NASA TECHNICAL MEMORANDUM

NASA TM X-73595

(NASA-TM-73595) COMPUTER PROGRAM FOR FLAT SECTOR THRUST BEARING PERFORMANCE (NASA) 74 p HC A04/MF A01 CSCL 09B

N77-27751

Unclas

G3/61 36844

NASA TM X-73595

COMPUTER PROGRAM FOR FLAT SECTOR THRUST BEARING PERFORMANCE

by Alden F. Presler and Izhak Etsion
Lewis Research Center
Cleveland, Ohio 44135

June 1977

1. Report No. NASA TM X-73595	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle COMPUTER PROGRAM FOR FLAT SECTOR THRUST BEARING PERFORMANCE		5. Report Date
		6. Performing Organization Code
7. Author(s) Alden F. Presler and Izhak Etsion		8. Performing Organization Report No. E-8930
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A versatile computer program is presented which achieves a rapid, numerical solution of the Reynolds equation for a flat sector thrust pad bearing with either compressible or liquid lubricants. Program input includes a range in values of the geometric and operating parameters of the sector bearing. Performance characteristics are obtained from the calculated bearing pressure distribution. These are the load capacity, center-of-pressure coordinates, frictional energy dissipation, and flow rates of liquid lubricant across the bearing edges. Two sample problems are described.

17. Key Words (Suggested by Author(s)) Computer program; Software; Numerical analysis; Reynolds equations; Lubrication; Thrust bearing analysis	18. Distribution Statement Unclassified - unlimited STAR Category 61

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

COMPUTER PROGRAM FOR FLAT SECTOR

THRUST BEARING PERFORMANCE

by Alden F. Presler and Izhak Etsion

Lewis Research Center

SUMMARY

A versatile computer program is presented which achieves a rapid, numerical solution of the Reynolds equation for a flat sector thrust pad bearing with either compressible or liquid lubricants. Program input includes a range in values of the geometric and operating parameters of the sector bearing. Performance characteristics are obtained from the calculated bearing pressure distribution. These are the load capacity, center-of-pressure coordinates, frictional energy dissipation, and flow rates of liquid lubricant across the bearing edges. Two sample problems are described and solved, one each for gas and liquid lubricants.

E-8930

INTRODUCTION

The computer program presented in this report calculates the performance characteristics of both gas and liquid lubricated flat sector pad thrust bearings.

A typical pad configuration is shown in figure 1. The bearing consists of several pads each of which has an extent angle β and inner and outer radii r_i and r_o, respectively. Each pad assumes both pitch and roll with respect to the rotating runner to provide a (generally) converging film thickness in the direction of rotation.

In a recent paper (ref. 1) it was shown that any pitch and roll of a sector shaped pad about a certain point can be transformed to a corresponding pure pitch about a certain radial line. This can be understood from figure 1 by visualizing a plane parallel to the runner that goes through the origin of the sector (point 0 in fig. 1). The radial pivot line is the intersection between this parallel plane and the plane of the tilted sector, and it can be either within or outside the sector boundaries.

Based on this observation the flat sector thrust pad has been analyzed for both compressible and incompressible lubricants in references 1 and 2.

The objects of this report are to: (1) describe the numerical analysis and solution of the basic Reynolds' equation, (2) document the resulting computer programs FSTBP1 and FSTBP2 for compressible (gas) and incompressible (liquid) lubricants, respectively, and (3) serve as a users guide for these two programs.

Input data for the programs describe the physical characteristics and the geometry of the sector pad. These are inner-to-outer radius ratio, pad angle extent, pad pivot angle, the ratio of pad pitch to minimum film thickness, and bearing compressibility number (this is not specified for liquid films).

The computed results include the pad thrust loading, the frictional power loss coefficient, and the center-of-pressure coordinates. Additional calculated results are flow leakage from the downstream edges for the liquid film case. (For a complete bearing the results of the several pads are added.)

This report also contains six appendices which give complete detsils of the numerical methods of solution, two FORTRAN listings of the computer programs, and two sample problems with output listings.

STATEMENT OF THE PROBLEM

It is required to develop a computer program that numerically solves the lubrication boundary value problem defined physically by the Reynolds equation over a tilted sector pad.

The Reynolds equations are essentially diffusion equations for the lubricant film pressure. In cylindrical coordinates the equation for the isothermal compressible case with density proportional to pressure is

$$\frac{\partial}{\partial r}\left(\frac{rph^3}{\mu}\frac{\partial p}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{ph^3}{\mu}\frac{\partial p}{\partial \theta}\right) = 6r\omega\frac{\partial (ph)}{\partial \theta} \tag{1}$$

and for the incompressible lubricant film

$$\frac{\partial}{\partial r}\left(\frac{rh^3}{\mu}\frac{\partial p}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial \theta}\right) = 6r\omega\frac{\partial h}{\partial \theta} \tag{2}$$

The lubricant film thickness is expressed in terms of the independent variables r and θ. By considering the clearance h_o along the pivot line as a reference, the film thickness at any point (r, θ) is given by

$$h = h_o + \gamma r \sin(\theta_p - \theta) \tag{3}$$

where γ is the amount of tilt or pitch about this line. All of the symbols used in these and the following equations are defined in appendix A.

The normalized (dimensionless) form of these equations are

$$\frac{\partial}{\partial R}\left(H^3RP\frac{\partial P}{\partial R}\right)+\frac{1}{R}\frac{\partial}{\partial \theta}\left(H^3P\frac{\partial P}{\partial \theta}\right)=\Lambda H_2^2R\frac{\partial}{\partial \theta}(PH) \tag{4}$$

for compressible films, and

$$\frac{\partial}{\partial R}\left(RH^3\frac{\partial P}{\partial R}\right)+\frac{1}{R}\frac{\partial}{\partial \theta}\left(H^3\frac{\partial P}{\partial \theta}\right)=H^2R\frac{\partial H}{\partial \theta} \tag{5}$$

for an incompressible lubricant. From equation (3), the film thickness becomes

$$H = 1 + \epsilon R \sin(\theta_p - \theta)$$

Normalization of the variables leading to equations (4) to (6) is described in references 1 and 2.

The pressure distribution over the pad area is obtained by numerically solving equation (4) or (5) under boundary conditions which are defined in the next section. Further sector pad calculations are based on this pressure distribution.

The following bearing performance characteristics are then calculated:

(1) Pad load $\overline{W}$

(2) Center-of-pressure coordinates R_{cp}, θ_{cp}

(3) Power loss coefficient (normalized coefficient of friction) $\overline{F}/\overline{W}$

(4) Volumetric lubricant flow rates across the sector pad edges (liquids only) q_{le}, q_{te}, q_{so}, and q_{si}

Inputs are in vector arrays with a range of design parameter values:

(1) Pad dimensions -

(a) Inner radius ratio $R_i = r_i/r_o > 0$

(b) Sector angle β in degrees

(2) Pivot line angle ratio θ_p/β

(3) Compressibility factor (also called "bearing number") Λ, for the gas film case

(4) Ratio of pad slope to minimum pad-runner clearance $\epsilon/H_2 > 0$

METHOD OF SOLUTION

The two forms of the Reynolds equation are first transformed to the following boundary value problems, which are then solved numerically for specific boundary conditions.

Find a function $u(R, \theta)$ that satisfies the equation

$$L(u) = f(R, \theta) \tag{7}$$

on the domain

$$\mathscr{D} = \left(\theta, R \middle| 0 \le \theta \le \beta;\ R_i \le R \le 1;\ \beta - \frac{\pi}{2} < \theta_p < \frac{\pi}{2}\right) \tag{8}$$

In the compressible case, L is the nonlinear operator

$$\left.\begin{aligned} L &= \frac{\partial^2}{\partial R^2} + \frac{1}{R^2}\frac{\partial^2}{\partial \theta^2} - \left(\frac{\partial}{\partial R}\ln\frac{H}{R}\right)\frac{\partial}{\partial R} - \left(\frac{1}{R^2}\frac{\partial}{\partial \theta}\ln\frac{H}{R} + \frac{\Lambda H_2^2}{H\sqrt{Q}}\right)\frac{\partial}{\partial \theta} \\ u &= Q = (PH)^2 \\ f &= 0 \\ \text{and} \quad u &= H^2 \text{ on boundary } \partial\mathscr{D},\ (P = 1) \end{aligned}\right\} \tag{9}$$

In the incompressible case, L is the linear operator

$$\left.\begin{aligned} L &= \frac{\partial^2}{\partial R^2} + \frac{1}{R^2}\frac{\partial^2}{\partial \theta^2} + \left(\frac{\partial}{\partial R}\ln RH^3\right)\frac{\partial}{\partial R} + \left(\frac{1}{R^2}\frac{\partial}{\partial \theta}\ln RH^3\right)\frac{\partial}{\partial \theta} \\ u &= P \\ f &= \left(\frac{H_2^2}{H^3}\right)\frac{\partial H}{\partial \theta} \\ \text{and} \quad u &= 0 \text{ on boundary } \partial\mathscr{D},\ (P = 0) \end{aligned}\right\} \tag{10}$$

Note again that on the pad boundary $P = 1$ (compressible) and $P = 0$ (incompressible). On the boundary $\partial\mathscr{D}$ the pressure is fixed at the ambient value, $p = p_a$, for both gas and liquid lubricant cases. But the definition of dimensionless pressure differs:

$$\left.\begin{aligned} P &= \frac{p}{p_a} \text{ (compressible)} \\ P &= \frac{p - p_a}{K} \text{ (incompressible)} \end{aligned}\right\} \tag{11}$$

where

$$K = \frac{6\mu\omega r_o^2}{h_2^2}$$

Numerical solution of equation (9) or (10) is described in appendix B. These boundary value equations are approximated by finite difference equations on a polar mesh over the sector pad area as indicated in figure 2. In order to adopt Simpson Rule integration formula, the R and θ intervals are divided into even numbers of increments.

As indicated in the previous section, the solution of the equations is in the form of the film pressure distribution over the pad area. From this distribution the thrust pad performance characteristics are obtained by Simpson Rule integration of the following expressions:

Normalized load capacity

$$\overline{W} = \frac{W}{p_a r_o^2} = \int_{R_i}^{1} \int_{0}^{\beta} (P - 1)\, R\, d\theta\, dR \text{ (compressible)} \tag{12a}$$

or

$$\overline{W} = \frac{W}{K r_o^2} = \int_{R_i}^{1} \int_{0}^{\beta} PR\, d\theta\, dR \text{ (incompressible)} \tag{12b}$$

Unit load

$$\left.\begin{aligned} UL &= \frac{W}{P_a A} \text{ (compressible)} \\ UL &= \frac{W}{KA} \text{ (incompressible)} \end{aligned}\right\} = \frac{2\overline{W}}{\beta\left(1 - R_i^2\right)} \tag{13}$$

where the $\overline{W}$ is calculated from equation (12a) or (12b) depending on fluid type.

Center-of-pressure radial coordinate

$$R_{cp} = \int_0^\beta \int_{R_i}^1 \frac{(P - 1)R^2 \, dR \, d\theta}{\overline{\overline{W}}} \text{ (compressible)} \tag{14a}$$

or

$$R_{cp} = \int_0^\beta \int_{R_i}^1 \frac{PR^2 \, dR \, d\theta}{\overline{\overline{W}}} \text{ (incompressible)} \tag{14b}$$

Center-of-pressure angle coordinate

$$\theta_{cp} = \sin^{-1}\left[\int_0^\beta \int_{R_i}^1 \frac{(P - 1)R^2 \, dR \sin \theta \, d\theta}{R_{cp}\overline{\overline{W}}}\right] \text{ (compressible)} \tag{15a}$$

or

$$\theta_{cp} = \sin^{-1}\left(\int_0^\beta \int_{R_i}^1 \frac{PR^2 \, dR \sin \theta \, d\theta}{R_{cp}\overline{\overline{W}}}\right) \text{ (incompressible)} \tag{15b}$$

Center-of-pressure distance from pivot line

$$X_{cp} = R_{cp} \sin(\theta_{cp} - \theta_p) \tag{16}$$

Power loss coefficient

$$\frac{\overline{\overline{F}}}{\overline{\overline{W}}} = \frac{1}{6\overline{\overline{W}}} \int_0^\beta \int_{R_i}^1 \left(\frac{\Lambda R^3}{H/H_2} + 3R \frac{H}{H_2} \frac{\partial P}{\partial \theta}\right) dR \, d\theta \tag{17}$$

Equation (17) holds for both compressible fluids (Λ variable) and incompressible fluids. In the incompressible case, the program puts $\Lambda = 1$.

Volumetric flow rates across the pad edges are:

Trailing edge:

$$q_{te} = \frac{1}{2}\left(1 - R_i^2\right) + \frac{1}{3}\left(1 - R_i^3\right)\sin(\theta_p - \beta) - \int_{R_i}^{1}\left[\frac{H^3}{H_2^3 R}\left(\frac{\partial P}{\partial \theta}\right)\right]_{\theta=\beta} dR \qquad (18)$$

Leading edge:

$$q_{le} = \frac{1}{2}\left(1 - R_i^2\right) + \frac{1}{3}\left(1 - R_i^3\right)\sin\theta_p - \int_{R_i}^{1}\left[\frac{H^3}{H_2^3 R}\left(\frac{\partial P}{\partial \theta}\right)\right]_{\theta=0} dR \qquad (19)$$

Outer arc:

$$q_{so} = -\int_{0}^{\beta}\left[\left(\frac{H}{H_2}\right)^3\left(\frac{\partial P}{\partial R}\right)\right]_{R=1} d\theta \qquad (20)$$

Inner arc:

$$q_{si} = +R_i\int_{0}^{\beta}\left[\left(\frac{H}{H_2}\right)^3\left(\frac{\partial P}{\partial R}\right)\right]_{R=R_i} d\theta \qquad (21)$$

Flow is defined as positive in the direction of increasing R and θ.

FORTRAN PROGRAM

General Description

The foregoing analysis has resulted in two thrust pad computer programs: FSTBP1 for compressible fluid films, and FSTBP2 for incompressible lubricant films. The FORTRAN listing for each program is given in appendix C, and flow chart diagrams are presented in appendix D. The dictionary of the FORTRAN symbols used in the computer programs is appendix E.

Both programs have identical structure in the number and function of the subprograms, and in the general format of the input data.

The first flow diagram in appendix D, that of the supervisory module MAIN2, presents a compact overview of the logical sequence which the computer programs follow in producing pad performance characteristics from input operating conditions.

The first part of the computer program, which includes the first four subroutines called by the module MAIN2, accomplishes the numerical solution of the Reynolds equation using a Gauss-Seidel iterative method with under- or over-relaxation. Upon convergence of the iterations, the calculated film pressure distribution under the sector pad is passed to the second part of the program which performs the numerical double integrations on equations (12) to (17) resulting in the bearing pad performance characteristics.

A brief explanation of the function of each of the program modules follows:

(1) MAIN2 is the executive routine for processing multiple cases, and has primary control of logical flow throughout the complete program. The executive routine also controls the printing of the results.

(2) EUCLID creates the mesh ΔR, $\Delta\theta$, and converts all angles to radians.

(3) XBEGN2 tests the given angular position of the pad pivot line against the pad coordinates, and then calculates the minimum film thickness between pad and runner, the pad slope, and the maximum-to-minimum film thickness ratio.

(4) COEFF generates the values of the nodal coefficients for the finite difference representation of the Reynolds equation. It also provides the initial values of the dependent variable for the first iteration of the Gauss-Seidel process.

(5) RELAX is the basic working routine for solving the Reynolds equation by Gauss-Seidel iterative method with a choice of relaxation parameter.

(6) TABULT is an integration subroutine completing the calculation of the pad loading, center-of-pressure coordinates, friction power loss, and lubricant flow rates.

(7) RSIMP uses the Simpson Rule to integrate tabulated functions along the radii at each angle mesh position.

No special effort was made to determine the optimum relaxation factor for the program with given input data. Initially the sequence for $\Omega_k = k/4$, where k was incremented from 1 to 7, was tested for iteration efficiency. It was soon determined that $\Omega_5 = 1.25$ was generally superior to other values tried, and that value was used for most calculations. As compressibility number increased to 100 the optimum value of Ω decreased to 0.75.

Using the Program

The program always starts by reading in a three-card input deck. The contents of these cards is now described (all symbols are repeated in appendix E).

Card 1 (FORMAT 3I6, F8.2, 2E8.1)

NR	number of radial increments (even)
NA	number of angular increments (even)
INTRMX	maximum number of iterations allowed if convergence is not achieved in the solution.
OMEGA	relaxation parameter in the solution procedure.
HALT	cutoff value for minimum film thickness. There is an error return and a warning printout if the calculated HMIN is less than HALT.
RESIDL	convergence criterion; test on maximum change in dependent variable between iterations in subroutine RELAX.

Card 2 (FORMAT 4L6)

Values on this card control logical switches.

DEBUG	when TRUE the values of the dependent variable are printed for all mesh points for each iteration. To avoid printout use FALSE.
TABOUT	when TRUE the film pressure array over all mesh points is printed after convergence of the iteration routine. The value FALSE stops this printout.
OLDQ	a TRUE value saves the dependent variable array after convergence of the iterative procedure so that this array can be used as the starting value for a new iterative calculation when multiple input cases are being calculated. A value of FALSE defines initial pressure as ambient over pad area.
VARGRD	a TRUE value creates a variable mesh grid over the sector pad (fig. 2). Only needed for liquid lubricant calculations.

Card 3 (FORMAT 5I10)

This card sets the size indices for parameter arrays which are read in immediately after this card through namelist "VARBLE."

NTHETA	quantity of θ_p/β values
NRATIO	number of ϵ/H_2 values
NUMRI	selection of RI ratios
NUMBET	number of β values
NUMLMB	how many Λ; can be left blank for liquid calculations.

The parameter data whose array sizes are defined by the values on card 3 are read into the MAIN2 subprogram through the namelist "VARBLE" input, utilizing as many cards as is necessary. These are without format description, and are now listed.

