NASTRAN Structural Model for the Large 64-Meter Antenna Pedestal Part III – Applications to Hydrostatic Bearing Oil Film

C. T. Chian and D. Schonfeld
Ground Antennas and Facilities Engineering Section

Investigations were conducted on the 64-meter antenna hydrostatic bearing oil film thickness under a variety of loads and elastic moduli. These parametric studies used a NASTRAN pedestal structural model to determine the deflections under the hydrostatic bearing pad. The deflections formed the input for a computer program developed by the Franklin Institute to determine the hydrostatic bearing oil film thickness. For the future 64-meter to 70-meter antenna extension and for the 2.2-meter (86-in.) haunch concrete replacement cases, the program predicted safe oil film thickness (greater than 0.13 mm (0.005 in.) at the corners of the pad). The effects of varying moduli of elasticity for different sections of the pedestal and the film height under distressed runner conditions were also studied.

I. Introduction

This is the third and final article in a series of reports on the static analysis and computer modeling for the large 64-meter antenna pedestal. The pedestal structural model previously reported in Refs. 1 and 2 was developed using the MSC version of the NASTRAN Program.

The top surface deflection of the pedestal obtained from the NASTRAN model was used as an input to the hydrostatic bearing oil film program (Ref. 3) to determine the minimum oil film thickness between the hydrostatic bearing pad and the runner. The knowledge of the oil film thickness was necessary to conduct a variety of hydrostatic bearing rehabilitation studies. A minimum oil film thickness of 0.13 mm (0.005 in.) is considered necessary for safe operation, to avoid any metal-to-metal contact between the hydrostatic bearing, and to accommodate a variety of runner malfunctions and placement tolerances.

A cross-sectional diagram of the hydrostatic bearing is shown in Fig. 1. Deflected shapes of the hydrostatic bearing pad and runner surface are illustrated in Fig. 2.

Three parametric studies were conducted to evaluate the performance of the hydrostatic bearing system. Effects on the oil film thickness due to the following factors were considered in each of the three parametric studies:

(1) The height of the new concrete in the pedestal haunch area.

(2) The different moduli of elasticity of the concrete in the pedestal wall and haunch area.

(3) The hydrostatic bearing pad load increase due to the planned antenna aperture extension from 64-meter to 70-meter.

The results of these parametric studies will be presented in Section III.

II. Description of the Oil Film Computer Program

The hydrostatic bearing computer program was developed by the Franklin Institute (Philadelphia, Pa.) under contract with the Jet Propulsion Laboratory (Ref. 3). The program's original use was to support the design of the 64-m antenna. At that time, the program included a number of capabilities previously unavailable in other models. Among these capabilities was the ability to analyze nonuniform film thickness, tilting moments, and various lubricant supply modes. This program is used in conjunction with the NASTRAN pedestal model to predict hydrostatic bearing oil film thicknesses under a variety of load conditions. In this section, a description of the Franklin program is presented to indicate how it was used for the 64-m antenna pedestal studies.

The derivation of the mathematical equations used in the program is based on a number of assumptions. These assumptions are:

(1) Incompressible fluid.

(2) Two-dimensional laminar flow.

(3) Steady-statê conditions.

For bearings with a negligible amount of relative motion, the Reynolds Equation becomes

$$\frac{\partial}{\partial x}\left(h^3 \frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(h^3 \frac{\partial P}{\partial y}\right) = 0 \tag{1}$$

The program solves Eq. (1) in its dimensionless form. The dimensionless form is obtained using a characteristic length L, a characteristic oil film thickness c, and a characteristic pressure P_r.

The result is:

$$\left(\frac{\partial^2 P}{\partial X^2} + \frac{\partial^2 P}{\partial Y^2}\right) + \frac{3}{H}\left(\frac{\partial H}{\partial X}\frac{\partial P}{\partial X} + \frac{\partial H}{\partial Y}\frac{\partial P}{\partial Y}\right) = 0 \tag{2}$$

$$P \equiv \frac{P - P_{atm}}{P_r - P_{atm}}$$

$$H = h/c$$

$$X = \frac{x}{L} \qquad Y = \frac{y}{L}$$

where P_{atm} is the atmospheric pressure.

The program makes use of the fact that Eq. (2) is linear in pressure, P, in order to obtain a solution by superposition. Superposition is obtained by assuming that each recess is pressurized in turn with the pressure at other recesses equal to zero (Fig. 3). The final pressure distribution can then be expressed as a linear combination of the individual solutions:

$$P(X, Y) = \sum_j \alpha_j P_j (X, Y) \tag{3}$$

where α_j is a dimensionless pressure weighting factor for each recess:

$$\alpha_j = \frac{(P_r)_j - P_{atm}}{P_{ref} - P_{atm}} \tag{4}$$

The program has the ability to solve for various lubricant supply schemes, with the following options:

(1) Separate pumps feed each recess.

(2) Separate pumps feed opposite pairs of recesses with capillary compensation.

(3) A common manifold feeds all recesses with capillary compensation.

For the work presented here, option (1) was used throughout, since that is the supply scheme on the 64-m antennas. Once the program obtains a pressure distribution map $P(X, Y)$, other quantities can be computed as well. In particular we are interested in the clearance distribution $H(X, Y)$.

