PRESSURE	=	82.613	LB/SQ FT
TOTAL AIR FLOW	=	37.213	CU FT/SEC
TOTAL CUSHION FLOW	=	11.602	CU FT/SEC
FLOW PLENUM TO CUSHION	=	0.000	CU FT/SEC
FLOW,PLENUM TO TRUNK	=	25.099	CU FT/SEC
FLOW,TRUNK TO CUSHION	=	11.602	CU FT/SEC
FLOW,TRUNK TO ATMOSPHERE	=	13.498	CU FT/SEC
FLOW,PLENUM TO ATMOSPHERE	=	12.113	CU FT/SEC
STALL MARGIN	=	47.917	PERCENT
HEAVE STIFFNESS	=	614.716	LBS/INCHES
PITCH STIFFNESS	=	60.983	FT LB/DEGREES
THEORETICAL FAN POWER	=	5.638	HP

STATIC CHARACTERISTICS

LOAD (LBS)	HORIZ CG DISTANCE(FT)	CG ELEV (FT)	PITCH (DEGREES)	AIR GAP (SQ FT)	CUSHION PRESSURE (LBS/SQ FT)	TRUNK PRESSURE (LBS/SQ FT)	TOTAL FLOW (CU FT/SEC)
332.7212	1.5400	1.2110	-5.7296	.7963	.2739	108.1573	35.9108
886.3071	-.0000	1.2110	0.0000	0.0000	126.0283	126.7003	33.8542
332.7212	-1.5400	1.2110	5.7296	.7963	.2739	108.1573	35.9108
195.9637	1.7830	1.2710	-5.7296	1.1790	.1463	90.6281	36.8383
4.4748	-.0000	1.2710	0.0000	.6746	.6363	61.1673	38.5592
195.9637	-1.7830	1.2710	5.7296	1.1790	.1463	90.6281	36.8383
103.1946	2.0025	1.3310	-5.7296	1.6341	.0880	77.7562	37.4578
1.1162	-.0000	1.3310	0.0000	1.3491	.1587	61.0109	38.5717
103.1956	-2.0025	1.3310	5.7296	1.6341	.0880	77.7562	37.4578

DYNAMIC SIMULATION

NO.	TIME SEC	FAN FLOW CFS	CG X COORDN FT	TRUNK PRESSURE PSFG	CUSHION PRESSURE PSFG	PITCH ANGLE DEGREE	FLOW TRK-CUSH CFS	FLOW TRK-ATM CFS	FLOW CUSH-ATM CFS	CG HEIGHT FT	GAP AREA SQFT	ACCEL a	SINK RATE FPS
1	0.000	37.4976	0.0000	77.7562	0.0000	5.0000	17.6323	14.1059	17.6323	1.7110	5.4980	-1.0000	0.0000
2	.001	37.6225	.0733	75.5443	.0000	5.0000	17.3797	13.9038	17.4366	1.7110	5.4978	-1.0000	-.0322
3	.002	37.7313	.1466	73.6124	.0000	5.0000	17.1561	13.7249	17.4402	1.7109	5.4973	-1.0000	-.0644
4	.003	37.8426	.2198	71.9292	.0000	5.0000	16.9588	13.5670	17.4703	1.7109	5.4964	-1.0000	-.0966
5	.004	37.9307	.2931	70.4657	.0000	5.0000	16.7854	13.4283	17.5242	1.7107	5.4951	-1.0000	-.1288
6	.005	38.0218	.3663	69.1957	.0000	5.0000	16.6334	13.3067	17.5995	1.7106	5.4935	-1.0000	-.1610
7	.006	38.0976	.4395	68.0956	.0000	5.0000	16.5007	13.2005	17.6941	1.7104	5.4915	-1.0000	-.1932
8	.007	38.1649	.5127	67.1440	.0000	5.0000	16.3850	13.1080	17.8057	1.7102	5.4891	-1.0000	-.2254
9	.008	38.2242	.5859	66.3220	.0000	5.0000	16.2844	13.0275	17.9324	1.7100	5.4864	-1.0000	-.2576
10	.009	38.2764	.6591	65.6127	.0000	5.0000	16.1971	12.9577	18.0724	1.7097	5.4833	-1.0000	-.2898
11	.010	38.3240	.7322	65.0014	.0000	5.0000	16.1214	12.8972	18.2241	1.7094	5.4798	-1.0000	-.3220
12	.011	38.3618	.8054	64.4750	.0000	5.0000	16.0560	12.8448	18.3860	1.7091	5.4760	-1.0000	-.3542
13	.012	38.3965	.8785	64.0221	.0000	5.0000	15.9995	12.7996	18.5568	1.7087	5.4718	-1.0000	-.3864
14	.013	38.4206	.9516	63.6326	.0000	5.0000	15.9508	12.7606	18.7350	1.7083	5.4673	-1.0000	-.4186
15	.014	38.4526	1.0247	63.2979	.0000	5.0000	15.9088	12.7270	18.9207	1.7078	5.4624	-1.0000	-.4508
16	.015	38.4752	1.0978	63.0104	.0000	5.0000	15.8726	12.6981	19.1118	1.7074	5.4571	-1.0000	-.4830
17	.016	38.4946	1.1708	62.7635	.0000	5.0000	15.8415	12.6732	19.3080	1.7069	5.4515	-1.0000	-.5152
18	.017	38.5114	1.2439	62.5516	.0000	5.0000	15.8147	12.6518	19.5086	1.7063	5.4455	-1.0000	-.5474
19	.018	38.5259	1.3169	62.3698	.0000	5.0000	15.7917	12.6334	19.7129	1.7058	5.4391	-1.0000	-.5796
20	.019	38.5383	1.3899	62.2139	.0000	5.0000	15.7720	12.6176	19.9205	1.7052	5.4324	-1.0000	-.6118
21	.020	38.5491	1.4629	62.0802	.0000	5.0000	15.7550	12.6040	20.1308	1.7046	5.4253	-1.0000	-.6440
22	.021	38.5583	1.5359	61.9655	.0000	5.0000	15.7405	12.5924	20.3436	1.7039	5.4179	-1.0000	-.6762
23	.022	38.5662	1.6 89	61.8672	.0000	5.0000	15.7280	12.5824	20.5584	1.7032	5.4101	-1.0000	-.7084
24	.023	38.5730	1.6818	61.7830	.0000	5.0000	15.7173	12.5738	20.7750	1.7025	5.4019	-1.0000	-.7406
25	.024	38.5788	1.7548	61.7108	.0000	5.0000	15.7081	12.5665	20.9931	1.7017	5.3934	-1.0000	-.7728

(Only the first page of the dynamic results is reproduced here.)

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