TRATIO (I) I=1, NTHETA	array of pivot line angles θ_p/β
ERATIO (I) I=1, NRATIO	array of input parameters $\gamma r_o/h_2 = \epsilon/H_2$
VRI (J) J=1, NUMRI	array of inner to outer radius ratios, r_i/r_o
VBETA (J) J=1, NUMBET	array for pad angle size β
VLMBDA (J) J=1, NUMLMB	for compressible films, the array of bearing numbers Λ

Documented description of the data input decks are provided at the end of each of the two programs FSTBP1 and FSTBP2 in appendix C.

CONCLUDING REMARKS

We have described a numerical method and computer program for solving two forms of the Reynolds equation within a circular sector region. These two forms of the equation are for compressible and incompressible fluid films.

The numerical method uses a curvilinear cell at each mesh point to derive the finite difference analog to the Reynolds equation. This represents a system of nonlinear equations with prescribed constant boundary values. Two computer programs were developed to solve the finite difference systems representing the compressible and incompressible fluid cases. The programs use a Gauss-Seidel iterative method with relaxation capability.

Input flexibility was built into the programs to allow a wide variation in sector geometry and operating conditions. This allows the program user to quickly evaluate alternative thrust bearing design configurations in order to find the optimum cases.

The programs are easy to use, and have enough generality to be used as the "black box" in situations where steady state solutions to the Reynolds equation are required for circular sector regions.

A rather coarse mesh of about 100 points is sufficient for the bearing load and moment calculations (8 radial divisions and 12 angular divisions). Edge leakage calculations which utilize pressure gradients at the boundaries require a finer mesh (14 radial and 20 angular divisions).

Each case required at most 40 to 50 iterations to satisfy the convergence criterion, and averaged 1 to 2 seconds total time on the UNIVAC 1100/42 computer.

APPENDIX A

MATHEMATICAL SYMBOLS

A	pad area, $\beta\left(r_o^2 - r_i^2\right)/2$
$\mathscr{R}$	closed domain over pad area
$\partial\mathscr{R}$	boundary of pad domain
F	friction power loss
$\overline{F}$	nondimensional power loss, $F/p_a \omega h_2 r_o^2$ (incompressible)
$\overline{F}/\overline{W}$	power loss coefficient, $F/W\omega h_2$
f	forcing function in eq. (7)
H	nondimensional film thickness, h/h_o
H_1	maximum film thickness ratio, h_1/h_o
H_2	minimum film thickness ratio, h_2/h_o
h	film thickness
h_o	constant film thickness along the pivot line
h_1, h_2	maximum and minimum film thickness, respectively
K	$6\mu\omega r_o^2/h_2^2$
L	operator in Reynolds equation (eq. (7))
P	nondimensional pressure, p/p_a (compressible); or $(p - p_a)/K$ (incompressible)
p	pressure
p_a	ambient pressure
Q	$(PH)^2$
q	volumetric edge flow rates, eqs. (18) to (21)
R	nondimensional radius, r/r_o
R_{cp}	nondimensional radius to center of pressure
R_i	nondimensional inner radius, r_i/r_o

r	radial coordinate
r_i	pad inner radius
r_o	pad outer radius
U_{ij}	dependent variable at node (i, j) in difference eq. (E-3)
UL	unit load (eq. (13) $= 2\overline{W}/\beta\left(1 - R_i^2\right)$
u	dependent variable in Reynolds equation (eq. (7))
W	pad load capacity
$\overline{W}$	nondimensional load, $W/p_a r_o^2$ (compressible); or W/Kr_o^2 (incompressible)
α_θ	tilt about a tangent line (roll)
α_r	tilt about a radial line (pitch)
β	angular extent of pad
γ	pitch about pivot line
Δ	finite difference increment
ϵ	tilt parameter, $\gamma r_o/h_o$
ϵ/H_2	clearance parameter, $\gamma r_o/h_2$
θ	angular coordinate
Λ	bearing compressibility number, $6\mu\omega r_o^2/p_a h_2^2$
Ω	relaxation factor
ω	bearing shaft speed

APPENDIX B

NUMERICAL ANALYSIS

Numerical solutions of the Reynolds equations (7) to (10) are obtained by discretizing the partial differential equations and solving the resulting set of difference equations by an iterative technique over the closed region $\mathcal{S}$ of the sector pad area.

The sector pad is partitioned into a polar mesh (fig. 2(a)) with an even number of increments in both coordinates, resulting in an odd number of nodes. A variable mesh capability is provided for the liquid lubricant cases. The finest mesh starts at the pad boundary (fig. 2(b)). The enlarged view of the central difference mesh is shown in figure 3.

In central difference formulations, the dependent variable $U_{i,j}$ at node (i, j) is a function of U at the four surrounding nodes. The central difference operators for the Reynolds equations (7) to (10) are

$$\left.\begin{aligned}
\frac{\partial^2 U}{\partial R^2} &\sim \frac{U_{i+1,j} - 2U_{ij} + U_{i-1,j}}{(\Delta R)^2} \\
\frac{1}{R^2}\frac{\partial^2 U}{\partial \theta^2} &\sim \frac{U_{i,j+1} - 2U_{ij} + U_{i,j-1}}{R_i^2(\Delta\theta)^2} \\
\frac{\partial U}{\partial R} &\sim \frac{U_{i+1,j} - U_{i-1,j}}{2\,\Delta R} \\
\frac{\partial U}{\partial \theta} &\sim \frac{U_{i,j+1} - U_{i,j-1}}{2\,\Delta\theta}
\end{aligned}\right\} \qquad \text{(B-1)}$$

where

$$\left.\begin{aligned}
\Delta\theta &= \frac{\beta}{NA} \\
\Delta R &= \frac{1 - RI}{NR}
\end{aligned}\right\} \qquad \text{(B-2)}$$

The errors in the finite difference operators (B-1) are all of the order $(\Delta R)^2$ and $(\Delta\theta)^2$.

When these finite differences are substituted for the partial derivatives in the L-operator of equation (7), and the coefficient functions of the first order derivatives are expanded, the solution for U_{ij} in terms of the U's at the four surrounding nodes is obtained:

$$U_{ij} = \frac{A_{ij} \cdot U_{i+1,j} + B_{ij} \cdot U_{i-1,j} + C_{ij} \cdot U_{i,j+1} + D_{ij} \cdot U_{i,j-1} + F_{ij}}{E_{ij}} \qquad \text{(B-3)}$$

where the coefficients are given in table B-1.

The solution of equation (B-3) proceeds from an initial estimate of the $U_{ij}^{(1)}$ over the mesh $1 \le i \le NR + 1$, $1 \le j \le NA + 1$. It is always safe, if not efficient, to start with ambient pressure across the film mesh, that is,

$$\left.\begin{aligned} P_{ij}^{(1)} &= 1 \\ U_{ij}^{(1)} &= H_{ij}^{2} \text{ (compressible)} \\ U_{ij}^{(1)} &= 0 \text{ (incompressible)} \end{aligned}\right\} \qquad \text{(B-4)}$$

Subsequent calculations of the $U_{ij}^{(n+1)}$ continue from the preceding values of the n^{th} estimates $U_{ij}^{(n)}$, using equation (B-3). In the Gauss-Seidel iterative procedure, the $U_{ij}^{(n)}$ are immediately replaced in the storage array by $U_{ij}^{(n+1)}$ upon calculation, which modifies equation (B-3) to

$$U_{ij}^{(n+1)} = \frac{A_{ij} U_{i+1,j}^{(n)} + B_{ij} U_{i-1,j}^{(n+1)} + C_{ij} U_{i,j+1}^{(n)} + D_{ij} \cdot U_{i,j-1}^{(n+1)} + F_{ij}}{E_{ij}} \qquad \text{(B-5)}$$

over the domain $2 \le i \le NR$, $2 \le j \le NA$.

It is noted from table B-1 that for the compressible films the coefficients C_{ij} and D_{ij} contain the nonlinear term $\sqrt{U_{ij}}$ by way of G_{ij}. This creates no problem as the preceding iterate $U_{ij}^{(n)}$ is always used in the G_{ij} for equation (B-5).

Relaxation of the basic iterative numerical procedure is used in this report to hasten convergence of the calculations. The relaxation method modifies equation (B-5) to the form

$$U_{ij}^{(n+1)} = \frac{(1-\Omega)U_{ij}^{(n)} + \Omega\left[A_{ij}\cdot U_{i+1,j}^{(n)} + \cdot B_{ij}\cdot U_{i-1,j}^{(n+1)} + C_{ij}\cdot U_{ij+1}^{(n)} + D_{ij}\cdot U_{i,j-1}^{(n+1)} + F_{ij}\right]}{E_{ij}} \tag{B-6}$$

where the relaxation factor Ω is between 0 and 2. For $\Omega = 1$, the regular Gauss-Seidel form of equation (B-5) results.

Between successive iterations the change in the solution of equation (B-6) is denoted by

$$\text{TEST} = \left| U_{ij}^{(n+1)} - U_{ij}^{(n)} \right| \tag{B-7}$$

The largest value of TEST in one complete solution of equation (B-6) across the domain $\mathscr{S}$ is stored as STRERR. At the completion of each solution on $\mathscr{S}$, the maximum deviation or error between iterations is tested against a convergence criterion called RESIDL. When STRERR < RESIDL the numerical solution of equation (B-6) is defined as accomplished.

The pressure distribution over the pad domain $\mathscr{S}$ is determined from the last solution U_{ij} after convergence using the definitions in equations (9) and (10):

$$\left.\begin{aligned} P_{ij} &= \frac{\sqrt{U_{ij}}}{H_{ij}} \quad \text{(compressible)} \\ P_{ij} &= U_{ij} \quad \text{(incompressible)} \end{aligned}\right\} \tag{B-8}$$

The bearing performance characteristics $\overline{W}$, R_{cp}, and θ_{cp} are expressed by equations (11), (13), and (14), respectively. The numerical integrations are accomplished using Simpson's 1/3 Rule, and are in two steps. The first carries out the radial integration

$$XF_{j,K} = \frac{\Delta R}{3}\left\{(P_{i,j} - 1)R_1^K - (P_{NR+1,j} - 1) + \sum_{i=1}^{NR/2}\left[4(P_{2i,j} - 1)R_{2i}^K + 2(P_{2i+1,j} - 1)R_{2i+1}^K\right]\right\} \qquad K = 1, 2 \tag{B-9}$$

The circumferential integration step completes the calculation:

$$INT_K = \frac{\Delta\theta}{3}\left[XF_{1,K} - XF_{NA+1,K} + \sum_{i=1}^{NA/2}(4XF_{2i,K} + 2XF_{2i+1,K})\right]$$

where

$$\overline{W} = INT_{K=1}$$

and

$$R_{cp} = INT_{K=2} \qquad \text{(B-10)}$$

The θ_{cp} calculation requires first

$$AA = \frac{\Delta\theta}{3}\left[- XF_{NA+1,2}\sin\beta + \sum_{i=1}^{NA/2}(4XF_{2i,2}\sin\theta_{2i} + 2XF_{2i+1,2}\sin\theta_{2i+1}\right]$$

(B-11)

and finally

$$\theta_{cp} = \sin^{-1}\frac{AA}{(\overline{W}\cdot R_{cp})} \qquad \text{(B-12)}$$

The terms $(P_{ij} - 1)$ in equation (B-9) are correct only for the compressible case, and represent gage pressures. These terms must be just P_{ij} for the incompressible solution as is derived from the second expression in equation (B-8).

The power loss coefficient, equation (17), and the leakage integrals, equations (18) to (21), require the evaluation of the first derivatives of pressure along the domain boundary $\partial\mathcal{D}$. In order to achieve the same order of accuracy for the finite difference approximations on the boundaries as for the central difference expressions in equations (B-1), the following forward difference operation at the leading edge and inside radius are used:

$$\left(\frac{\partial P}{\partial\theta}\right)_{\substack{\theta=0\\ R_i<R<1}} \cong \frac{-3P_{i,1} + 4P_{i,2} - P_{i,3}}{2\,\Delta\theta} \qquad \text{(B-13)}$$

$$\left(\frac{\partial P}{\partial R}\right)_{\substack{\theta=\theta_j \\ R=R_i}} \cong \frac{-3P_{1,j} + 4P_{2,j} - P_{3,j}}{2\,\Delta R} \tag{B-14}$$

At the trailing edge, and along the outside radius of the pad, the backward difference operators are used:

$$\left(\frac{\partial P}{\partial \theta}\right)_{\substack{\theta=\beta \\ R_i<R<1}} \cong \frac{P_{i,NA-1} - 4P_{i,NA} + 3P_{i,NA+1}}{2\,\Delta\theta} \tag{B-15}$$

$$\left(\frac{\partial P}{\partial R}\right)_{\substack{\theta=\theta_j \\ R=1}} \cong \frac{P_{NR-1,j} - 4P_{NR,j} + 3P_{NR+1,j}}{2\,\Delta R} \tag{B-16}$$

As with the central difference operators (B-1), the forward and backward difference operators (B-13) to (B-16) are of the order $(\Delta R)^2$ and $(\Delta\theta)^2$ in error.

Since the pressures in the gradient expressions can be gage pressures, and since gage $P_{ij} = 0$ on $\partial\mathcal{R}$, equations (B-13) to (B-16) can be further simplified to

$$\left(\frac{\partial P}{\partial \theta}\right)_{\substack{\theta=0 \\ R_i<R<1}} \cong \frac{4P_{i,2} - P_{i,3}}{2\,\Delta\theta}$$

$$\left(\frac{\partial P}{\partial R}\right)_{\substack{\theta=\theta_j \\ R=R_i}} \cong \frac{4P_{2,j} - P_{3,j}}{2\,\Delta R}$$

$$\left(\frac{\partial P}{\partial \theta}\right)_{\substack{\theta=\beta \\ R_i<R<1}} = \frac{P_{i,NA-1} - 4P_{i,NA}}{2\,\Delta\theta}$$

$$\left(\frac{\partial P}{\partial R}\right)_{\substack{\theta=\theta_j \\ R=1}} = \frac{P_{NR-1,j} - 4P_{NR,j}}{2\,\Delta R}$$

TABLE B-1. - COEFFICIENTS FOR CENTRAL DIFFERENCE

APPROXIMATION OF REYNOLDS EQUATION (EQ. (B-3))

Coefficient	Compressible films $U_{ij} = Q_{ij} = (P_{ij}H_{ij})^2$	Incompressible films $U_{ij} = P_{ij}$
A_{ij}	$\frac{1}{(\Delta R)^2} + \frac{1}{2 \cdot R_i H_{ij} \cdot \Delta R}$	$\frac{1}{(\Delta R)^2} + \frac{1}{2 \cdot R_i \cdot \Delta R}\left(4 - \frac{3}{H_{ij}}\right)$
B_{ij}	$\frac{1}{(\Delta R)^2} - \frac{1}{2 \cdot R_i H_{ij} \cdot \Delta R}$	$\frac{1}{(\Delta R)^2} - \frac{1}{2 \cdot R_i \cdot \Delta R}\left(4 - \frac{3}{H_{ij}}\right)$
C_{ij}	$\frac{1}{R_i^2(\Delta \theta)^2} + \frac{\epsilon \cdot \cos(\theta_p - \theta_j)}{2 \cdot R_i H_{ij} \cdot \Delta \theta} - G_{ij}$	$\frac{1}{R_i^2(\Delta \theta)^2} - \frac{3 \cdot \epsilon \cdot \cos(\theta_p - \theta_j)}{2 \cdot R_i H_{ij} \cdot \Delta \theta}$
D_{ij}	$\frac{1}{R_i^2(\Delta \theta)^2} - \frac{\epsilon \cdot \cos(\theta_p - \theta_j)}{2 \cdot R_i H_{ij} \cdot \Delta \theta} + G_{ij}$	$\frac{1}{R_i^2(\Delta \theta)^2} + \frac{3 \cdot \epsilon \cdot \cos(\theta_p - \theta_j)}{2 \cdot R_i H_{ij} \cdot \Delta \theta}$
E_{ij}	$2 \cdot \left[\frac{1}{(\Delta R)^2} + \frac{1}{R_i^2(\Delta \theta)^2}\right]$	$2 \cdot \left[\frac{1}{(\Delta R)^2} + \frac{1}{R_i^2(\Delta \theta)^2}\right]$
F_{ij}	0	$\frac{R_i \cdot H_2^2 \cdot \epsilon \cdot \cos(\theta - \theta_j)}{H_{ij}^3}$
G_{ij}	$\frac{\Lambda \cdot H_2^2}{2 \cdot H_{ij} \cdot \sqrt{U_{ij}}\ \Delta \theta}$	0
H_{ij}	$1 + \epsilon \cdot R_i \cdot \sin(\theta_p - \theta_j)$	$1 + \epsilon \cdot R_i \cdot \sin(\theta_p - \theta_j)$