The general shape of the clearance distribution can be obtained either by the evaluation of an appropriate analytic function or by point-by-point input. The program contains a number of coefficients, $A_1, A_2, \cdots A_{23}$ that are used to specify possible functions for $H(X, Y)$. The general formula is:

$$\begin{aligned} H(X, Y) = {} & A_1 + A_2 s + A_3 t + A_4 s^2 + A_5 t^2 + A_6 st \\ & + A_7 s^3 + A_8 t^3 + A_9 s^2 t + A_{10} st^2 \\ & + A_{11}\sqrt{A_{12} + A_{13} + A_{14} t^2} \\ & + A_{15}\cos(A_{16}s) + A_{17}\cos(A_{18}t) \\ & + A_{19}\cos(A_{16}s)\cos(A_{18}t) \\ & + A_{20}\Big\{e^{-A_{21}X}\cos(A_{21}X) \\ & + e^{-A_{21}(1-X)}\cos[A_{21}(1-X)] \\ & - 2e^{-A_{21}/2}\cos(A_{21}/2)\Big\} \end{aligned} \tag{5}$$

In this formula, the dimensionless coordinates s and t are given by:

$$s = X - X_0 = X - A_{22}$$
$$t = Y - Y_0 = Y - A_{23} \tag{6}$$

with X_0 and Y_0 denoting the geometric center of the pad. As an example, for a uniform clearance distribution A_1 = constant and all A_i $(i \neq 1) = 0$. A doubly-parabolic shape was assumed to approximate the actual runner deflection pattern and hence the clearance distribution, and has provided acceptable results. In terms of the formula shown above, the resulting equation is:

$$H(X, Y) = A_1 + A_4 s^2 + A_5 t^2 \tag{7}$$

The tie-in between the input to the Franklin program and the NASTRAN pedestal model output is the runner deflection map. Given a set of pedestal/bearing loads and elastic properties, the NASTRAN model predicts a deflection map for the runner area under the pad (Fig. 4). The deflections at the end points of the center line $(s, t) = (0, 1/3), (0, -1/3), (0.5, 0)$ and at the center point $(0, 0)$ are used to find the coefficients A_i in Eq. (5). Fitting these points gives a representation of the whole surface to within 5% of the actual deflections, which is considered sufficiently accurate.

To obtain the actual oil film thickness, the A_1 coefficient is varied until the pad load computed by the Franklin program is equal to the actual load on the pad. For most of our work, we determined oil film thickness based on the pad 3 load of 1.1×10^6 kg (2.4×10^6 lb). For the planned 70-meter extension load analysis, we varied this load to a maximum of 1.6×10^6 kg (3.6×10^6 lb).

The flexibility of Eq. 5 allowed various other deflection configurations to be tried, in particular, the case of twist in the runner. The clearance equation for this case is given by

$$H(X, Y) = A_1 + A_4 s^2 + A_5 t^2 + A_6 st \tag{8}$$

or, for a simpler planar twist:

$$H(X, Y) = A_1 + A_6 st \tag{9}$$

Note that this is taken as an extreme case of runner distress, reflecting actual profile measurements in the past.

Another advantage of Eq. 5 is that it allows us to consider pad deflection. By reducing the s^2 term in Eq. 5, for example, one can account for a parabolic deflection in the s-direction of the pad. The t-direction deflection was not considered because most pad deflection occurred in the circumferential direction (s). The results showed that minimum oil film thickness occurred at the corners of the pad. Based on previous operational experience, a 0.13-mm (0.005-in.) oil film thickness at the pad corners is considered a minimum acceptable value. The flow chart of the Franklin computer program is given in the Appendix and Ref. 3.

III. Parametric Studies

Three parametric studies were conducted to evaluate the operability of the large 64-meter antenna:

(1) Effect on the oil film thickness due to the height variation of the new concrete in the pedestal haunch.

(2) Effect on the oil film thickness due to the variation of concrete elastic moduli in the pedestal wall and haunch area.

(3) Effect on the oil film thickness due to the pad load increase for an antenna aperture extension from 64 meters to 70 meters.

A NASTRAN pedestal model was used to obtain the pedestal top surface deflections. These in turn served as the input to the hydrostatic bearing computer program for determining the oil film thickness between the hydrostatic bearing pad and the runner.

Two design characteristics are used to evaluate the sensitivity of the hydrostatic bearing pad operation to the modulus of elasticity. The first characteristic is the maximum pad out-of-flatness. Deflected shapes of the hydrostatic bearing pad and runner surface are illustrated in Fig. 2. Relative deflections within the hydrostatic bearing pad and within the runner surface (from centerline to edge of pad) are shown as Δ_p and Δ_r, respectively.

Design criteria (Ref. 4) require that the mismatch of deflected surfaces, $\Delta\delta$, be within 0.101 mm (0.004 in.). (This is the variation of the film height between the pad and the runner.) Out of this a maximum mismatch of deflected shapes of 0.076 mm (0.003 in.) was established as the allowance for creep during construction before the bearing pads could be moved. The remaining 0.025 mm (0.001 in.) was the design criteria for mismatch of elastic deformations (Ref. 4). Since creep strains have been compensated for by releveling of the runner, the maximum pad out-of-flatness, a $\Delta\delta$ of 0.101 mm (0.004 in.), can now all be accounted for by elastic deformations. These elastic deformations are part of the NASTRAN output.