APPENDIX C

FORTRAN PROGRAMS

FSTBP1

Flat Sector Pad Thrust Bearing Program Number 1 -- gas lubricant.


```
*TPF$(O).MAIN2
      C
      C**MAIN EXECUTIVE FOR GAUSS-SEIDEL ITERATION
      C
            REAL LAMBDA,OMEGA
            LOGICAL DEBUG,TABOUT,OLDQ,VARGRD
      C
            COMMON/BLOGIC/DEBUG,TABOUT,OLDQ,VARGRD
            COMMON/GEOM/ANGB,THPR,DR,DA
            DIMENSION EXIT(5),TRATIO(15),ERATIO(26)
            DIMENSION VRI(10),VBETA(10),VLMBDA(10)
            NAMELIST/VARBLE/TRATIO,ERATIO,VRI,VBETA,VLMBDA
      C
       1    FORMAT(3I6,F8.2,2E8.1)
       2    FORMAT(4L6)
       3    FORMAT(5I10)
       4    FORMAT(2X,12HNO. OF ROWS=,I3,16H    NO. OF COLS=,I3,26H    MAX NO.
           1 OF ITERATIONS=,I4,25H    RELAXATION PARAMETER=,F4.2,19H    RESIDU
           2AL ERROR=,F10.7/2X,36HSMALLEST ALLOWED FILM THICKNESS HALT =,
           3G10.4//)
       5    FORMAT(2X,39HTHE MINIMUM FILM THICKNESS IS LESS THAN,G10.4//)
      C
      C
            READ(5,1)NR,NA,ITERMX,OMEGA,HALT,RESIDL
            READ(5,2)DEBUG,TABOUT,OLDQ,VARGRD
            READ(5,3)NTHETA,NRATIO,NUMRI,NUMBET,NUMLMB
            READ(5,VARBLE)
      C
            WRITE(6,4)NR,NA,ITERMX,OMEGA,RESIDL,HALT
            WRITE(6,900)                      @ HEADING PRINTOUT..
            IPRINT=0                          @ INITIALIZE PRINT SWITCH...
      C
            DO 500 NRI=1,NUMRI                @ INCREMENT INNER RADIUS VALUES..
               RI=VRI(NRI)
      C
            DO 400 NBETA=1,NUMBET             @ INCREMENT BETA VALUES..DEGREES.
               BETA=VBETA(NBETA)
      C
            DO 300 NLMBD=1,NUMLMB             @ INCREMENT BEARING NUMBER VALUES
               LAMBDA=VLMBDA(NLMBD)
      C
            DO 200 NANGLE=1,NTHETA            @ INCREMENT THETAP/BETA RATIO
               XXTHTP=TRATIO(NANGLE)
               CALL EUCLID(NR,NA,RI,BETA,XXTHTP)    @ RETURNS GEOMETRIC PARAMS.
               KOUNT=0
      C
      C
                              IF(IPRINT.GT.0)GO TO 8
                              WRITE(6,910)
                              GO TO 10
       8                      WRITE(6,915)      @PRINT START TOP OF PAGE..
       10                     WRITE(6,920)
                              WRITE(6,930)RI,BETA,LAMBDA,XXTHTP
                              WRITE(6,940)
                              WRITE(6,950)
      C
               DO 100 NFILM=1,NRATIO          @ INCREMENT EPS/H2 RATIO
```

```
            ERAT=ERATIO(NFILM)
C
C
          CALL BEGIN2(EPS,HALT,HMIN,HRAT,ERAT,RI,$12)    @FILM THICKNESS CALCS..
          GO TO 15
C
 12       WRITE(6,5)HMIN                      @ ERROR EXIT..
        GO TO 100
C
 15       HLMBDA=LAMBDA*HMIN**2
          IF(KOUNT.GT.0)GO TO 21
          CALL ARRAYS(NR,NA,EPS,KOUNT,RI,HLMBDA)    @FINITE DIFF. COEFFS.
          CALL RELAX(NR,NA,OMEGA,ITERMX,RESIDL)  @SOLVE REYNOLDS EQUATION.
          CALL TABULT(NR,NA,RI,EXIT,LAMBDA,HMIN)  @INTEGRALS OF PRESSURE
                                                  @OVER PAD AREA..
C
        GO TO 22
C
 21       CALL RARRAY(EPS,KOUNT,HLMBDA)         @ENTRY TO SUBROUTINE ARRAYS.
          CALL RRELAX                       @DITTO FOR THE GAUSS-SEIDEL ROUTINE.
          CALL RTAB(EXIT,LAMBDA,HMIN)  @ENTRY TO INTEGRAL CALCS..
C
 22                            RR=EXIT(1)
                               AA=EXIT(2)
                               WW=EXIT(3)
                               FF=EXIT(4)
                            WUNIT=EXIT(5)
C
                               XCP=RR*SIN(ANGB*AA-THPR)
                               HCP=1.-EPS*XCP
                               H2CP=HMIN/HCP
                               HINVRS=1./HMIN
                               R3=ERAT
                               R7=FF/WW
C
C
C
          WRITE(6,960)HRAT,HINVRS,R3,WW,WUNIT,FF,R7,H2CP,RR,AA,XCP
C
          KOUNT=KOUNT+1
 100    CONTINUE
        IPRINT=IPRINT+1
 200    CONTINUE
C
 300    CONTINUE
 400    CONTINUE
 500    CONTINUE
C
 900    FORMAT(1H1//40X,40HNUMERICAL RESULTS - GAS BEARING ANALYSIS/40X,
       128HLEWIS RESEARCH CENTER (NASA)////)
 910    FORMAT(50X,17HSYSTEM PARAMETERS//15X,4H(P1),25X,4H(P2),28X,4H(P3),
       127X,4H(P4)///)
 915    FORMAT(1H1//50X,17HSYSTEM PARAMETERS//15X,4H(P1),25X,4H(P2),28X,
       14H(P3),27X,4H(P4)///)
 920    FORMAT(10X,17HINNER/OUTER RADII,14X,17HBEARING PAD ANGLE,14X,14HBE
       1ARING NUMBER,14X,17HPIVOT ANGLE RATIO//14X,5HRI/RO,22X,14HBETA (DE
       2GREES),19X,7HLAMBDA ,20X,11HTHETAP/BETA//)
```

```
930  FORMAT(15X,G10.5,20X,G10.5,20X,G10.5,20X,G10.5///)
940  FORMAT(50X,17HNUMERICAL RESULTS//5X,4H(R1),8X,4H(R2),8X,4H(R3),8X,
    14H(R4),8X,4H(R5),8X,4H(R6),8X,4H(R7),8X,4H(R8),8X,4H(R9),8X,5H(R10
    2),7X,5H(R11)//)
950  FORMAT(5X,5HH1/H2,7X,4H1/H2,5X,10HEPSILON/H2,3X,9HLOAD,WBAR,3X,9HU
    1NIT-LOAD,2X,10HFRICTION,F,4X,6HF/WBAR,5X,8HH2/H(CP),5X,5HR(CP),5X,
    210HTHETA(CP)/,4X,5HX(CP)/117X,4HBETA//)
960  FORMAT(11(2X,G10.5)/)
C
     STOP
     END
```

```
*TPF$(0).XCART
      SUBROUTINE EUCLID(NR,NA,RI,BETA,THRAT)
C
C..SUBPROGRAM PRODUCES COMMON BLOCK CONTAINING GEOMETRIC PARAMETERS..
C
      COMMON/GEOM/ANGB,THPR,DR,DA
C
      FACT=6.2831853/360.       @ 2 PI RADIANS/360 DEGREES...
      ANGB=BETA*FACT           @BETA IN RADIANS..
      THPR=THRAT*ANGB          @THETAP(PIVOT ANGLE) IN RADIANS..
      DR=(1.-RI)/FLOAT(NR)     @RADIAL INCREMENT..
      DA=ANGB/FLOAT(NA)        @ANGLE INCREMENT IN RADIANS..
C
      RETURN
      END
```

```
TPF$(D).XBEGN2
        SUBROUTINE BEGIN2(E,HALT,HMIN,HRATIO,ERATIO,RI,$)
C
        COMMON/GEOM/BTR,THPR,DR,DA
        THETAP=THPR
        BETA=BTR
        RAD90=1.5707963         @90 DEGREES IN RADIANS..
C
C
C..CALCULATE MINIMUM FILM RATIO AND BEARING NUMBER..
C
C
C..REGION NUMBER 1....PIVOT ANGLE = THETAP .LT. 0 ...
 10     IF(THETAP.GE.0.0) GO TO 20
           EPS=ERATIO/(1.-ERATIO*SIN(THETAP-BETA))
           HMIN=EPS/ERATIO
           HRATIO=(1.+EPS*RI*SIN(THETAP))/HMIN
           IF(HMIN.LT.HALT) RETURN 7
           GO TO 100
C
C..REGION NUMBER 2....THETAP .GE. ZERO AND .LE. BETA ...
 20     IF(THETAP.GT.BETA) GO TO 30
           EPS=ERATIO/(1.-ERATIO*SIN(THETAP-BETA))
           HMIN=EPS/ERATIO
           HRATIO=(1.+EPS*SIN(THETAP))/HMIN
           IF(HMIN.LT.HALT) RETURN 7
           GO TO 100
C
C..REGION NUMBER 3....THETAP .GT. BETA AND .LT. 90 DEGREES ...
 30     IF(THETAP.GT.RAD90)GO TO 40
           EPS=ERATIO/(1.-ERATIO*RI*SIN(THETAP-BETA))
           HMIN=EPS/ERATIO
           HRATIO=(1.+EPS*SIN(THETAP))/HMIN
           IF(HMIN.LT.HALT) RETURN 7
           GO TO 100
C
C..REGION NUMBER 4.... THETAP .GT. 90 DEGREES ...
 40        EPS=ERATIO/(1.-ERATIO*RI*SIN(THETAP-BETA))
           HMIN=EPS/ERATIO
           HRATIO=(1.+EPS)/HMIN
           IF(HMIN.LT.HALT)RETURN 7
C
 100    CONTINUE
        E=EPS
        RETURN
C
        END
```

```
*TPF$(D).COEFF
        SUBROUTINE ARRAYS(NR,NA,EPS,KK,RI,HLMBDA)
C
C..SUBPROGRAM CALCULATES VALUES OF THE NODAL COEFFICIENTS AND THE INITIAL
C..VALUES OF THE DEPENDENT VARIABLE FOR THE FIRST ITERATION
C
        LOGICAL DEBUG,OLDQ
C
        COMMON/GEOM/ANGB,THPR,DR,DA
        COMMON/BLKA/A(15,21)/BLKB/B(15,21)/BLKC/C(15,21)/BLKD/D(15,21)
        COMMON/BLKE/E(15,21)/BLKG/G(15,21)/BLKH/H(15,21)/BLKQ/Q(15,21)
        COMMON/BLKR/R(15)/BLKTH/TH(21)
        COMMON/BLOGIC/DEBUG,TABOUT,OLDQ,VARGRD
C
C
        LASTR=NR+1
        LASTA=NA+1
        CR1=.5/DR
        CR2=1./DR**2
        CA1=.5/DA
        CA2=1./DA**2
        GO TO 5
C
C
        ENTRY RARRAY(EPS,KK,HLMBDA)
 5      THETA=0.D
        DO 2 JA=1,LASTA
           RAD=RI
           TH(JA)=THETA
           ANG=(THPR-THETA)          @ANGLE FROM PIVOT LINE IN RADIANS
           STRIG=EPS*SIN(ANG)
           CTRIG=EPS*COS(ANG)
C
           DO 1 JR=1,LASTR
              R(JR)=RAD
              HRA=1.+RAD*STRIG
C
              IF(KK.EQ.0) GO TO 6
              IF(.NOT.OLDQ) GO TO 6
              IF(JA.EQ.1.OR.JA.EQ.NAP1) GO TO 6
              IF(JR.EQ.1.OR.JR.EQ.NRP1) GO TO 6
C
              HRATIO=HRA/H(JR,JA)
              Q(JR,JA)=Q(JR,JA)*HRATIO**2
              GO TO 7
C
 6            Q(JR,JA)=HRA**2
 7            H(JR,JA)=HRA
              FRST=1./RAD-STRIG/HRA
              SCND=CTRIG/(RAD*HRA)
              CA2RAD=CA2/RAD**2
C
              A(JR,JA)=CR2+CR1*FRST
              B(JR,JA)=CR2-CR1*FRST
              C(JR,JA)=CA2RAD+CA1*SCND
              D(JR,JA)=CA2RAD-CA1*SCND
              E(JR,JA)=2.*(CR2+CA2RAD)
```

```
          G(JR,JA)=HLMBDA*CA1/HRA
C
          IF(.NOT.DEBUG)GO TO 4
          WRITE(6,3)JR,JA,THETA,RAD      @BEGIN DEBUG SEARCH
          WRITE(6,3)JR,JA,STRIG,CTRIG
          WRITE(6,3)HRA,Q(JR,JA),A(JR,JA),B(JR,JA),C(JR,JA),D(JR,JA),
     1    E(JR,JA),G(JR,JA)
C
    4     RAD=RAD+DR
    1   CONTINUE
        THETA=THETA+DA
    2 CONTINUE
    3 FORMAT( )       @FORMAT-FREE WRITE STATEMENT FOR DEBUG
      RETURN
      END
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
*TPF$(0).SEIDEL
      SUBROUTINE RELAX(NR,NA,OMEGA,ITERMX,RESIDL)
C
C..GAUSS-SEIDEL ITERATION WITH CONVERGENCE WHEN LARGEST DIFFERENCE BETWEEN
C..SUCCESSIVE ITERATIONS FOR ANY MATRIX ELEMENT IS LESS THAN THE INITIALIZED
C..PARAMETER "RESIDL"
C
      COMMON/BLKA/A(15,21)/BLKB/B(15,21)/BLKC/C(15,21)/BLKD/D(15,21)
      COMMON/BLKE/E(15,21)/BLKG/G(15,21)/BLKH/H(15,21)/BLKQ/Q(15,21)
      COMMON/BLKP/PNORM(15,21)/BLKR/R(15)/BLKTH/TH(21)
      COMMON/BLOGIC/DEBUG,TABOUT,OLDQ,VARGRD
C
      LOGICAL DEBUG,TABOUT
      REAL OMEGA
C
 30   FORMAT( )      @FORMAT FREE WRITE FOR DEBUG
 35   FORMAT(1H0,30X,43HARRAY OF NORMALIZED PRESSURE PNORM(ROW,COL)//
     140X,23HRADII FROM INNER RADIUS//22X,11F10.3//)
 36   FORMAT(1H0,1X,6HTHETA=,F10.4,3X,2HP=,11F10.4//)
C
      GO TO 40
C
      ENTRY RRELAX
 40   DO 300 KK=1,ITERMX
         STRERR=0.0
         DO 200 JJ=2,NA
            DO 100 II=2,NR
               STORQ=Q(II,JJ)             @  Q-VALUE AT LAST ITERATION.
               GSQT=G(II,JJ)/SQRT(STORQ)
               CCOF=C(II,JJ)-GSQT
               DCOF=D(II,JJ)+GSQT
C
               Q(II,JJ)=(1.-OMEGA)*STORQ+OMEGA*(A(II,JJ)*Q(II+1,JJ)+
     1                  B(II,JJ)*Q(II-1,JJ)+CCOF*Q(II,JJ+1)+
     2                  DCOF*Q(II,JJ-1))/E(II,JJ)
               ERROR=Q(II,JJ)-STORQ
C
               IF(.NOT.DEBUG)GO TO 50                      @  DEBUG SWITCH
               WRITE(6,30)II,JJ,STORQ,ERROR,STRERR         @  DEBUG TRACE
 50            TEST=ABS(ERROR)
C
               IF(TEST.LE.STRERR)GO TO 100
               STRERR=TEST                          @UPDATE LARGEST RESIDUAL
               ISTORE=II                            @ROW OF LAST UPDATE
               JSTORE=JJ                            @COLUMN OF LAST UPDATE
               QSTORE=Q(II,JJ)                      @Q-VALUE AT LARGEST RESIDUAL
 100        CONTINUE
 200     CONTINUE
         IF(STRERR.LT.RESIDL)GO TO 400
 300  CONTINUE
 400  CONTINUE
C
      IF(.NOT.DEBUG)GO TO 440
      WRITE(6,30)KK,STRERR,QSTORE,ISTORE,JSTORE,RESIDL
C
 440  LASTR=NR+1
      LASTA=NA+1
```

```
      IF(DEBUG)WRITE(6,30)KK,STRERR,QSTORE,ISTORE,JSTORE @DATA AT END OF
                                                         @ITERATIONS...
C
      DO 460 JA=1,LASTA
         DO 450 JR=1,LASTR
         PNORM(JR,JA)=SQRT(Q(JR,JA)/H(JR,JA)**2)-1.  @NORMALIZED PRESSURE
                                                     @RELATIVE TO ATMOSPHERE
  450    CONTINUE
  460 CONTINUE
C
      IF(.NOT.TABOUT)GO TO 500                       @SKIP NORMALIZED
                                                     @ PRESSURE PRINTOUT
      WRITE(6,35)(R(K),K=1,LASTR)
C
      DO 470 L=1,LASTA
         WRITE(6,36)(TH(L),(PNORM(M,L),M=1,LASTR))
  470 CONTINUE
  500 CONTINUE
C
      RETURN
      END
```

```
TPF$(0).PADCTR
      SUBROUTINE TABULT(NR,NA,RI,EXIT,LAMBDA,HMIN)
C
C..EXECUTIVE FOR INTEGRAL CALCULATIONS TRYING THE SIMPSON 1/3 RULF
C..FOR ANGULAR COORDINATES...
C
      REAL LAMBDA
      COMMON/GEOM/ANGP,THPR,DR,DA
      COMMON/BLKXXX/XF(21,3)     @ARRAY OF INTEGRATION RESULTS FROM SUBR. RSIMP
      DIMENSION ODD(4),EVEN(4),END(4),EXIT(5)
C
      NA2=NA/2-1
      LASTA=NA+1
      GO TO 1
C
      ENTPY RTAB(EXIT,LAMBDA,HMIN)
 1    CALL RSIMP(NR,NA,LAMBDA,HMIN)      @RADIAL INTEGRATION SUBROUTINE
C
      DO 5 I=1,4          @ SET STORAGE VECTORS TO ZERO..
         END(I)=0.0
         EVEN(I)=0.0
         ODD(I)=0.0
 5    CONTINUE
C
      END(1)=END(1)+XF(1,1)+XF(LASTA,1)
      END(2)=END(2)+XF(1,2)+XF(LASTA,2)
      END(3)=END(3)+XF(LASTA,2)*SIN(ANGB)
      END(4)=END(4)+XF(1,3)+XF(LASTA,3)
C
      DO 10 JA=1,NA2                          @INTEGRATION ON INTERIOR ORDS.
         EVEN(1)=EVEN(1)+XF(2*JA,1)
         EVEN(2)=EVEN(2)+XF(2*JA,2)
         EVEN(3)=EVEN(3)+XF(2*JA,2)*SIN(DA*FLOAT(2*JA-1))
         EVEN(4)=EVEN(4)+XF(2*JA,3)
         ODD(1)=ODD(1)+XF(2*JA+1,1)
         ODD(2)=ODD(2)+XF(2*JA+1,2)
         ODD(3)=ODD(3)+XF(2*JA+1,2)*SIN(DA*FLOAT(2*JA))
         ODD(4)=ODD(4)+XF(2*JA+1,3)
 10   CONTINUE
      EVEN(1)=EVEN(1)+XF(NA,1)           @LAST EVEN ORDINATE
      EVEN(2)=EVEN(2)+XF(NA,2)
      EVEN(3)=EVEN(3)+XF(NA,2)*SIN(DA*FLOAT(NA-1))
      EVEN(4)=EVEN(4)+XF(NA,3)
C
C
      WW=DA*(END(1)+4.*EVEN(1)+2.*ODD(1))/3.  @LOAD INTEGRAL.
      RR=DA*(END(2)+4.*EVEN(2)+2.*ODD(2))/3.  @RADIAL MOMENT.
      AA=DA*(END(3)+4.*EVEN(3)+2.*ODD(3))/3.  @ANGLE MOMENT.
      FF=DA*(END(4)+4.*EVEN(4)+2.*ODD(4))/6.  @FRICTION INTEGRAL.
C
      AA=(ASIN(AA/RR))/ANGB                      @ANGULAR C.P. COORDINATE.
      RR=RR/WW                                   @RADIAL C.P. COORDINATE.
      WUNIT=2.*WW/(ANGB*(1.-RI**2))             @UNIT LOAD.
C
                    EXIT(1)=RR
                    EXIT(2)=AA
                    EXIT(3)=WW
```

```
                   EXIT(4)=FF
                   EXIT(5)=WUNIT
C
      RETURN
      END
```

```
!*TPFS(0).SIMPSN
        SUBROUTINE RSIMP(NR,NA,LAMBDA,HMIN)
C
C..SIMPSON INTEGRATION METHOD ALONG PAD RADII.
C
C
        REAL LAMBDA
        COMMON/GEOM/ANGP,THPR,DR,DA
        COMMON/BLKP/P(15,21)/BLKR/R(15)/BLKH/H(15,21)
        COMMON/BLKXXX/XF(21,3)
        DIMENSION END(3),EVEN(3),ODD(3),CC(5,3)
        DATA CC/-1.,4.,-3.,3*0.0,1.,0.0,-1.,3*0.0,3.,-4.,1./
C
C
C..USAGE OF FUNCTION DEFINITIONS ..
C          F    INTEGRAND FOR LOADS AND MOMENTS,
C         H2    RATIO OF FILM THICKNESS TO MINIMUM FILM THICKNESS,
C          X    INTEGRAND FOR FRICTION MOMENT CALCULATIONS ..
C
C
        DEFINE H2(JP,JA)=H(JR,JA)/HMIN
        DEFINE F(K,JR,JA)=P(JR,JA)*R(JR)**K
        DEFINE X(M,JR,JA)=(CC(1,M)*P(JR,JA+2)+CC(2,M)*P(JR,JA+1)+
       1   CC(3,M)*P(JR,JA)+CC(4,M)*P(JR,JA-1)+
       2   CC(5,M)*P(JR,JA-2))*R(JR)*H2(JR,JA)/(2.*DA)+
       3   LAMBDA*R(JR)**3/(3.*H2(JR,JA))
C
C
        NEND=NR/2-1
        LASTR=NR+1
        LASTA=NA+1
        M=1
        DO 50 JA=1,LASTA
           IF(JA.EQ.LASTA) M=3
C
           DO 10 I=1,3          @ SET STORAGE VECTORS TO ZERO..
              END(I)=0.0
              EVEN(I)=0.0
              ODD(I)=0.0
 10        CONTINUE
C
           END(1)=END(1)+F(1,1,JA)+F(1,LASTR,JA)
           END(2)=END(2)+F(2,1,JA)+F(2,LASTR,JA)
           END(3)=END(3)+X(M,1,JA)+X(M,LASTR,JA)
C
           DO 40 JJ=1,NEND
              EVEN(1)=EVEN(1)+F(1,2*JJ,JA)
              EVEN(2)=EVEN(2)+F(2,2*JJ,JA)
              EVEN(3)=EVEN(3)+X(M,2*JJ,JA)
              ODD(1)=ODD(1)+F(1,2*JJ+1,JA)
              ODD(2)=ODD(2)+F(2,2*JJ+1,JA)
              ODD(3)=ODD(3)+X(M,2*JJ+1,JA)
 40        CONTINUE
           EVEN(1)=EVEN(1)+F(1,NR,JA)      @LAST EVEN ORDINATE
           EVEN(2)=EVEN(2)+F(2,NR,JA)
           EVEN(3)=EVEN(3)+X(M,NR,JA)
C
```

```
      DO 30 II=1,3
         XF(JA,II)=DR*(END(II)+4.*EVEN(II)+2.*ODD(II))/3.
 30   CONTINUE
C
      M=2
 50   CONTINUE
C
      RETURN
      END
```

```
TPF$(0).ELT
      SAMPLE DATA INPUT AS READ BY SUBROUTINE 'MAIN'..
    *CARD 1-FORMAT 3I6,F8.2,2E8.1        NR     -NUMBER RADIAL MESH INCREMENTS,
                                         NA     -NUMBER ANGULAR MESH INCREMENTS,
                                         ITERMX-MAXIMUM ITERATIONS IN GAUSS-
                                                SEIDEL ROUTINE IF CONVERGENCE
                                                FAILS,
                                         OMEGA -RELAXATION FACTOR IN GAUSS-
                                                SEIDEL METHOD,
                                         HALT  -MIN LUBRICANT FILM THICKNESS..
                                         RESIDL-CONVERGENCE CRITERION=TEST ON
                                                MAXIMUM CHANGE IN Q-VARIABLE
                                                BETWEEN ITERATIONS..

        NR     NA  ITERMX   OMEGA    HALT    RESIDL
         8     12   400     1.25    .1E-3    .1E-4


    *CARD 2-FORMAT 4L6            DEBUG (.TRUE.= PRINTOUT OF COMPLETE ARRAY OF
                                                 DEPENDENT Q-VARIABLE FROM
                                                 GAUSS-SEIDEL ROUTINE AT EACH
                                                 ITERATION),
                                  TABOUT (.TRUE.= PRINTOUT OF PRESSURE ARRAY
                                                  OVER PAD AREA AT
                                                  CONVERGENCE),
                                  OLDQ (.TRUE. = USE CONVERGED VALUES OF Q-
                                                 VARIABLE AS STARTING ESTIMATES
                                                 FOR NEW CALCULATIONS WITH
                                                 DIFFERENT INITIAL CONDITIONS).
                                  VARGRD (.TRUE.= CREATES VARIABLE MESH GRID
                                                  OVER SECTOR PAD FOR LIQUID
                                                  FILM CALCULATIONS).


     'BUG  TAB' OLD'  VAR'D
    FALSE FALSE TRUE  TRUE


    *CARD 3-FORMAT 5I10     ..INDICES FOR PARAMETER ARRAYS IN NAMELIST
                              INPUT "VARBLE" ...

        NTHETA    NRATIO     NUMRI    NUMBET    NUMLMB
             1        20         1         1         1


    *CARDS 4,5,,,       ..DATA INPUT FOR NAMELIST "VARBLE" ...
          ...DESCRIPTION OF INPUT PARAMETER ARRAYS ...

          NUMBER OF          PARAMETER         PARAMETER DESCRIPTION
           DATA               ARRAY
```

```
     ********            ********            *****************

      NTHETA             TRATIO              PAD PIVOT ANGLE,THETAP/BETA
      NRATIO             ERATIO              PAD SLOPE FACTOR,EPSILON/HMIN
      NUMRI              VRI                 PAD INNER RADII, RI
      NUMBET             VBETA               PAD ANGLE DIMENSION, BETA
      NUMLMB             VLMBDA              BEARING NUMBER, LAMBDA

     ...INPUT FOLLOWS ...
$VARBLE TRATIO=1.0,VPI=.5,VBETA=45.,VLMBDA=50.,
        ERATIO=.5,1.,1.5,2.,2.5,3.,3.5,4.,4.5,5.,5.5,6.,6.5,7.,7.5,8.,
              8.5,9.,9.5,10.,
$END
```

FSTBP2

Flat Sector Pad Thrust Bearing Program Number 2 -- liquid lubricant.

```
*TPFS(0).MAIN2
C
C**MAIN EXECUTIVE FOR GAUSS-SEIDEL ITERATION..LIQUID LUBRICANT..
C
      LOGICAL DEBUG,TABOUT,OLDQ,VARGRD
C
      COMMON/BLOGIC/DEBUG,TABOUT,OLDQ,VARGRD
      COMMON/GEOM/ANGB,THPR,DR,DA
      DIMENSION EXIT(9),TRATIO(15),ERATIO(26)
      DIMENSION VRI(10),VBETA(10),VLMBDA(10)
C
      NAMELIST/VARBLE/TRATIO,ERATIO,VRI,VBETA,VLMBDA
C
 1    FORMAT(3I6,F8.2,2E8.1)
 2    FORMAT(4L6)
 3    FORMAT(5I10)
 4    FORMAT(2X,12HNO. OF ROWS=,I3,16H    NO. OF COLS=,I3,26H     MAX NO.
     1 OF ITERATIONS=,I4,25H    RELAXATION PARAMETER=,F4.2,19H    RESIDU
     2AL ERROR=,F10.7/2X,38HSMALLEST ALLOWED FILM THICKNESS HALT =,
     3G10.4//)
 5    FORMAT(2X,39HTHE MINIMUM FILM THICKNESS IS LESS THAN,G10.4//)
C
C
      READ(5,1)NR,NA,ITERMX,OMEGA,HALT,RESIDL
      READ(5,2)DEBUG,TABOUT,OLDQ,VARGRD
      READ(5,3)NTHETA,NRATIO,NUMRI,NUMBET
      READ(5,VARBLE)
C
      WRITE(6,4)NR,NA,ITERMX,OMEGA,RESIDL,HALT   @NUMERICAL SOLUTION
                                                  @PRINTOUT...
      WRITE(6,900)                         @ HEADING PRINTOUT..
      IPRINT=0                             @ INITIALIZE PRINT SWITCH...
C
      DO 500 NRI=1,NUMRI                   @ INCREMENT INNER RADIUS VALUES..
         RI=VRI(NRI)
C
      DO 400 NBETA=1,NUMBET                @ INCREMENT BETA VALUES..DEGREES.
         BETA=VBETA(NBETA)
C
C
      DO 200 NANGLE=1,NTHETA               @ INCREMENT THETAP/BETA RATIO
         XXTHTP=TRATIO(NANGLE)
         CALL EUCLID(NR,NA,RI,BETA,XXTHTP,VARGRD)  @CALCULATES GEOMETRIC
C                                                   PARAMETERS...
         KOUNT=0
C
                        IF(IPRINT.GT.0)GO TO 8
                        WRITE(6,910)
                        GO TO 10
 8                      WRITE(6,915)      @PRINT START TOP OF PAGE..
 10                     WRITE(6,920)
                        WRITE(6,930)RI,BETA,XXTHTP
                        WRITE(6,940)
                        WRITE(6,950)
C
         DO 100 NFILM=1,NRATIO             @ INCREMENT EPS/H2 RATIO
         ERAT=ERATIO(NFILM)
```

```
C
C
        CALL BEGIN2(EPS,HALT,HMIN,HRAT,ERAT,RI,$12)    @FILM THICKNESS
                                                       @ CALCULATIONS..
        GO TO 15
C
 12     WRITE(6,5)HMIN                      @ ERROR EXIT..
      GO TO 100
C
 15     IF(KOUNT.GT.0)GO TO 21
C
C..THREE SUBROUTINES TO SET UP AND SOLVE THE FINITE DIFFERENCE
C..REYNOLDS EQUATION, AND RETURN INTEGRALS OF PRESSURE OVER PAD AREA..
        CALL ARRAYS(NR,NA,EPS,KOUNT,RI,HMIN)
        CALL RELAX(NR,NA,OMEGA,ITERMX,RESIDL,VARGRD)
        CALL TABULT(NR,NA,HMIN,RI,EXIT,VARGRD,EPS)
      GO TO 22
C
 21     CALL RARRAY(EPS,KOUNT,HMIN)         @ENTRY TO SUBROUTINE ARRAYS.
        CALL RRELAX            @DITTO FOR GAUSS-SEIDEL ROUTINE..
        CALL RTAB(HMIN,EXIT)   @ENTRY TO INTEGRAL CALCS..
C
 22                          R1= ERAT                   @RATIO EPS/HMIN ..
                             R2= HRAT                   @RATIO H1/H2 ..
                             R3= EXIT(7)                @UNIT LOAD ..
                             R4= EXIT(3)/EXIT(1)        @FRICTION/LOAD ..
                             R5= EXIT(4)                @RO SIDE LEAKAGE ..
                             R6= EXIT(5)                @RI SIDE LEAKAGE ..
C
C                            **R7 IS TRAILING EDGE LEAKAGE,,,
C                            **R8 IS FLOW INTO LEADING EDGE ...
                             R7= EXIT(9)
                             R8= EXIT(8)
C
                             R9=(EXIT(2)-RI)/(1.-RI)
                            R10= EXIT(6)                @THETA C.P. ..
                            R11= EXIT(2)*SIN(ANGB*R10-THPR)
C
C
C
        WRITE(6,960)R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11
C
        KOUNT=KOUNT+1
 100  CONTINUE
      IPRINT=IPRINT+1
 200  CONTINUE
C
 400  CONTINUE
 500  CONTINUE
C
 900  FORMAT(1H1//40X,43HNUMERICAL RESULTS - INCOMPRESSIBLE ANALYSIS/
     140X,28HLEWIS RESEARCH CENTER(NASA)////)
 910  FORMAT(50X,17HSYSTEM PARAMETERS//15X,4H(P1),25X,4H(P2),28X,4H(P3),
     127X,4H(P4)//)
 915  FORMAT(1H1//50X,17HSYSTEM PARAMETERS//15X,4H(P1),25X,4H(P2),28X,
     14H(P3),27X,4H(P4)//)
 920  FORMAT(10X,17HINNER/OUTER RADII,14X,17HBEARING PAD ANGLE,14X,17HPI
```

```
     1VOT ANGLE RATIO//14X,5HRI/RO,22X,14HBETA (DEGREES),19X,11HTHETAP/B
     2ETA//)
 930  FORMAT(15X,G10.5,20X,G10.5,20X,G10.5///)
 940  FORMAT(50X,17HNUMERICAL RESULTS//5X,4H(R1),8X,4H(R2),8X,4H(R3),8X,
     14H(R4),8X,4H(R5),8X,4H(R6),8X,4H(R7),8X,4H(R8),8X,4H(R9),8X,5H(R10
     2),7X,5H(R11)//)
 950  FORMAT(1X,10HEPSILON/H2,5X,5HH1/H2,5X,9HUNIT-LOAD,4X,9HFRICTION/,
     14X,7HRO SIDE,4X,7HRI SIDE,6X,4HEDGE,8X,6HINSIDE,3X,11H(R(CP)-RI)/,
     22X,10HTHETA(CP)/,4X,5HX(CP)/44X,4HLOAD,4X,7HLEAKAGE,4X,7HLEAKAGE,
     35X,7HLEAKAGE,7X,4HFLOW,7X,6H(1-RI),10X,4HBETA//)
 960  FORMAT(11(2X,G10.5)/)
 970  FORMAT(3(G15.5))
C
      STOP
      END
```

```
*TPF$(O).XCART
        SUBROUTINE EUCLID(NR,NA,RI,BETA,THRAT,VARGRD)
    C
    C..SUBPROGRAM PRODUCES COMMON BLOCK CONTAINING GEOMETRIC PARAMETERS..
    C
        LOGICAL  VARGRD
        COMMON/GEOM/ANGB,THPR,DR,DA/BLKR/R(23),DELR(23)
        COMMON/BLKTH/TH(25),DELTH(25)/BLKSIN/XSIN(25),TSIN(25),TCOS(25)
        COMMON/INDEX/LN(23),LS(23),LE(25),LW(25)
        INTEGER HALFR,HALFA
    C
        FACT=6.2831853/360.      @ 2 PI RADIANS/360 DEGREES...
        ANGB=BETA*FACT           @BETA IN RADIANS..
        THPR=THRAT*ANGB          @THETAP(PIVOT ANGLE) IN RADIANS..
        DR=(1.-RI)/FLOAT(NR)     @RADIAL INCREMENT..
        DA=ANGB/FLOAT(NA)        @ANGLE INCREMENT IN RADIANS..
    C
    C
           INTEGR = 1
           IF(VARGRD)INTEGR=9
           LASTR=NR+INTEGR
           LASTA=NA+INTEGR
           HALFR=NR/2+1
           HALFA=NA/2+1
    C
           IF(VARGRD)GO TO 1
             DELTH(1)      = DA
             DELTH(LASTA)  = DA
              DELR(1)      = DR
              DELR(LASTR)  = DR
              GO TO 2
    C
     1                  DR4   = .25*DR
                        DA4   = .25*DA
                        DR2   =  2.*DR4
                        DA2   =  2.*DA4
                     DELR(1)  = DR4
                    DELTH(1)  = DA4
                 DELR(LASTR)  = DR4
                DELTH(LASTA)  = DA4
    C
     2     R(1)=RI
           R(LASTR)=1
           TH(1)=0.0
           TH(LASTA)=ANGB
           XSIN(1)    =0.0
           XSIN(LASTA)=SIN(ANGB)
           TSIN(1) = SIN(THPR)
           TSIN(LASTA)=SIN(THPR-ANGB)
           TCOS(1)=COS(THPR)
           TCOS(LASTA)=COS(THPR-ANGB)
    C..INDICES FOR VAPIABLE MESH DIFFERENCE EOUATIONS...
           KPLUS=1
           MINUS=LASTR
    C
           LE(1)=1
           LW(LASTA)=LASTA
```

```
          LS(1)=1
          LN(LASTR)=LASTR
C
      DO 100 J=1,HALFR
          K=1
          DDR=DR
          IF(.NOT.VARGRD)GO TO 30
          IF(J.GT.2) GO TO 30
          GO TO (10,20),J
C
 10       K=3
          DDR=DR4
          NOW=1
          GO TO 30
C
 20       K=2
          NOW=2
          DDR=DR2
C
 30       DO 50 L=1,K
             IF(J.EQ.3)NOW=2
             KPLUS=KPLUS+1
             MINUS=LASTR+1-KPLUS
             LS(KPLUS)=KPLUS-NOW
             LN(KPLUS)=KPLUS+1
             LS(MINUS)=MINUS-1
             LN(MINUS)=MINUS+NOW
             DELR(KPLUS) = DDR
             DELR(MINUS) = DDR
                R(KPLUS) = R(KPLUS-1)+DELR(KPLUS-1)
                R(MINUS) = R(MINUS+1)-DELR(MINUS+1)
             NOW=1
 50       CONTINUE
C
 100  CONTINUE
C
C
          KPLUS=1
          MINUS=LASTA
C
      DO 200 J=1,HALFA
          K=1
          DDA=DA
          IF(.NOT.VARGRD)GO TO 130
          IF(J.GT.2) GO TO 130
          GO TO (110,120),J
C
 110      K=3
          DDA=DA4
          NOW=1
          GO TO 130
C
 120      K=2
          DDA=DA2
          NOW=2
C
 130      DO 150 L=1,K
```

```
            IF(J.EQ.3)NOW=2
            KPLUS=KPLUS+1
            MINUS=LASTA+1-KPLUS
            LW(KPLUS)=KPLUS-NOW
            LE(KPLUS)=KPLUS+1
            LE(MINUS)=MINUS+NOW
            LW(MINUS)=MINUS-1
           DELTH(KPLUS) = DDA
           DELTH(MINUS) = DDA
              TH(KPLUS) = TH(KPLUS-1)+DELTH(KPLUS-1)
              TH(MINUS) = TH(MINUS+1)-DELTH(MINUS+1)
                  TEMP1 = TH(KPLUS)
                  TEMP2 = TH(MINUS)
            XSIN(KPLUS)=SIN(TEMP1)
            XSIN(MINUS)= SIN(TEMP2)
            TSIN(KPLUS)=SIN(THPR-TEMP1)
            TSIN(MINUS)= SIN(THPR-TEMP2)
            TCOS(KPLUS)=COS(THPR-TEMP1)
            TCOS(MINUS)=COS(THPR-TEMP2)
            NOW=1
 150     CONTINUE
C
 200  CONTINUE
C
      RETURN
      END
```

```
*TPF$(0).XBEGN2
          SUBROUTINE BEGIN2(E,HALT,HMIN,HRATIO,ERATIO,RI,$)
      C
          COMMON/GEOM/ANGB,THPR,DR,DA
          THETAP=THPR
          BETA=ANGB
          RAD90=1.5707963         @90 DEGREES IN RADIANS..
      C
      C
      C..CALCULATE MINIMUM FILM RATIO AND BEARING NUMBER..
      C
      C
      C..REGION NUMBER 1....PIVOT ANGLE = THETAP .LT. 0 ...
       10   IF(THETAP.GE.0.0) GO TO 20
               EPS=ERATIO/(1.-ERATIO*SIN(THETAP-BETA))
               HMIN=EPS/ERATIO
               HRATIO=(1.+EPS*RI*SIN(THETAP))/HMIN
               IF(HMIN.LT.HALT) RETURN 7
               GO TO 100
      C
      C..REGION NUMBER 2....THETAP .GE. ZERO AND .LE. BETA ...
       20   IF(THETAP.GT.BETA) GO TO 30
               EPS=ERATIO/(1.-ERATIO*SIN(THETAP-BETA))
               HMIN=EPS/ERATIO
               HRATIO=(1.+EPS*SIN(THETAP))/HMIN
               IF(HMIN.LT.HALT) RETURN 7
               GO TO 100
      C
      C..REGION NUMBER 3....THETAP .GT. BETA AND .LT. 90 DEGREES ...
       30   IF(THETAP.GT.RAD90)GO TO 40
               EPS=ERATIO/(1.-ERATIO*RI*SIN(THETAP-BETA))
               HMIN=EPS/ERATIO
               HRATIO=(1.+EPS*SIN(THETAP))/HMIN
               IF(HMIN.LT.HALT) RETURN 7
               GO TO 100
      C
      C..REGION NUMBER 4.... THETAP .GT. 90 DEGPEES ...
       40      EPS=ERATIO/(1.-ERATIO*RI*SIN(THETAP-BETA))
               HMIN=EPS/ERATIO
               HRATIO=(1.+EPS)/HMIN
               IF(HMIN.LT.HALT)RETURN 7
      C
       100  CONTINUE
            E=EPS
            RETURN
      C
            END
```

```
TPF$(D).COEFF
      SUBROUTINE ARRAYS(NR,NA,EPS,KK,RI,HMIN)
C
C..SUBPROGRAM CALCULATES VALUES OF THE NODAL COEFFICIENTS AND THE INITIAL
C..VALUES OF THE DEPENDENT VARIABLE FOR THE FIRST ITERATION. LIQUID LUBE
C
      LOGICAL OLDQ,VARGRD
C
      COMMON/BLKA/A(23,25)/BLKB/B(23,25)/BLKC/C(23,25)/BLKD/D(23,25)
      COMMON/BLKE/E(23,25)/BLKF/F(23,25)/BLKH/H(23,25)/BLKQ/Q(23,25)
      COMMON/BLKR/R(23),DELR(23)/BLOGIC/DEB,TAB,OLDQ,VARGRD
      COMMON/BLKTH/TH(25),DELTH(25)/BLKSIN/XSIN(25),TSIN(25),TCOS(25)
C
C
      INTEGR=1
      IF(VARGRD)INTEGR=9
      LASTA=NA+INTEGR
      LASTR=NR+INTEGR
      GO TO 5
C
C
      ENTRY RARRAY(EPS,KK,HMIN)
 5    DO 2 JA=1,LASTA