The second characteristic used to evaluate the operability of the hydrostatic bearing is the minimum oil film thickness between the pad and the runner. Based on previous operational experience, a minimum oil film thickness, h, of 0.127 mm (0.005 in.) is considered necessary for safe operation. Each of the three parametric studies is explained below.

A. Height of New Concrete in the Pedestal Haunch

In Ref. (1) we used the original pedestal model without including the pedestal haunch lip. The pedestal concrete, with an initial modulus of elasticity E of 2.1×10^{10} N/m^2 (3×10^6 psi), was replaced by a new concrete with the modulus of elasticity of 3.5×10^{10} N/m^2 (5×10^6 psi) at various heights from the top.

In Ref. (2) we used the improved pedestal model, which included the pedestal haunch lip. As before, the pedestal concrete with an initial modulus of elasticity E of 2.1×10^{10} N/m^2 (3×10^6 psi) was replaced by a new concrete with the modulus of elasticity of 3.5×10^{10} N/m^2 (5×10^6 psi) at different heights from the top. Results of this parametric study are shown in Tables 1 and 2, as well as in Figs. 5 and 6.

B. Variation of Concrete Elastic Moduli in the Pedestal Wall and Haunch Area:

The severity of the concrete deterioration with accompanying reduction in compressive strength and modulus of elasticity varies widely throughout the pedestal mass. Studies to date have shown that the most serious damage was in the haunch area. A height of 2.2 m (86 in.) of the concrete in the haunch area has been replaced as part of the rehabilitation efforts.

Portions of the remaining pedestal concrete not replaced have experienced moderate damage and are expected to drop further in strength and modulus of elasticity in the future since the alkali-aggregate reaction (the main reason of deteriorations) is continuous, and not fully understood. Therefore, this study was made to evaluate the operability of the hydrostatic bearing under these continuous deteriorations. The moduli of elasticity of the concrete in the pedestal wall and the haunch area were varied. This study was further subdivided into two parts:

(1) The new haunch area down to a depth 2.2 m (86 in.) was assigned a fixed modulus of elasticity of 3.5×10^{10} N/m^2 (5×10^6 psi), while the modulus of elasticity of the remaining wall was taken to be 2.1×10^{10} N/m^2 (3×10^6 psi), 1.4×10^{10} N/m^2 (2×10^6 psi), and 0.7×10^{10} N/m^2 (1×10^6 psi), to simulate time deteriorations. Note that tests made on replaced concrete showed $E > 3.5 \times 10^{10}$ N/m^2 (5×10^{16} psi).

(2) The pedestal wall was assumed to have a fixed modulus of elasticity of 1.4×10^{10} N/m^2 (2×10^6 psi), while the new haunch area was assigned a modulus of elasticity of 3.5×10^{10} N/m^2 (5×10^6 psi), 3.15×10^{10} N/m^2 (4.5×10^6 psi) and 2.8×10^{10} N/m^2 (4×10^6 psi) to simulate different values of the replaced concrete.

Results of this parametric study showing the effect on the oil film thickness due to the variation of concrete elastic moduli are summarized in Tables 3 and 4. Figures 7 and 8 also give the results of this study.

C. Pad Load Increase With an Antenna Aperture Extension From 64-meters to 70-meters

This study investigates the effects of the increased pad load of the antenna with an aperture extension from 64 meters to 70 meters on the pedestal deflection and the oil film thickness. Pad 3 was assumed to have a load of 1.1×10^6 kg (2.4×10^6 lb). In this study, four loads of 1.1×10^6 kg (2.4×10^6 lb), 1.3×10^6 kg (2.8×10^6 lb), 1.45×10^6 kg (3.2×10^6 lb), and 1.6×10^6 kg (3.6×10^6 lb) were considered for pad 3, which correspond to load factors of 1.00; 1.17; 1.33; and 1.50, respectively, relative to the estimated present 64-meter pad 3 load. This load was based on integration of recess pressure readings. The modulus of elasticity was assumed to be 3.5×10^{10} N/m^2 (5×10^6 psi) for both the pedestal wall and the haunch area. The maximum film height variation, $\Delta\delta$, and the minimum film thickness, h, are given in Table 5 for the four loads considered. The results are also shown in Fig. 9.

IV. Conclusions

In this study we reported on applications of the NASTRAN pedestal model to the hydrostatic bearing oil film for the large 64-meter antenna. The NASTRAN model gave as one result the top surface deflections of the pedestal. These deflections formed the input for the hydrostatic bearing oil film computer program to determine the minimum oil film thickness.

The knowledge of the minimum oil film thickness between the hydrostatic bearing pad and the runner was required to conduct a variety of hydrostatic bearing rehabilitation studies.

Based on results presented in this study, a height of 2.2 meters (86 in.) of concrete in the top-most pedestal haunch area has been replaced in the DSS 14 as part of the rehabilitation efforts. For a new concrete with the modulus of elasticity of 3.5×10^{10} N/m^2 (5×10^6 psi), the study predicted a safe oil film thickness of more than 0.13 mm (0.005 in.).

The effect on the oil film thickness due to the pad load increase for an antenna aperture extension from 64-meters to 70-meters was also investigated. For a pad load increase of up to 20%, the study predicted a safe oil film thickness.