         DA=DELTH(JA)
         CA1=.5/DA
         CA2=1./DA**2
         STRIG=EPS*TSIN(JA)
         CTRIG=EPS*TCOS(JA)
C
         DO 1 JR=1,LASTR
            RAD=R(JR)
            DR=DELR(JR)
            CR1=.5/DR
            CR2=1./DR**2
            RAD2=RAD**2
            HRA=1.+RAD*STRIG
C
            IF(KK.EQ.0) GO TO 6
            IF(.NOT.OLDQ) GO TO 6
            IF(JA.EQ.1.OR.JA.EQ.LASTA) GO TO 6
            IF(JR.EQ.1.OR.JR.EQ.LASTR) GO TO 6
C
            GO TO 7
C
 6          Q(JR,JA)=0.0
 7          H(JR,JA)=HRA
                RH = RAD*HRA
              FRST = CR1*(4.*HRA-3.)/RH
              SCND = 3.*CTRIG*CA1/RH
             CA2RAD = CA2/RAD2
C
            A(JR,JA)=CR2+FRST
            B(JR,JA)=CR2-FRST
            C(JR,JA)=CA2RAD-SCND
            D(JR,JA)=CA2RAD+SCND
            E(JR,JA)=2.*(CR2+CA2RAD)
            F(JR,JA)=CTRIG*RAD*HMIN**2/HRA**3
```

```
C
C
    1     CONTINUE
    2 CONTINUE
C
      RETURN
      END
```

```
*TPFS(O).SEIDEL
        SUBROUTINE RELAX(NR,NA,OMEGA,ITERMX,RESIDL,VARGRD)
      C
      C..GAUSS-SEIDEL ITERATION WITH CONVERGENCE WHEN LARGEST DIFFERENCE BETWEEN
      C..SUCCESSIVE ITERATIONS FOR ANY MATRIX ELEMENT IS LESS THAN THE INITIALIZED
      C..PARAMETER "RESIDL"
      C
            COMMON/BLKA/A(23,25)/BLKB/B(23,25)/BLKC/C(23,25)/BLKD/D(23,25)
            COMMON/BLKE/E(23,25)/PLKF/F(23,25)/BLKH/H(23,25)/BLKQ/Q(23,25)
            COMMON/INDEX/LN(23),LS(23),LE(25),LW(25)
      C
            LOGICAL VARGRD
            REAL OMEGA
      C
            INTEGR=1
            IF(VARGRD)INTEGR=9
            LASTR=NR+INTEGR-1
            LASTA=NA+INTEGR-1
      C
            GO TO 40
      C
            ENTRY RRELAX
       40   DO 300 KK=1,ITERMX
               STRERR=0.0
               DO 200 JJ=2,LASTA
                      IE=LE(JJ)                              @ ANGULAR INDICES...
                      IW=LW(JJ)
      C
                  DO 100 II=2,LASTR
                           IN=LN(II)                         @ RADIAL INDICES...
                           IS=LS(II)
                        STORQ=Q(II,JJ)        @ Q-VALUE AT LAST ITERATION...
                        FIRST=(1.-OMEGA)*STORQ
                       RADIAL=A(II,JJ)*Q(IN,JJ)+B(II,JJ)*Q(IS,JJ)
                       ANGULR=C(II,JJ)*Q(II,IE)+D(II,JJ)*Q(II,IW)
                     Q(II,JJ)=FIRST+OMEGA*(RADIAL+ANGULR+F(II,JJ))/E(II,JJ)
                     ERROR=Q(II,JJ)-STORQ
      C
        50           TEST=ABS(ERROR)
      C
                     IF(TEST.LE.STRERR)GO TO 100
                     STRERR=TEST                          @UPDATE LARGEST RESIDUAL
                     ISTORE=II                            @ROW OF LAST UPDATE
                     JSTORE=JJ                            @COLUMN OF LAST UPDATE
                     QSTORE=Q(II,JJ)                      @Q-VALUE AT LARGEST RESIDUAL
       100        CONTINUE
       200     CONTINUE
               IF(STRERP.LT.RESIDL)GO TO 400
       300  CONTINUE
       400  CONTINUE
      C
      C
            RETURN
            END
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
*TPF$(0).PADCTR
      SUBROUTINE TABULT(NR,NA,HMIN,RI,EXIT,VARGRD,EPS)
C
C..EXECUTIVE FOR INTEGRAL CALCULATIONS TRYING THE SIMPSON 1/3 RULE
C..FOR ANGULAR COORDINATES...
C
      COMMON/GEOM/ANGB,THPR,DR,DA
      COMMON/BLKXXX/XF(25,6)    @INTEGRATION RESULTS FROM SUBR. RSIMP
      COMMON/BLKTH/TH(25),DTH(25)/BLKSIN/XSIN(25),TSIN(25),TCOS(25)
      COMMON/INDEX/LN(23),LS(23),LE(25),LW(25)
      DIMENSION EXIT(9),SUMMA(7)
C
      LOGICAL VARGRD
C
C..FUNCTION DEFINITION FOR SIMPSON INTEGRATION RULE..
C
      DEFINE AREA(J,K)=DTH(J+1)*(XF(J,K)+4.*XF(J+1,K)+XF(J+2,K))
      DEFINE TRIG(J) = DTH(J+1)*(XF(J,2)*XSIN(J)+
     1                 4.*XF(J+1,2)*XSIN(J+1)+XF(J+2,2)*XSIN(J+2))
C
         INTEGR=1
         IF(VARGRD)INTEGR=9
         LASTA=NA+INTEGR          @TRAILING EDGE NODE ..
         LASTR=NR+INTEGR          @OUTER RADIAL NODE ..
         IQUIT=(LASTA-1)/2        @ANGULAR MIDPOINT ..
          FAC1=1.-RI**2
          FAC2=(1.-RI**3)*EPS
C
      GO TO 1
C
      ENTRY RTAB(HMIN,EXIT)
 1    CALL RSIMP(LASTR,LASTA,HMIN)     @RADIAL INTEGRATION SUBROUTINE
          FAC3=.5*FAC1/HMIN
          FAC4=FAC2/(3.*HMIN)
C
      DO 2 I=1,7          @ SET STORAGE VECTORS TO ZERO..
         SUMMA(I)=0.0
 2    CONTINUE
C
C..INDEX LIST FOR STORAGE VECTORS AND FOR RETURN VECTOR "EXIT",,,
C          (1) CALCULATIONS FOR TOTAL LOAD..
C          (2)     "         "   RADIAL MOMENT AND C.P. COORDINATE..
C          (3)     "         "   PAD FRICTION..
C          (4)     "         "   LEAKAGE FROM OUTER PAD ARC (R=1) ..
C          (5)     "         "     "    "     INNER  "   "  (R=RI) ..
C          (6)     "         "   ANGULAR MOMENT AND C.P. COORDINATE ..
C          (7)     "         "   UNIT LOAD ..
C          (8)     "         "   FLOW INTO LEADING EDGE ..
C          (9)     "         "   TRAILING EDGE LEAKAGE ..
C
      DO 10 ISUM=1,IQUIT          @SUM OVER PAIRS OF INTERVALS..
         JFRD = 2*ISUM-1          @ODD NODES..
         DO 9 K=1,6               @TEMPORARY STORAGE..
            SUMMA(K)=SUMMA(K)+AREA(JFRD,K)
 9       CONTINUE
         SUMMA(7)=SUMMA(7)+TRIG(JFRD)
 10   CONTINUE
```

```
C
C
      DO 12 KKK=1,2                                            @EXIT VECTORS ..
C
         LL=4*(KKK-1)
         MM=LL+1
         NN=MM+2
C
         DO 11 ILK=MM,NN
            ILKO=ILK-(KKK/2)
            EXIT(ILKO) = SUMMA(ILK)/3.
 11      CONTINUE
C
 12   CONTINUE
C
      EXIT(6)=(ASIN(EXIT(6)/EXIT(2)))/ANGB
      EXIT(2)=EXIT(2)/EXIT(1)
      EXIT(3)=EXIT(3)/6.
      EXIT(7)=2.*EXIT(1)/(ANGB*FAC1)
      EXIT(8)=FAC3+FAC4*XSIN(1)-XF(1,4)
      EXIT(9)=FAC3+FAC4*XSIN(LASTA)-XF(LASTA,4)
C
      RETURN
      END
```

```
*TPF$(O).SIMPSN
        SUBROUTINE RSIMP(LASTR,LASTA,HMIN)
C
C..SIMPSON INTEGRATION METHOD ALONG PAD RADII,LIQUID CASE..
C
C
        COMMON/BLKQ/P(23,25)/BLKH/H(23,25)/BLKR/R(23),DR(23)
        COMMON/BLKXXX/XF(25,6)/BLKTH/TH(25),DTH(25)
        COMMON/INDEX/LN(23),LS(23),LE(25),LW(25)
        DIMENSION SUMMA(4),CC(5,3)
        DATA CC/-1.,4.,-3.,3*0.0,1.,0.0,-1.,3*0.0,3.,-4.,1./
C
C..USAGE OF FUNCTION DEFINITIONS ..
C       F     INTEGRAND FOR LOAD AND MOMENTS,
C      H2     RATIO OF FILM THICKNESS TO MINIMUM FILM THICKNESS,
C       Y     PARTIAL DERIVATIVE OF PRESSURE WITH RESPECT TO THETA,
C       X     INTEGRAND FOR FRICTION MOMENT CALCULATIONS,
C       Z          "      "  CALCULATION OF LEADING EDGE & TRAILING EDGE
C                                                   FLUID LEAKAGE ..
C
        DEFINE H2(JR,JA)=H(JR,JA)/HMIN
        DEFINE F(K,JR,JA)=P(JR,JA)*R(JR)**K
        DEFINE Y(M,JR,JA,JE,JW)=(CC(1,M)*P(JR,JE+1)+CC(2,M)*P(JR,JE)+
       1   CC(3,M)*P(JR,JA)+CC(4,M)*P(JR,JW)+
       2   CC(5,M)*P(JR,JW-1))/(2.*DTH(JA))
        DEFINE X(M,JR,JW,JE,JW)=3.*Y(M,JR,JA,JE,JW)*R(JR)*H2(JR,JA)+
       1                         R(JR)**3/H2(JR,JA)
        DEFINE Z(M,JR,JA,JE,JW)=Y(M,JR,JA,JE,JW)*H2(JR,JA)**3/R(JR)
C
C
        DEFINE  AREA1(K,JR,JA)= DR(JR+1)*(F(K,JR,JA)+4.*F(K,JR+1,JA) +
       1                                  F(K,JR+2,JA))
        DEFINE AREA2(M,JR,JA,JE,JW)=DR(JR+1)*(X(M,JR,JA,JE,JW)+
       1                                  4.*X(M,JR+1,JA,JE,JW)+
       2                                  X(M,JR+2,JA,JE,JW))
        DEFINE AREA3(M,JR,JA,JE,JW)=DR(JR+1)*(Z(M,JR,JA,JE,JW)+
       1                                  4.*Z(M,JR+1,JA,JE,JW)+
       2                                  Z(M,JR+2,JA,JE,JW))
        IQUIT=(LASTR-1)/2
        M=1
        DO 50 JA=1,LASTA
           IF(JA.EQ.LASTA) M=3
C
           DO 10 I=1,4           @ SET STORAGE VECTORS TO ZERO..
              SUMMA(I)=0.0
C
C
 10        CONTINUE
C
              JE=LE(JA)
              JW=LW(JA)
           DO 20 ISUM=1,IQUIT       @SUM OVER PAIRS OF INTERVALS..
              JR=2*ISUM-1           @ODD NODES..
              DO 15 K=1,2           @STORE RESULTS IN SUMMA VECTORS..
                 SUMMA(K)=SUMMA(K)+AREA1(K,JR,JA)
 15           CONTINUE
C
```

```
      SUMMA(3)=SUMMA(3)+AREA2(3,JR,JA,JE,JW)
      IF(M.EQ.1.OR.M.EQ.3)SUMMA(4)=SUMMA(4)+AREA3(M,JR,JA,JE,JW)
 20   CONTINUE
C
      DO 40 II=1,4
      XF(JA,II)=SUMMA(II)/3.
 40   CONTINUE
C
      XF(JA,5)=.5*(4.*P(LASTR-1,JA) -
     1              P(LASTR-2,JA))*H2(LASTR,JA)**3/DR(LASTR-1)
      XF(JA,6)=.5*P(1)*(-P(3,JA)+
     1              4.*P(2,JA))*H2(1,JA)**3/DR(1)
C
C
      M=2
 50   CONTINUE
C
C
      RETURN
      END
```

```
*TPF$(0).ELT
     SAMPLE DATA INPUT AS READ BY SUBROUTINE 'MAIN'..
   *CARD 1-FORMAT 3I6,F8.2,2E8.1       NR    -NUMBER RADIAL MESH INCREMENTS,
                                       NA    -NUMBER ANGULAR MESH INCREMENTS,
                                       ITERMX-MAXIMUM ITERATIONS IN GAUSS-
                                              SEIDEL ROUTINE IF CONVERGENCE
                                              FAILS,
                                       OMEGA -RELAXATION FACTOR IN GAUSS-
                                              SEIDEL METHOD,
                                       HALT  -MIN LUBRICANT FILM THICKNESS..
                                       RESIDL-CONVERGENCE CRITERION=TEST ON
                                              MAXIMUM CHANGE IN Q-VARIABLE
                                              BETWEEN ITERATIONS..

     NR    NA  ITERMX  OMEGA   HALT   RESIDL
     14    16   400    1.25   .1E-3   .1E-4


   *CARD 2-FORMAT 4L6            DEBUG (.TRUE.= PRINTOUT OF COMPLETE ARRAY OF
                                                DEPENDENT Q-VARIABLE FROM
                                                GAUSS-SEIDEL ROUTINE AT EACH
                                                ITERATION),
                                 TABOUT (.TRUE.= PRINTOUT OF PRESSURE ARRAY
                                                 OVER PAD AREA AT
                                                 CONVERGENCE),
                                 OLDQ (.TRUE. = USE CONVERGED VALUES OF Q-
                                                VARIABLE AS STARTING ESTIMATES
                                                FOR NEW CALCULATIONS WITH
                                                DIFFERENT INITIAL CONDITIONS).
                                 VARGRD (.TRUE.= CREATES VARIABLE MESH GRID
                                                 OVER SECTOR PAD FOR LIQUID
                                                 FILM CALCULATIONS).

    'BUG  TAB' OLD'  VAR'D
   FALSE FALSE TRUE  TRUE


   *CARD 3-FORMAT 5I10     ..INDICES FOR PARAMETER ARRAYS IN NAMELIST
                             INPUT "VARBLE" ...

     NTHETA    NRATIO     NUMRI     NUMBET     NUMLMB
          1        20         1          1          1


   *CARDS 4,5,,,       ..DATA INPUT FOR NAMELIST "VARBLE" ...
      ...DESCRIPTION OF INPUT PARAMETER ARRAYS ...

      NUMBER OF          PARAMETER          PARAMETER DESCRIPTION
       DATA               ARRAY
```

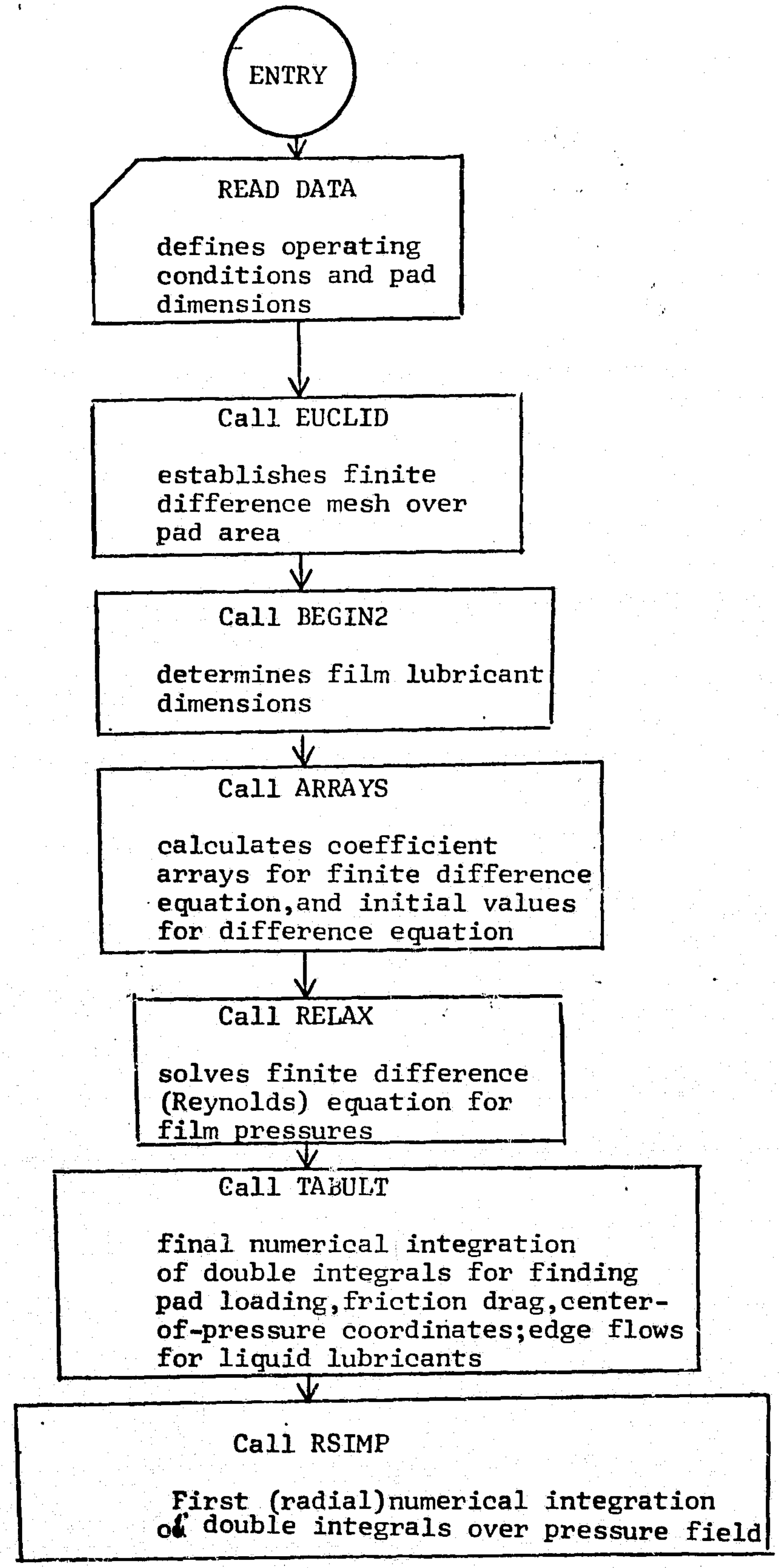
```
     ********          ********          *****************

      NTHETA           TRATIO            PAD PIVOT ANGLE,THETAP/BETA
      NRATIO           ERATIO            PAD SLOPE FACTOR,EPSILON/HMIN
      NUMRI            VRI               PAD INNER RADII, RI
      NUMBET           VBETA             PAD ANGLE DIMENSION, BETA
      NUMLMB           VLMBDA            BEARING NUMBER, LAMBDA

     ...INPUT FOLLOWS ...
 $VARBLE TRATIO=1.0,VRI=.5,VBETA=45.,VLMBDA=50.,
        ERATIO=.5,1.,1.5,2.,2.5,3.,3.5,4.,4.5,5.,5.5,6.,6.5,7.,7.5,8.,
              8.5,9.,9.5,10.,
 $END
```

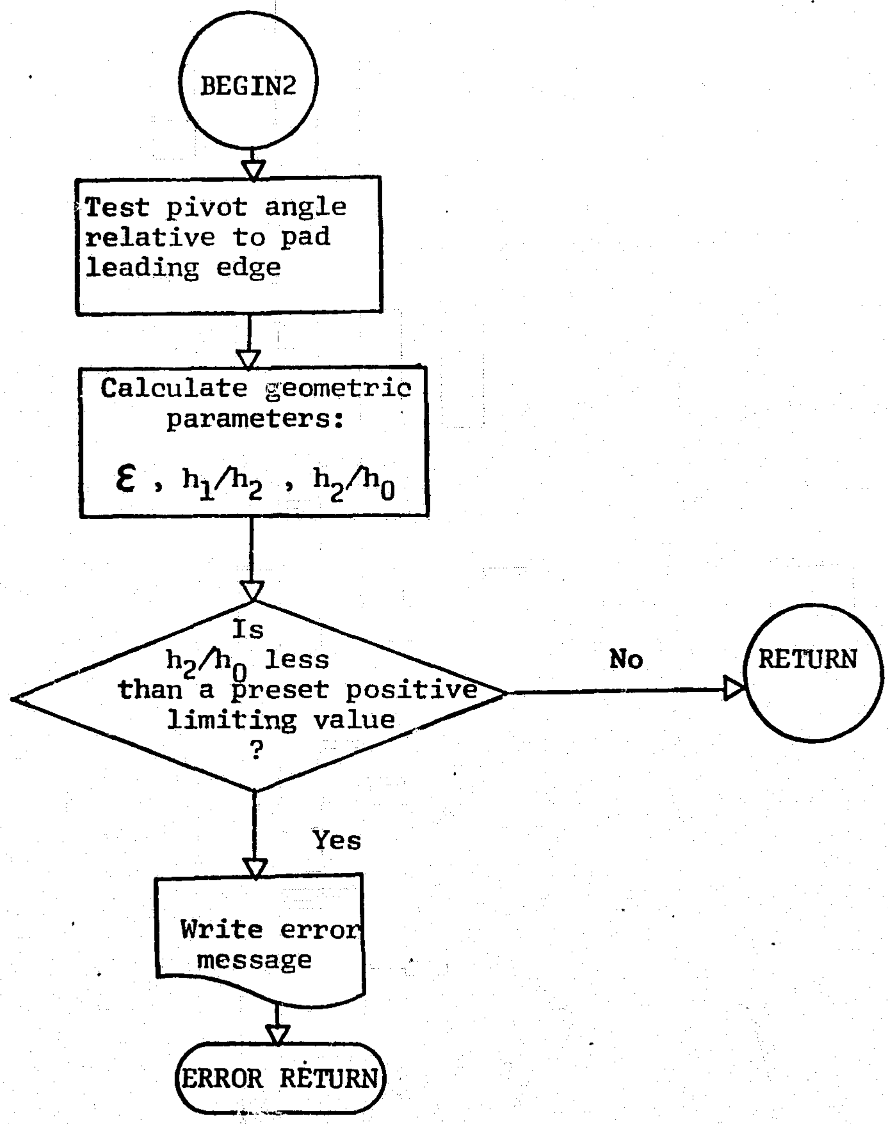
APPENDIX D

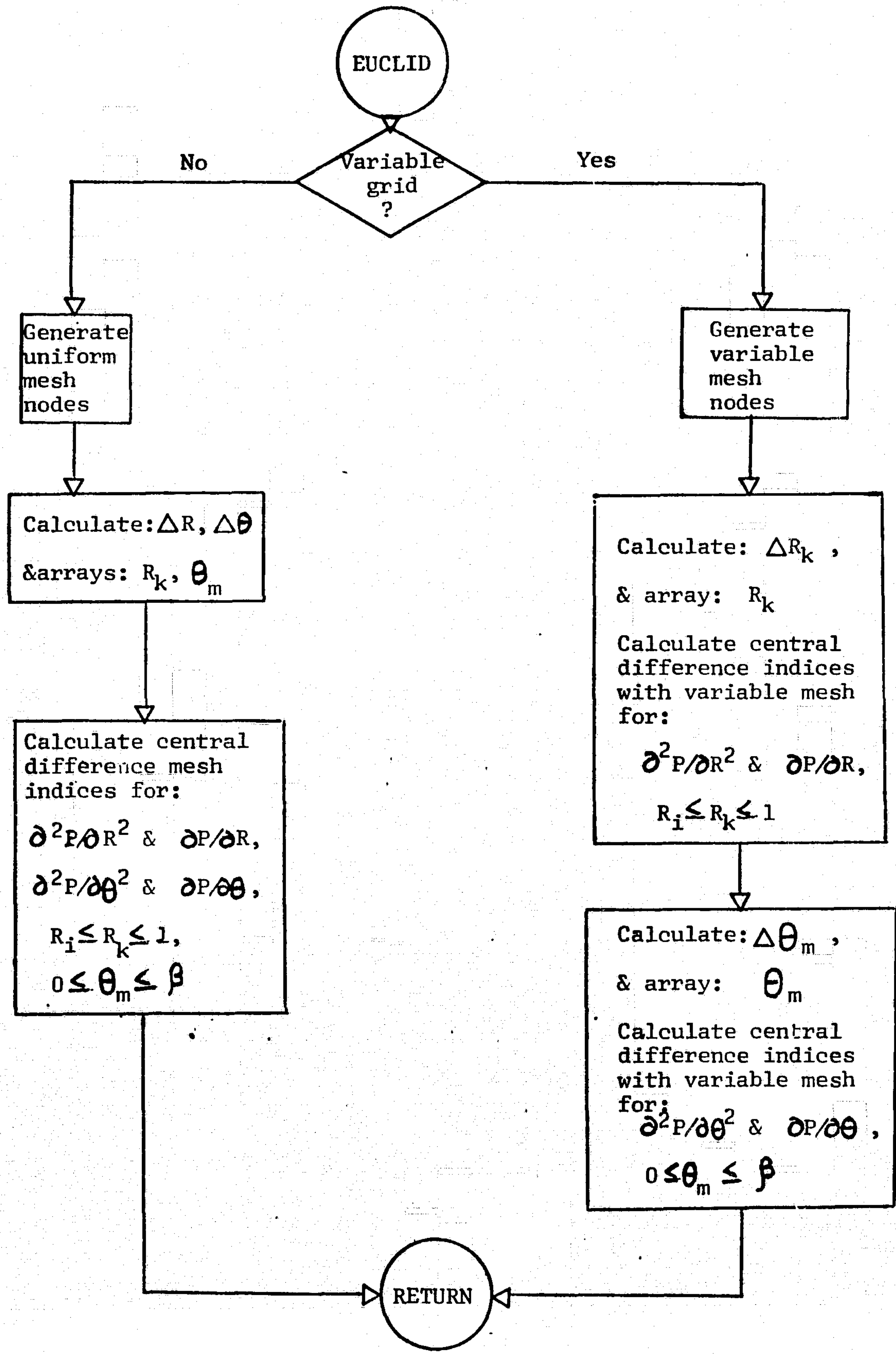
FLOW CHARTS

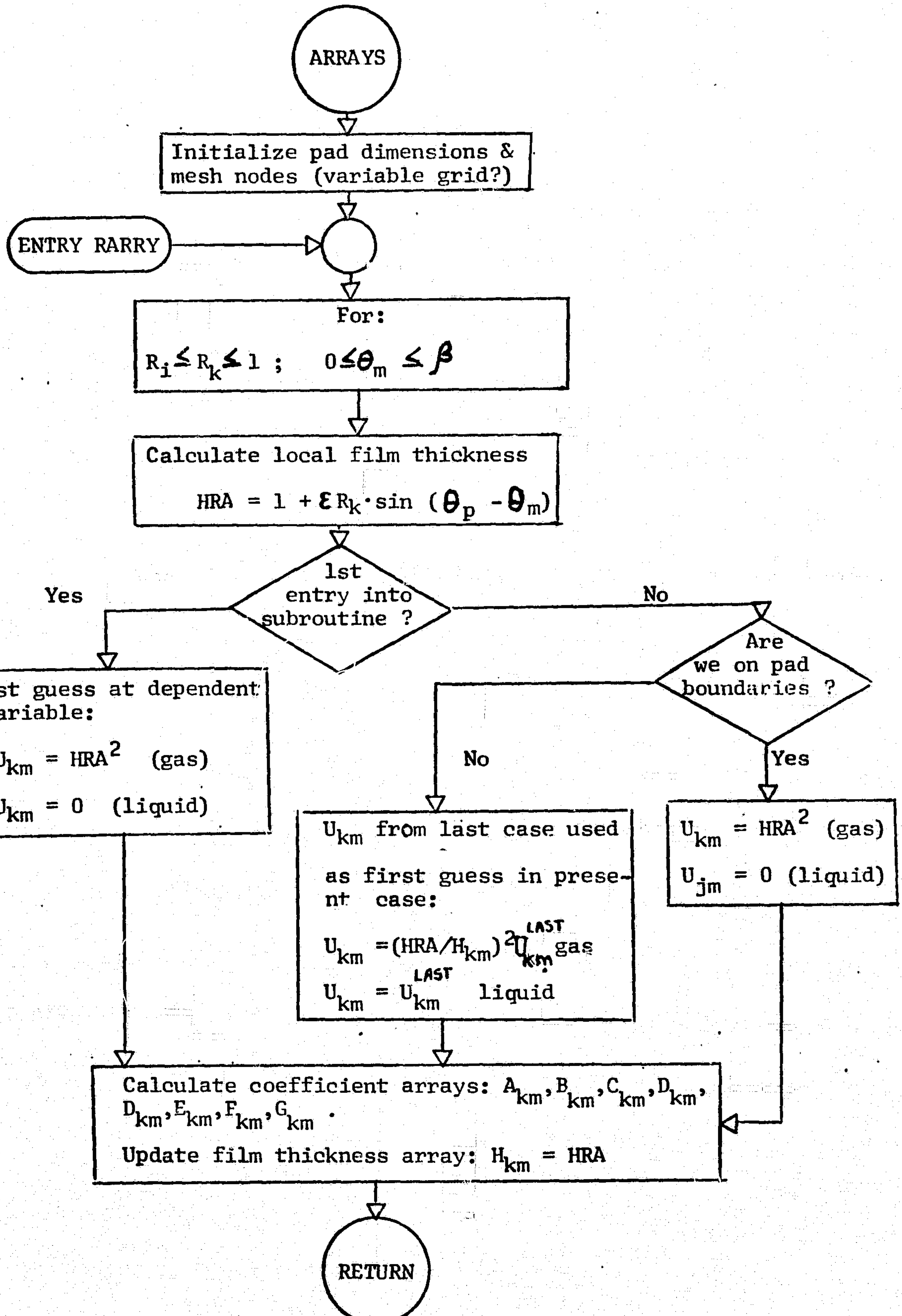
All FORTRAN symbols used in these flow charts are defined in appendix E.