The techniques developed in this study will also be applicable to future rehabilitation studies of the large 64-meter antennas in the DSSs 43 and 63.

Acknowledgments

The authors acknowledge the assistance given by H. Phillips, A. Riewe, F. Lansing, D. McClure, F. McLaughlin, M. Pompa, D. Wells, H. McGinness, M. S. Katow, and S. Rocci during the various steps of this work. We also gratefully acknowledge the assistance of Dr. V. Castelli (Xerox Palo Alto Research Center) with the Franklin Institute program.

References

1. Chian, C. T., M. S. Katow, and H. McGiness, "NASTRAN Structural Model for the Large 64-m Antenna Pedestal, Part I", *TDA Progress Report 42-74*. Jet Propulsion Laboratory, Pasadena, California, August 15, 1983.
2. Chian, C. T., "NASTRAN Structural Model for the Large 64-Meter Antenna Pedestal, Part II – Improved Model", *TDA Progress Report 42-75*. Jet Propulsion Laboratory, Pasadena, California, November 15, 1983.
3. Hinkle, J. G., and V. Castelli, *A Computer Solution for Hydrostatic Bearings with Variable Film Thickness*. The Franklin Institute, Philadelphia, Pennsylvania, Report No. F-B2015, Jan. 11, 1963. JPL reorder No. 63-615, NASA CR 56898.
4. TDA Technical Staff, *The NASA/JPL 64-Meter-Diameter Antenna at Goldstone California: Project Report*. JPL Technical Memorandum 33-671, Jet Propulsion Laboratory, Pasadena, California, July 15, 1974.

Table 1. Effect on the oil film thickness due to the height variation of the new concrete in the pedestal haunch[a,b]

Description, N/m^2 (psi)	Film height variation $\Delta\delta$, mm (in.)	Minimum oil film thickness h, mm (in.)
Entire pedestal: $E = 2.1 \times 10^{10}$ (3×10^6)	0.236 (0.0093)	0.100 (0.0042)
Top 1.4 m (56 in.): $E = 3.5 \times 10^{10}$ (5×10^6); Remaining pedestal: $E = 2.1 \times 10^{10}$ (3×10^6)	0.158 (0.0062)	0.190 (0.0075)
Top 2.2 m (86 in.): $E = 3.5 \times 10^{10}$ (5×10^6); Remaining pedestal: $E = 2.1 \times 10^{10}$ (3×10^6)	0.150 (0.0059)	0.193 (0.0076)

[a]See Section III.A.
[b]Based on the original pedestal model (Ref. 1).

Table 2. Effect on the oil film thickness due to the height variation of the new concrete in the pedestal haunch[a,b]

Description, N/m^2 (psi)	Film height variation $\Delta\delta$, mm (in.)	Minimum oil film thickness h, mm (in.)
Entire pedestal: $E = 2.1 \times 10^{10}$ (3×10^6)	0.147 (0.0058)	0.132 (0.0052)
Top 1.4 m (56 in.): $E = 3.5 \times 10^{10}$ (5×10^6); Remaining pedestal: $E = 2.1 \times 10^{10}$ (3×10^6)	0.102 (0.0040)	0.196 (0.0077)
Top 2.2 m (86 in.): $E = 3.5 \times 10^{10}$ (5×10^6); Remaining pedestal: $E = 2.1 \times 10^{10}$ (3×10^6)	0.097 (0.0038)	0.191 (0.0075)

[a]See Section III.A.
[b]Based on the improved pedestal model (Ref. 2).

Table 3. Effect of varying the modulus of elasticity of the pedestal wall[a,b]

Modulus of elasticity of the pedestal wall, N/m^2 (psi)	Film height variation $\Delta\delta$, mm (in.)	Minimum oil film thickness h, mm (in.)
2.1×10^{10} (3×10^6)	0.097 (0.0038)	0.193 (0.0076)
1.4×10^{10} (2×10^6)	0.102 (0.0040)	0.191 (0.0075)
0.7×10^{10} (1×10^6)	0.119 (0.0047)	0.178 (0.0070)

[a]See Section III.B.
[b]The modulus of elasticity of the top 2.2 m (86 in.) in the haunch is considered to be fixed at 3.5×10^{10} N/m^2 (5×10^6 psi).

Table 4. Effect of varying the modulus of elasticity of the haunch area[a,b]

Modulus of elasticity of the top 2.2 m (86 in.) in the haunch, N/m^2 (psi)	Film height variation $\Delta\delta$, mm (in.)	Minimum oil film thickness h, mm (in.)
3.5×10^{10} (5×10^6)	0.102 (0.0040)	0.191 (0.0075)
3.15×10^{10} (4.5×10^6)	0.112 (0.0044)	0.152 (0.0060)
2.8×10^{10} (4×10^6)	0.125 (0.0049)	0.152 (0.0060)

[a]See Section III.B.
[b]The modulus of elasticity of the pedestal wall is assumed to be fixed at 1.4×10^{10} N/m^2 (2×10^6 psi).