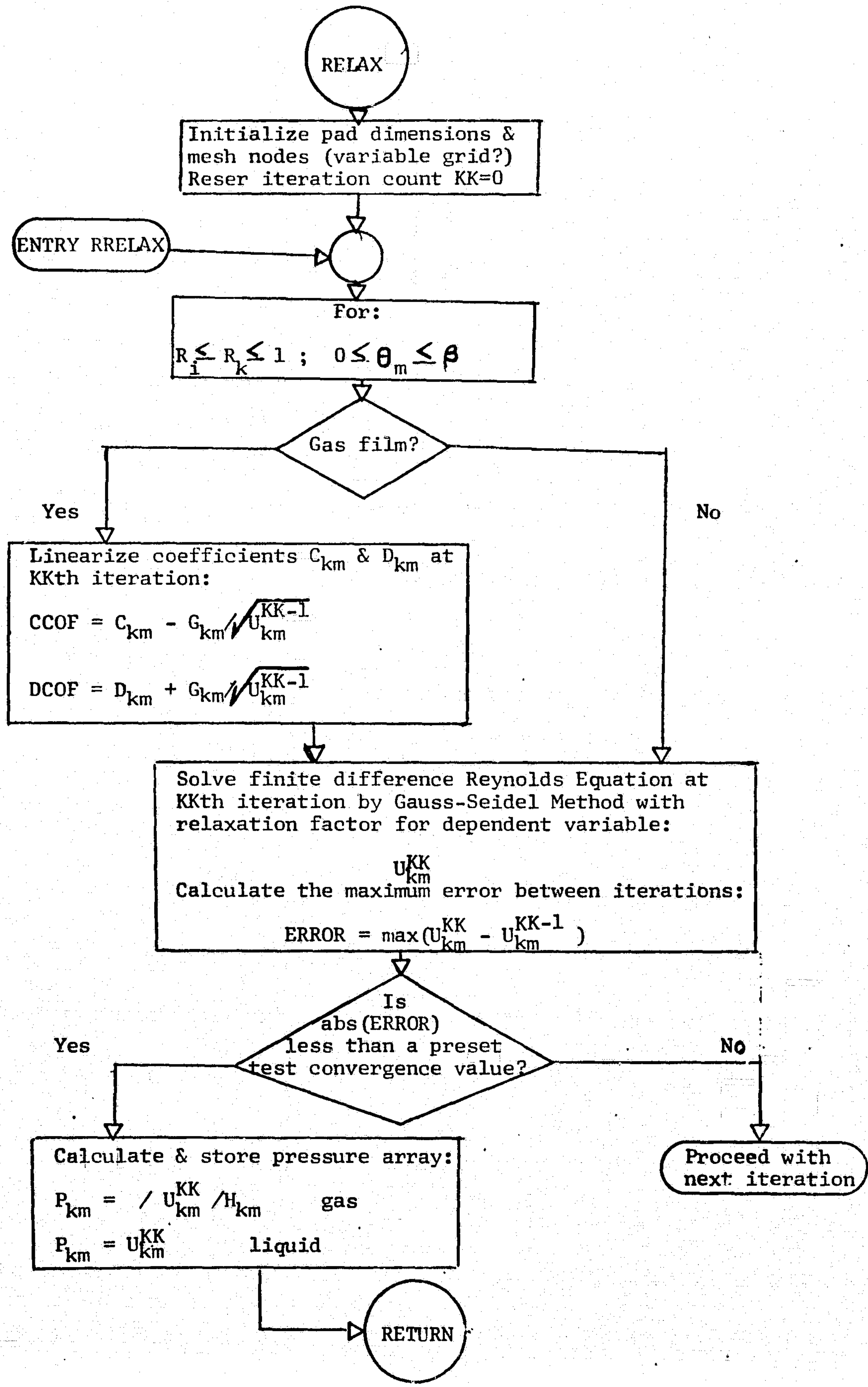
Executive Program MAIN2

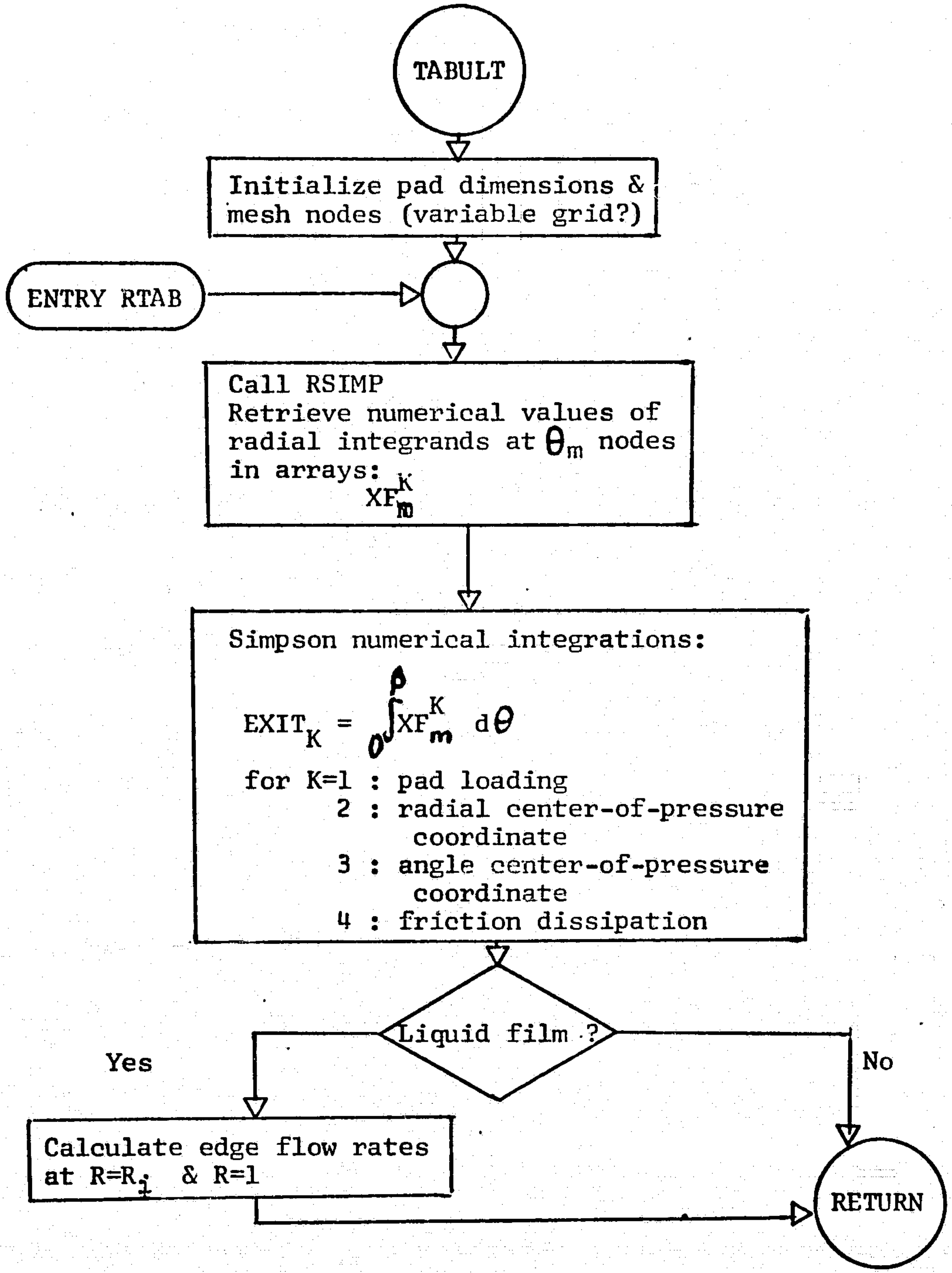


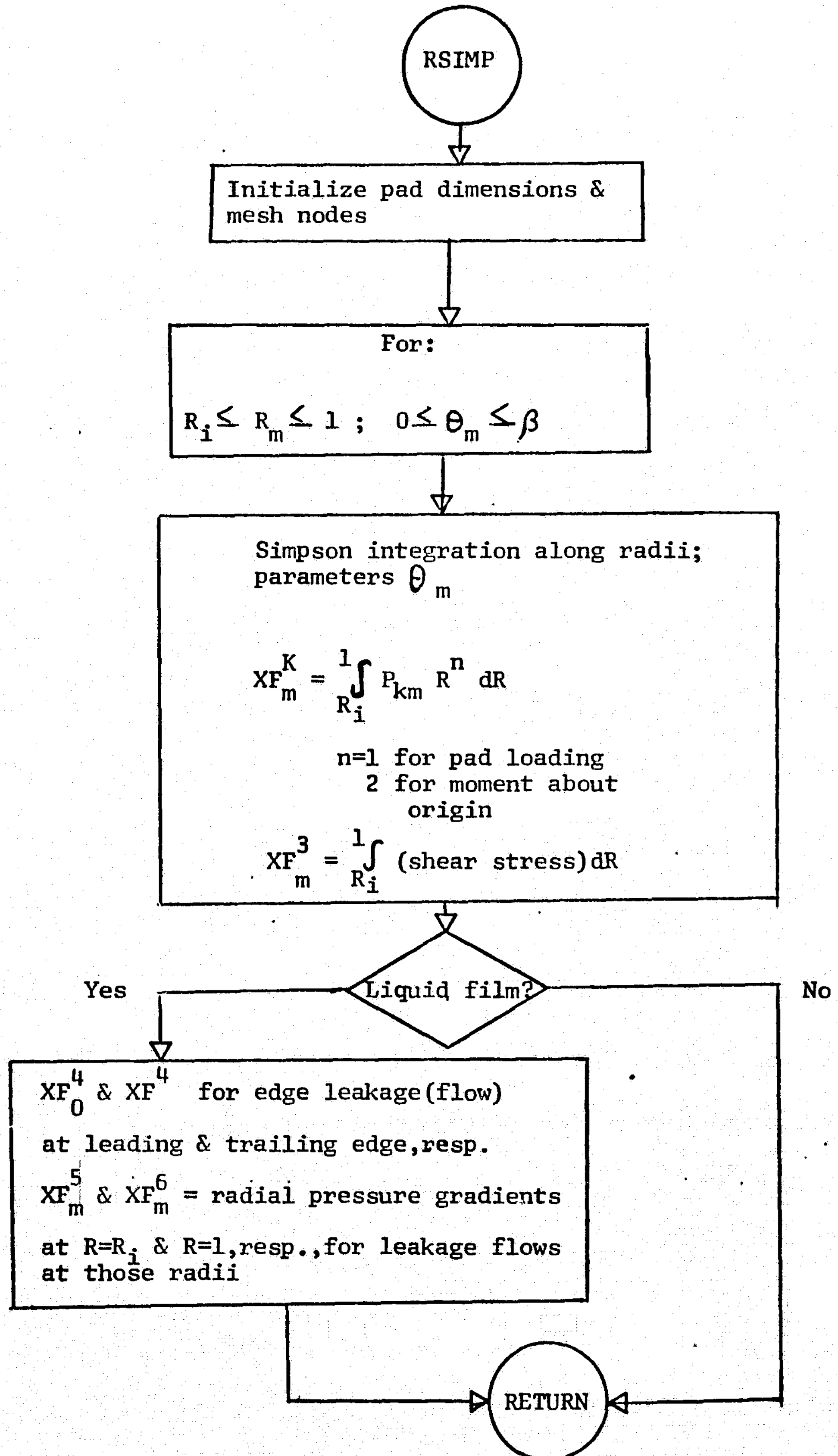

BEGIN2
Test pivot angle relative to pad leading edge
Calculate geometric parameters:
ε , h_1/h_2 , h_2/h_0
Is h_2/h_0 less than a preset positive limiting value ?
No
RETURN
Yes
Write error message
ERROR RETURN


EUCLID
Variable grid ?
No
Yes
Generate uniform mesh nodes
Generate variable mesh nodes
Calculate: ΔR, Δθ &arrays: R_k, θ_m
Calculate: ΔR_k, & array: R_k
Calculate central difference indices with variable mesh for: ∂²P/∂R² & ∂P/∂R, R_i ≤ R_k ≤ 1
Calculate central difference mesh indices for: ∂²P/∂R² & ∂P/∂R, ∂²P/∂θ² & ∂P/∂θ, R_i ≤ R_k ≤ 1, 0 ≤ θ_m ≤ β
Calculate: Δθ_m, & array: θ_m
Calculate central difference indices with variable mesh for: ∂²P/∂θ² & ∂P/∂θ, 0 ≤ θ_m ≤ β
RETURN


ARRAYS
Initialize pad dimensions & mesh nodes (variable grid?)
ENTRY RARRY
For:
$R_i \le R_k \le 1$; $0 \le \theta_m \le \beta$
Calculate local film thickness
$HRA = 1 + \varepsilon R_k \cdot \sin(\theta_p - \theta_m)$
1st entry into subroutine ?
Yes
No
1st guess at dependent variable:
$U_{km} = HRA^2$ (gas)
$U_{km} = 0$ (liquid)
Are we on pad boundaries ?
No
Yes
U_{km} from last case used as first guess in present case:
$U_{km} = (HRA/H_{km})^2 U_{km}^{LAST}$ gas
$U_{km} = U_{km}^{LAST}$ liquid
$U_{km} = HRA^2$ (gas)
$U_{jm} = 0$ (liquid)
Calculate coefficient arrays: $A_{km}, B_{km}, C_{km}, D_{km}, D_{km}, E_{km}, F_{km}, G_{km}$.
Update film thickness array: $H_{km} = HRA$
RETURN


RELAX
Initialize pad dimensions & mesh nodes (variable grid?) Reser iteration count KK=0
ENTRY RRELAX
For:
$R_i \leq R_k \leq 1$; $0 \leq \theta_m \leq \beta$
Gas film?
Yes
No
Linearize coefficients C_{km} & D_{km} at KKth iteration:
$CCOF = C_{km} - G_{km}/\sqrt{U_{km}^{KK-1}}$
$DCOF = D_{km} + G_{km}/\sqrt{U_{km}^{KK-1}}$
Solve finite difference Reynolds Equation at KKth iteration by Gauss-Seidel Method with relaxation factor for dependent variable:
U_{km}^{KK}
Calculate the maximum error between iterations:
$ERROR = \max(U_{km}^{KK} - U_{km}^{KK-1})$
Is abs(ERROR) less than a preset test convergence value?
Yes
No
Calculate & store pressure array:
$P_{km} = / U_{km}^{KK} / H_{km}$ gas
$P_{km} = U_{km}^{KK}$ liquid
Proceed with next iteration
RETURN


TABULT
Initialize pad dimensions & mesh nodes (variable grid?)
ENTRY RTAB
Call RSIMP
Retrieve numerical values of radial integrands at θ_m nodes in arrays:
XF_m^K
Simpson numerical integrations:
$EXIT_K = \int_0^\beta XF_m^K \, d\theta$
for K=1 : pad loading
2 : radial center-of-pressure coordinate
3 : angle center-of-pressure coordinate
4 : friction dissipation
Liquid film ?
Yes
No
Calculate edge flow rates at $R=R_i$ & $R=1$
RETURN


RSIMP
Initialize pad dimensions & mesh nodes
For:
$R_i \leq R_m \leq 1$; $0 \leq \theta_m \leq \beta$
Simpson integration along radii; parameters θ_m
$XF_m^K = \int_{R_i}^{1} P_{km} R^n dR$
n=1 for pad loading
2 for moment about origin
$XF_m^3 = \int_{R_i}^{1}$ (shear stress) dR
Liquid film?
Yes
No
XF_0^4 & XF^4 for edge leakage (flow) at leading & trailing edge, resp.
XF_m^5 & XF_m^6 = radial pressure gradients at $R=R_i$ & R=1, resp., for leakage flows at those radii
RETURN

APPENDIX E

FORTRAN SYMBOLS

A(15, 21)	coefficient array for $U_{i+1,\,j}$
AA	integral for θ_{cp} calculation
ANG	difference $\theta_p - \theta$
ANGB	angle β in radians
B(15, 21)	coefficient array for $U_{i-1,\,j}$
BETA	sector dimension β
C(15, 21)	coefficient array for $U_{i,\,j+1}$
CC(5, 3)	coefficient array for $\partial P/\partial \theta$ in fluid shear calculation
D(15, 21)	coefficient array for $U_{i,\,j-1}$
DA	$\Delta\theta$ of mesh
DEBUG	extensive printout logical switch; TRUE causes detailed output of iterative solution routine. FALSE prevents printout.
DR	ΔR of mesh
E(15, 21)	coefficient array for $U_{i,\,j}$
END(4)	storage array in numerical integration procedure
EPS	current value of clearance parameter ϵ
ERATIO(25)	input array of ϵ/H_2 values
ERROR	difference between U_{ij} values at k^{th} iteration and $(k - 1)_{st}$ iteration
EVEN(4)	storage array in numerical integration procedure
EXIT(5)	array of integration results from performance calculations
F(15, 21)	array of values for right hand side of nonhomogeneous Reynolds equation (liquid film)
F(K, I, J)	a DEFINE (local) function in radial integration subroutine for load (K=1) and moment (K=2) calculation
FF	integral of frictional energy dissipation