Table 5. Effect of the pad load increase due to the antenna extension[a,b]

Pad (No. 3) load, kg (lb)	Load factor	Film height variation, $\Delta\delta$, mm (in.)	Minimum oil film thickness, h, mm (in.)
1.09×10^6 (2.4×10^6)	1.00	0.089 (0.0035)	0.185 (0.0073)
1.27×10^6 (2.8×10^6)	1.17	0.104 (0.0041)	0.152 (0.0060)
1.45×10^6 (3.2×10^6)	1.33	0.119 (0.0047)	0.122 (0.0048)
1.63×10^6 (3.6×10^6)	1.50	0.135 (0.0053)	0.086 (0.0034)

[a]See Section III.C.
[b]The entire pedestal is assumed to have a modulus of elasticity of 3.5×10^{10} N/m^2 (5×10^6 psi) in all cases.

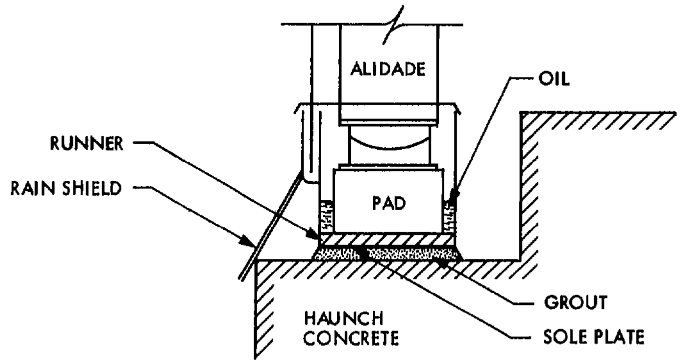