G(15, 21)	array of factors for nonlinear part of coefficients to $U_{i,\,j+1}$ and $U_{i,\,j-1}$
H(15, 21)	array of values of dimensionless film thickness h/h_o
HALT	test value for smallest HMIN
HLMBDA	ΛH_2^2
HMIN	minimum film thickness ratio, h_2/h_o
HRATIO	maximum-to-minimum film thickness ratio h_1/h_2
H2(I, J)	a DEFINE function in RSIMP for ratio h/h_2
ISTORE	i^{th} mesh position where occurs the maximum U_{ij} change between successive iterations
ITERMX	input value for maximum allowed number of iterations
JSTORE	j^{th} mesh position where occurs the maximum U_{ij} change between successive iterations
K	index in DEFINE function F(K, I, J)
LAMBDA	compressibility factor, Λ; sometimes called the "bearing number"
LASTA	trailing edge boundary node
LASTR	outer radial boundary node
LN(I), LS(I)	finite difference indices for $\partial P/\partial R$ and $\partial^2 P/\partial R^2$ at R(I); for variable mesh coding
LE(J), LW(J)	finite difference indices for $\partial P/\partial \theta$ and $\partial^2 P/\partial \theta^2$ at θ(J); for variable mesh coding
M	index in DEFINE function X(M, I, J)
NA	number of angular mesh increments
NR	number of radial mesh increments
NRATIO	number of ϵ/H_2 values input in ERATIO array
NTHETA	number of θ_p/β values input in TRATIO array
NUMBET	number of β values input in VBETA array
NUMLMB	number of Λ values input in VLMBDA array

NUMRI	number of radius ratio values in VRI array
ODD(4)	storage array in numerical integration procedure
OLDQ	logical switch for use of previous numerical solution array of U_{ij} as first guess for new calculation. FALSE returns ambient pressure as initial guess.
OMEGA	iteration relaxation factor, Ω
P(I, J), PNORM(I, J)	normalized lubricant film pressure relative to ambient pressure
Q(I, J)	the working storage array for the U_{ij} in the compressible gas program
QSTORE	value of the maximum change of U_{ij} for one iteration over the entire sector pad domain
R(15)	array of values r/r_o at the radial mesh nodes I = 1(1)LASTR
RESIDL	input error limit on maximum allowed difference of U_{ij} between successive iterations
RI	current value of radius ratios from VRI array
RR	integral of first moment for R_{cp}
STRERR	storage value of ERROR during search for maximum error within one iteration pass
TH(21)	array of θ_j values for all j-mesh
THPR	nodes J = 1(1)LASTA
TRATIO(10)	input array of θ_p/β values
VARGRD	variable mesh logical switch; TRUE causes finer finite difference mesh next to pad boundaries; FALSE utilizes a constant mesh increment in either coordinate
VLMBDI(10)	input array of Λ values
VRI(10)	input array of radius ratio values, RI
WUNIT	unit load capability of bearing, i.e., total load WW per unit area
WW	integral for bearing load capability

X(M, I, J)	a DEFINE (local) function in radial integration subroutine RSIMP for friction dissipation. M = 1 at J = 1, M = 2 for J = 2(1) LASTA-1, and M = 3 at J = LASTA
XF(21, K)	array of three functions from radial integration subroutine with values at each θ_j mesh point. K = 1, 2, 3 correspond to load, center of pressure, and friction calculations, respectively. K = 4, 5, 6 correspond to edge leakage.

APPENDIX F

SAMPLE PROBLEMS

Computer output listings are presented for two representative runs, one for a compressible lubricant case and one for liquid lubricant. Input data cards for both cases are shown with the computer program listings in appendix C.

In both runs β=45^{o}, θ_p/β=1., R_i=.5, and 20 values of ϵ/H_2=.5(.5)10. In addition Λ=50. for the compressible case.

The execution of all cases by the compiled programs required less than 1 minute of computer time on the UNIVAC 1100/42.

NUMERICAL RESULTS - GAS BEARING ANALYSIS
LEWIS RESEARCH CENTER (NASA)

SYSTEM PARAMETERS

(P1)	(P2)	(P3)	(P4)
INNER/OUTER RADII	BEARING PAD ANGLE	BEARING NUMBER	PIVOT ANGLE RATIO
RI/RO	BETA (DEGREES)	LAMBDA	THETAP/BETA
.50000	45.000	50.000	1.0000

NUMERICAL RESULTS

(R1) H1/H2	(R2) 1/H2	(R3) EPSILON/H2	(R4) LOAD,WBAR	(R5) UNIT-LOAD	(R6) FRICTION,F	(R7) F/WBAR	(R8) H2/H(CP)	(R9) R(CP)	(R10) THETA(CP)/BETA	(R11) X(CP)
1.3536	1.0000	.50000	.19982-01	.67847-01	1.3367	66.893	.90113	.77744	.63565	-.21945
1.7071	1.0000	1.0000	.32872-01	.11161	1.2000	36.504	.82331	.77395	.64226	-.21461
2.0607	1.0000	1.5000	.40893-01	.13885	1.0992	26.879	.76015	.77145	.64836	-.21036
2.4142	1.0000	2.0000	.45591-01	.15479	1.0214	22.403	.70773	.76960	.65414	-.20649
2.7678	1.0000	2.5000	.48056-01	.16317	.95907	19.957	.66346	.76819	.65967	-.20290
3.1213	1.0000	3.0000	.49046-01	.16652	.90772	18.506	.62555	.76708	.66496	-.19953
3.4749	1.0000	3.5000	.49071-01	.16661	.86441	17.616	.59267	.76619	.67000	-.19637
3.8284	1.0000	4.0000	.48472-01	.16458	.82718	17.065	.56384	.76545	.67480	-.19339
4.1820	1.0000	4.5000	.47480-01	.16121	.79466	16.737	.53833	.76484	.67936	-.19058
4.5355	1.0000	5.0000	.46247-01	.15702	.76589	16.561	.51555	.76431	.68369	-.18793
4.8891	1.0000	5.5000	.44875-01	.15236	.74016	16.494	.49508	.76386	.68779	-.18543
5.2426	1.0000	6.0000	.43433-01	.14747	.71693	16.506	.47655	.76346	.69168	-.18307
5.5962	1.0000	6.5000	.41968-01	.14249	.69580	16.579	.45967	.76311	.69537	-.18084

5.9497	1.0000	7.0000	.40508-01	.13754	.67645	16.699	.44423	.76280	.69888	-.17873
6.3033	1.0000	7.5000	.39075-01	.13267	.65862	16.855	.43003	.76252	.70220	-.17672
6.6569	1.0000	8.0000	.37680-01	.12794	.64210	17.041	.41691	.76227	.70537	-.17482
7.0104	1.0000	8.5000	.36332-01	.12336	.62674	17.250	.40476	.76204	.70838	-.17301
7.3640	1.0000	9.0000	.35036-01	.11896	.61239	17.479	.39344	.76183	.71125	-.17130
7.7175	1.0000	9.5000	.33793-01	.11474	.59895	17.724	.38288	.76164	.71398	-.16966
8.0711	1.0000	10.000	.32604-01	.11070	.58630	17.983	.37300	.76146	.71659	-.16810

@FIN

NUMERICAL RESULTS - INCOMPRESSIBLE ANALYSIS
LEWIS RESEARCH CENTER(NASA)/

SYSTEM PARAMETERS

(P1)	(P2)	(P3)	(P4)
INNER/OUTER RADII	BEARING PAD ANGLE	PIVOT ANGLE RATIO	
RI/RO	BETA (DEGREES)	THETAP/BETA	
.50000	45.000	1.0000	

NUMERICAL RESULTS

(R1)	(R2)	(R3)	(R4)	(R5)	(R6)	(R7)	(R8)	(R9)	(R10)	(R11)
EPSILON/H2	H1/H2	UNIT-LOAD	FRICTION/ LOAD	RO SIDE LEAKAGE	RI SIDE LEAKAGE	EDGE LEAKAGE	INSIDE FLOW	(R(CP)-RI)/ (1-RI)	THETA(CP)/ BETA	X(CP)
.50000	1.3536	.23536-02	40.132	.43651-01	.14749-01	.46783	.38495	.54650	.53403	-.27671
1.0000	1.7071	.34440-02	24.726	.89588-01	.29153-01	.45923	.39622	.54107	.55810	-.26209
1.5000	2.0607	.39366-02	19.844	.13708	.43063-01	.45196	.40841	.53748	.57776	-.25029
2.0000	2.4142	.41414-02	17.534	.18618	.56982-01	.44573	.42187	.53474	.59382	-.24067
2.5000	2.7678	.42036-02	16.228	.23734	.71215-01	.44030	.43701	.53253	.60688	-.23285
3.0000	3.1213	.41838-02	15.448	.28971	.85930-01	.43541	.45228	.53057	.61884	-.22569
3.5000	3.4749	.40978-02	15.056	.34215	.10026	.43113	.46703	.52912	.62988	-.21913
4.0000	3.8284	.39756-02	14.908	.39492	.11407	.42740	.48190	.52809	.63976	-.21330
4.5000	4.1820	.38353-02	14.928	.44785	.12746	.42413	.49672	.52735	.64874	-.20802
5.0000	4.5355	.36918-02	15.052	.50137	.14079	.42122	.51193	.52675	.65683	-.20327
5.5000	4.8891	.35519-02	15.248	.55575	.15432	.41860	.52777	.52621	.66409	-.19900
6.0000	5.2426	.34119-02	15.530	.61004	.16758	.41627	.54337	.52581	.67087	-.19502
6.5000	5.5962	.32794-02	15.859	.66515	.18106	.41417	.55955	.52544	.67704	-.19140
7.0000	5.9497	.31492-02	16.258	.71996	.19421	.41231	.57536	.52518	.68287	-.18798

7.5000	6.3033	.30279-02	16.690	.77568	.20766	.41061	.59180	.52492	.68819	-.18486
8.0000	6.6569	.29098-02	17.184	.83091	.22075	.40910	.60779	.52474	.69327	-.18189
8.5000	7.0104	.28005-02	17.703	.88719	.23421	.40773	.62449	.52455	.69793	-.17916
9.0000	7.3640	.26944-02	18.280	.94280	.24728	.40651	.64066	.52443	.70241	-.17653
9.5000	7.7175	.25965-02	18.877	.99960	.26078	.40539	.65760	.52430	.70652	-.17412
10.000	8.0711	.25049-02	19.502	1.0571	.27460	.40438	.67508	.52416	.71035	-.17187

aFREE LIQUID.

REFERENCES

1. Etsion, Izhak: Analysis of the Gas-Lubricated Flat-Sector-Pad Thrust Bearing. NASA TN D-8220, 1976.

2. Etsion, Izhak: Design Charts for Arbitrarily Pivoted, Liquid-Lubricated, Flat-Sector-Pad Thrust Bearing. NASA TN D-8344, 1976.

3. Salvadori, Mario G.; and Baron, Melvin L.: Numerical Methods in Engineering. Second ed., Prentice-Hall, Inc., 1961.

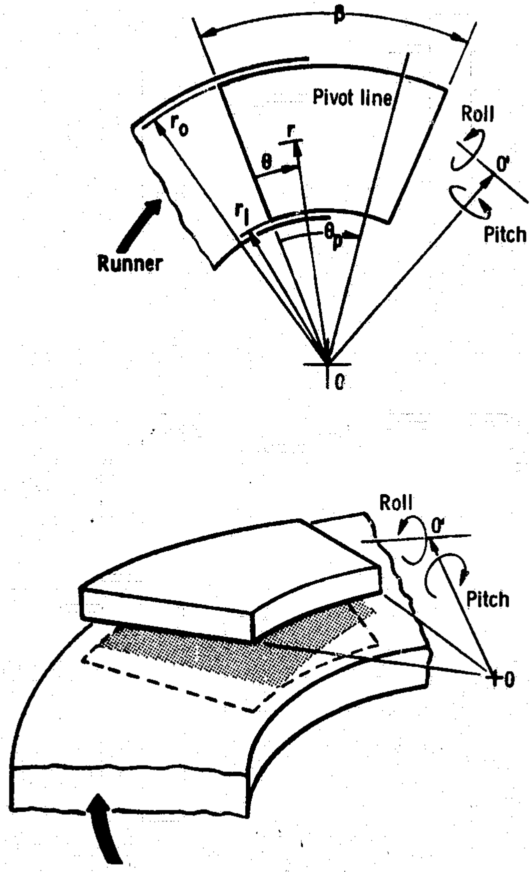


Figure 1. - Geometry of sector pad.

E-8930

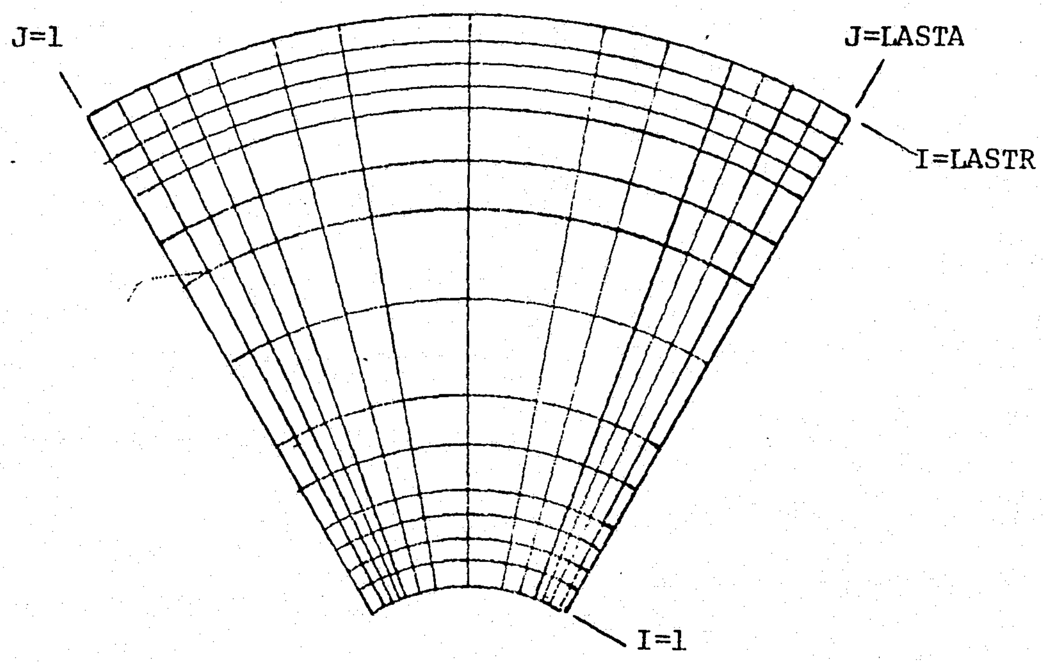


Figure 2. Sector Pad Mesh Definition for Finite Difference Scheme.

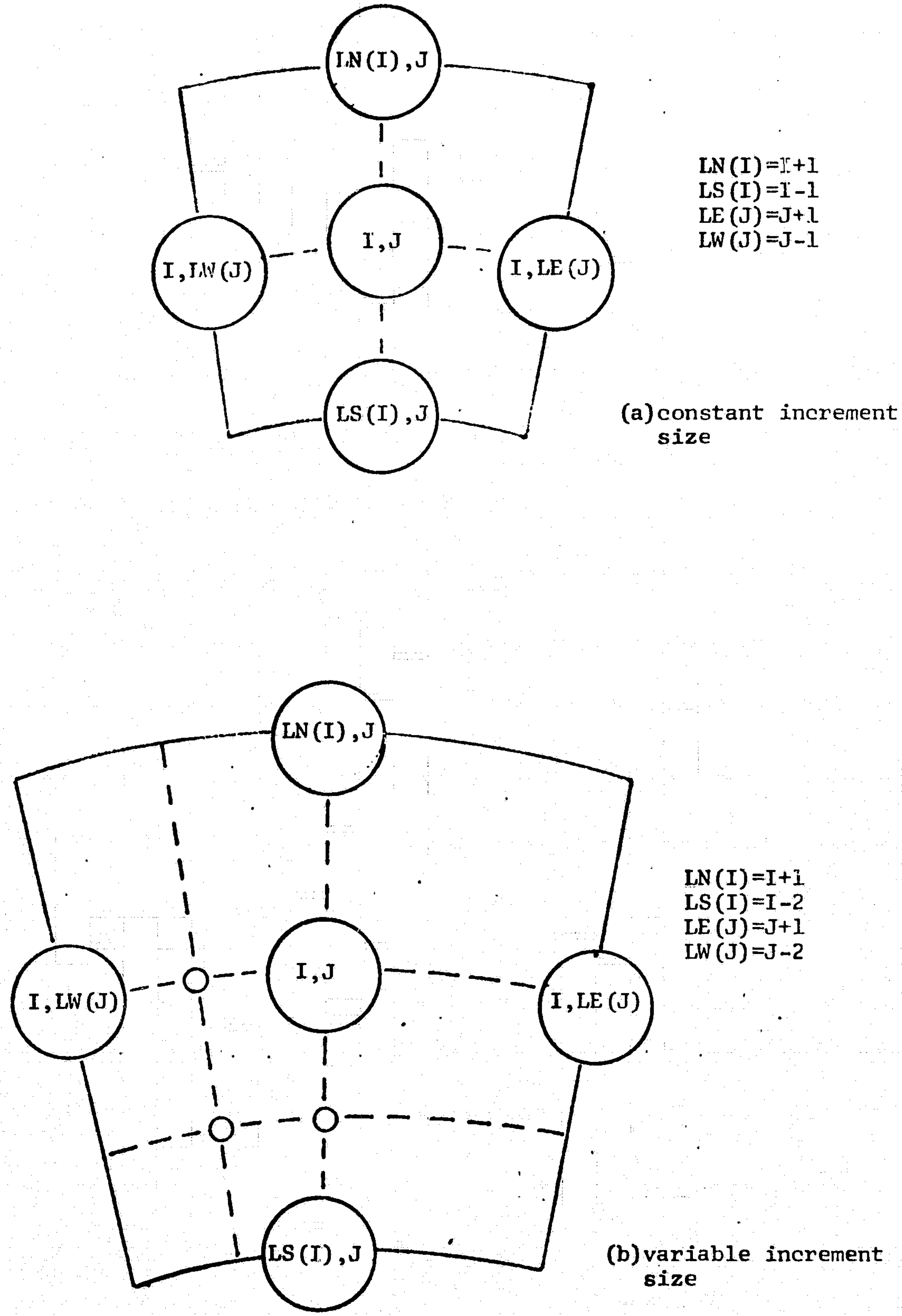


Figure 3. Central Difference Mesh for Partial Derivatives.