Fig. 1. Cross section of hydrostatic bearing system

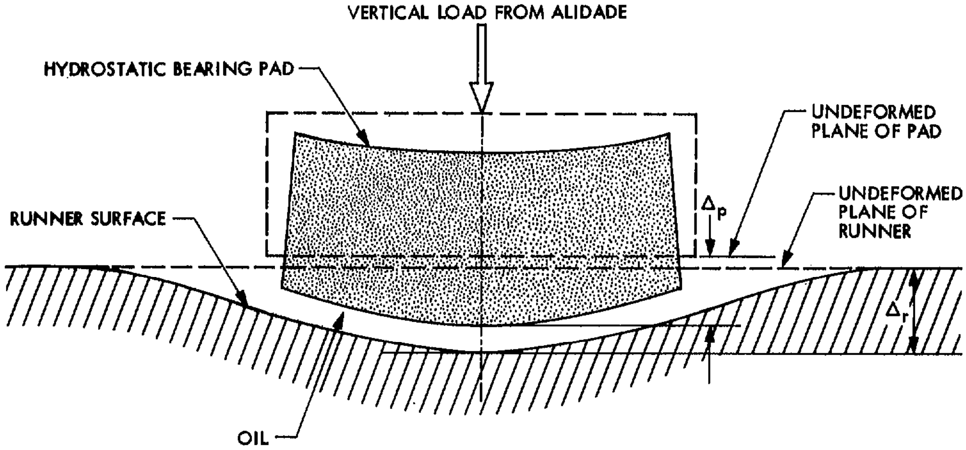


Fig. 2. Deflections of hydrostatic bearing pad and runner surface

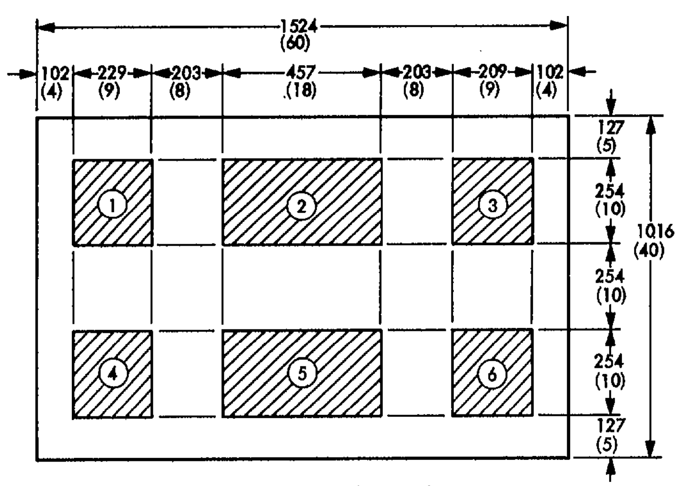
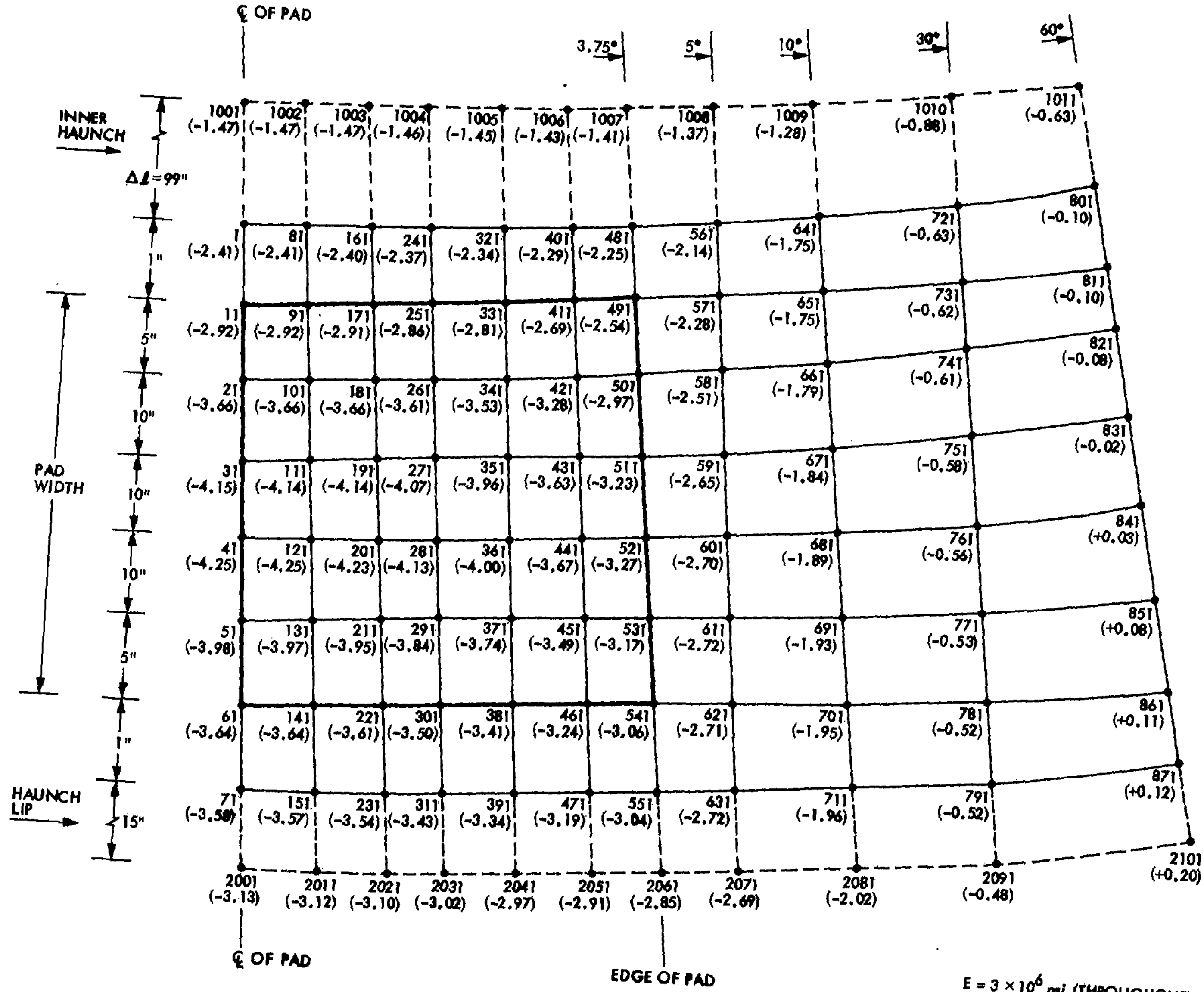


Fig. 3. Recess pattern of hydrostatic bearing pad



E = 3 × 10^6 psi (THROUGHOUT)
DIMENSIONS: 10^{-2} INCHES

Fig. 4. Typical deflection map of top pedestal surface

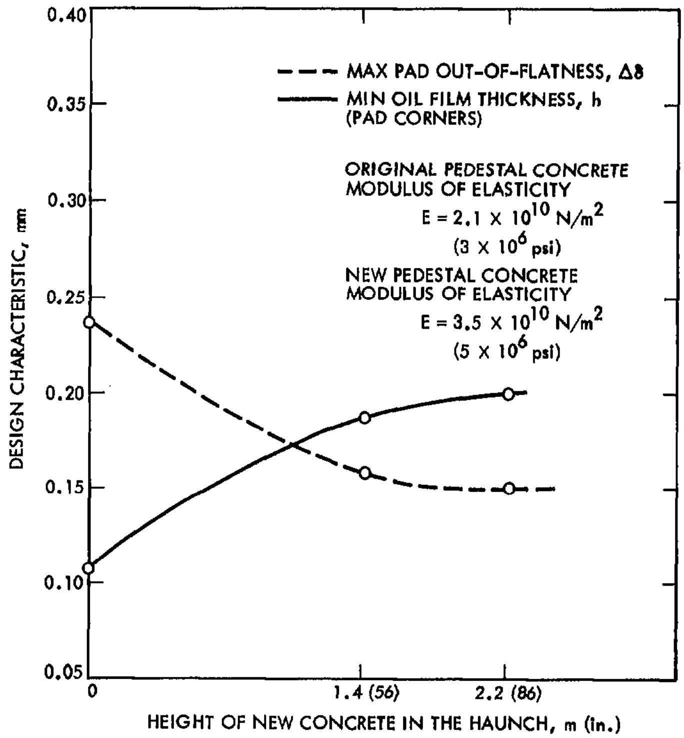


Fig. 5. Effect on the oil film thickness due to the height variation of the new concrete in the pedestal haunch (original pedestal model, Ref. 1)

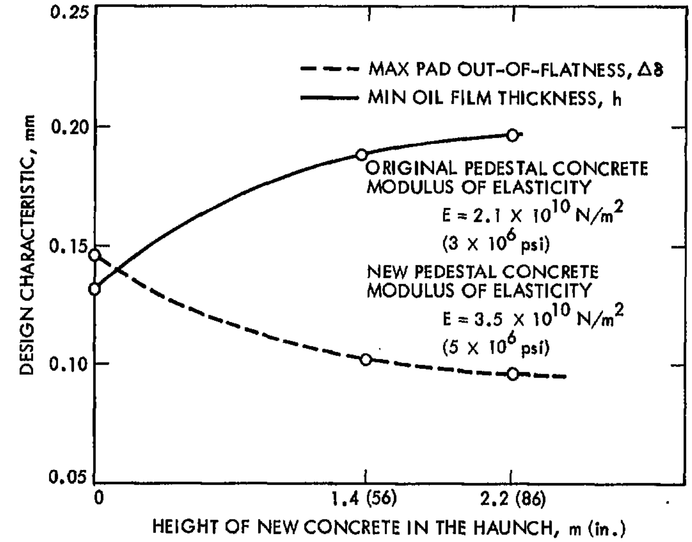


Fig. 6. Effect on the oil film thickness due to the height variation of the new concrete in the pedestal haunch (improved pedestal model, Ref. 2)

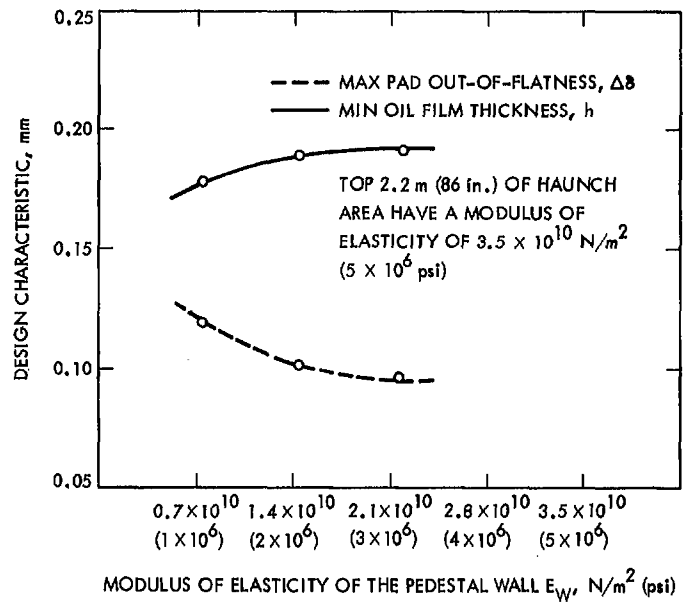


Fig. 7 Effect of varying the modulus of elasticity of the pedestal wall

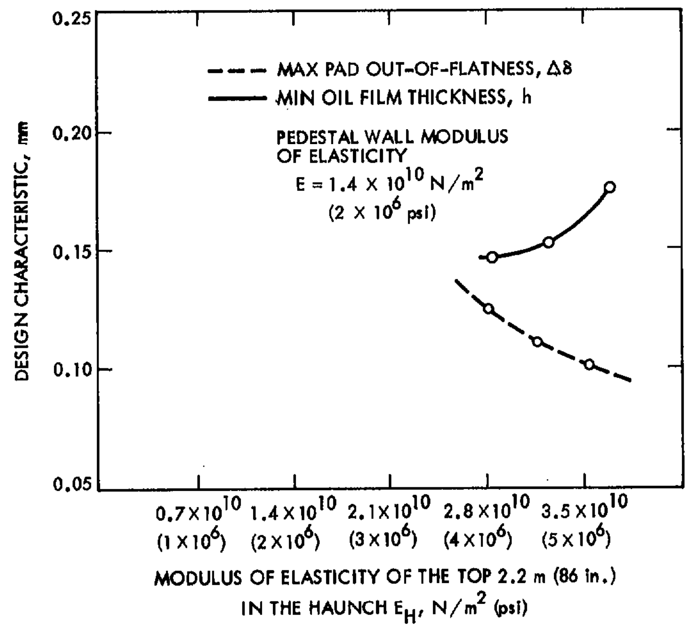


Fig. 8. Effect of varying the modulus of elasticity of the haunch area

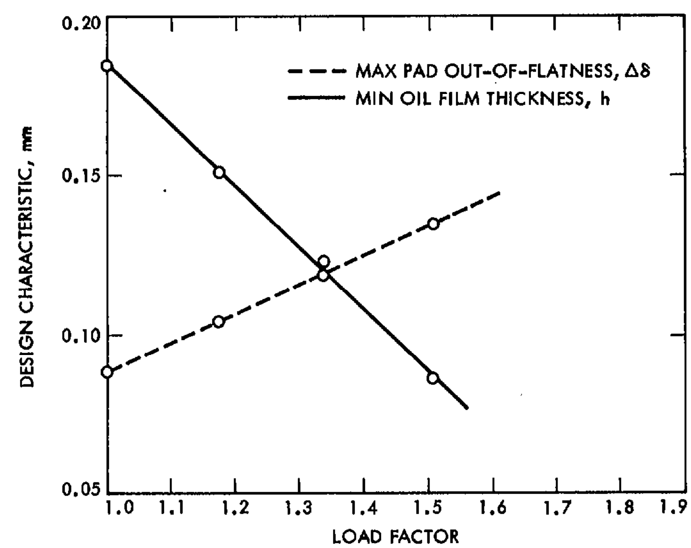


Fig. 9. Effect of the pad load increase due to the antenna extension

Appendix

Oil Film Computer Program Flow Chart

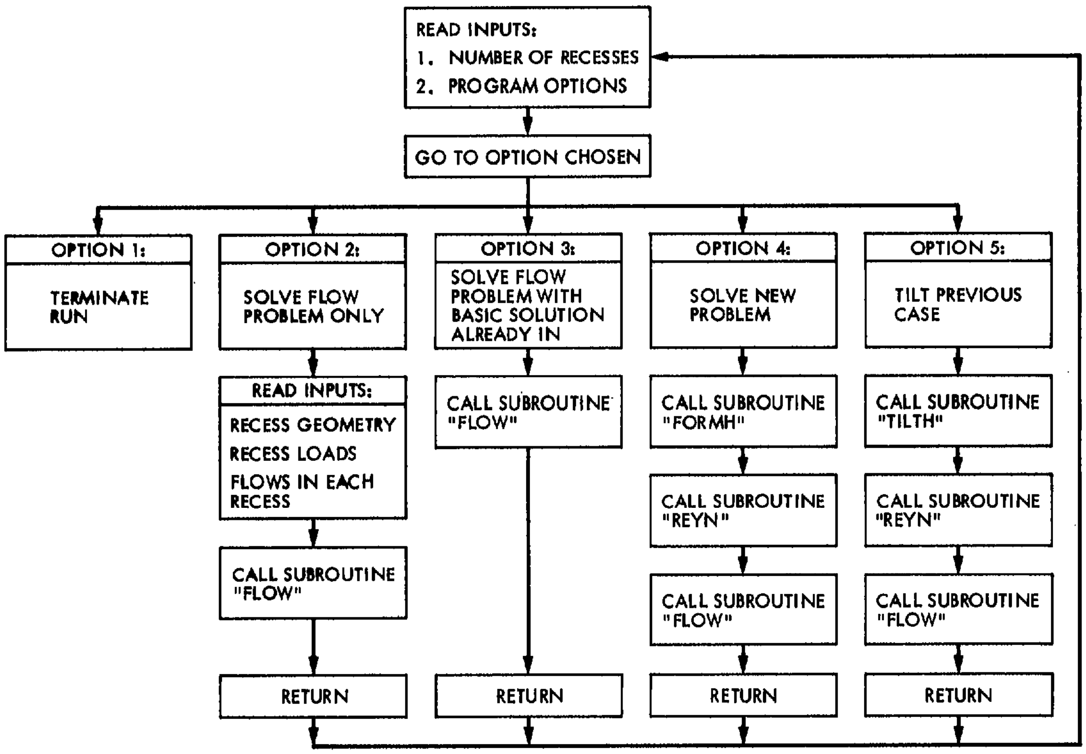


Fig. A-1. Main program

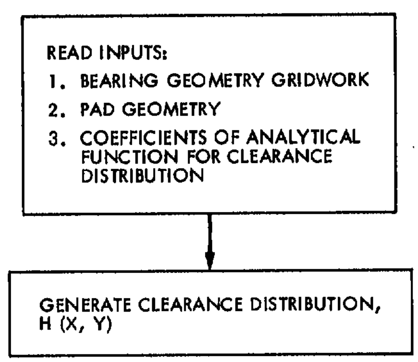


Fig. A-2. Subroutine "FORM H"

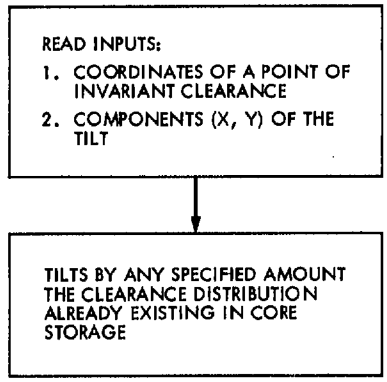


Fig. A-3. Subroutine "TILTH"

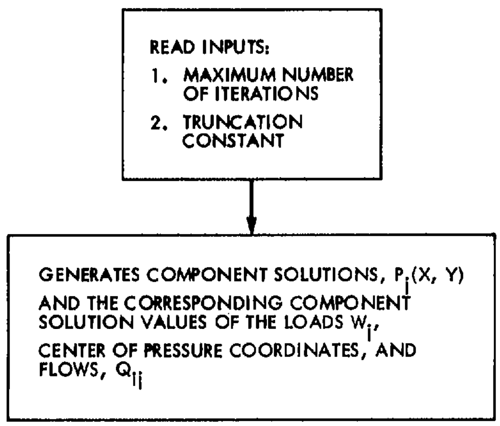


Fig. A-4. Subroutine "REYN"

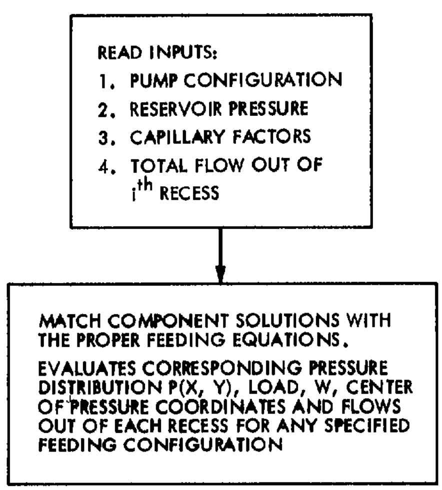


Fig. A-5. Subroutine "FLOW"