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A Gas Film Lubrication Study Part III Experimental Investigation of Pivoted Slider Bearings

Abstract: The results of experimental measurements on pivoted slider bearings are presented, the experimental methods are described, and the experimental data are compared with data obtained from a numerical solution of the Reynolds differential equation for a compressible fluid.

Introduction

The investigation covered by this paper was undertaken in order to establish the effect of various parameters on the performance of air-lubricated slider bearings and to develop techniques for predicting the performance of such bearings.

In addition to the experimental investigation, a numerical analysis was conducted concurrently, using an IBM 650 digital computer. The basis of this analysis was the Reynolds equation[1]

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{6\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{\rho h^3}{6\mu}\frac{\partial p}{\partial z}\right)=U\frac{\partial(\rho h)}{\partial x}. \quad (1)$$

This equation is derived from the Navier-Stokes equation and applies to low Reynolds number flow phenomena where viscous forces predominate. For a compressible fluid the density ρ cannot be considered constant. Assuming a perfect gas, the pressure-density relationship

$$p\rho^{-n}=\text{constant} \quad (2)$$

can be combined with Eq. (1) which results in

$$\frac{\partial}{\partial x}\left(\frac{p^{(1/n)}h^3}{6\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{p^{(1/n)}h^3}{6\mu}\frac{\partial p}{\partial z}\right)=U\frac{\partial}{\partial x}\left(p^{(1/n)}h\right).$$

The derivation, application, and restrictions of this equation and its solutions, for small gas bearings in general, are covered in Part I. This equation is most conveniently solved numerically by the techniques described in Part II. The work of Dr. W. A. Gross (Part I) and Dr. W. A. Michael (Part II) was of great help in establishing the direction taken in the experimental work. This project was a joint effort of the IBM San Jose Research Laboratories and the IBM San Jose Product Development Laboratories.

Flat slider bearings

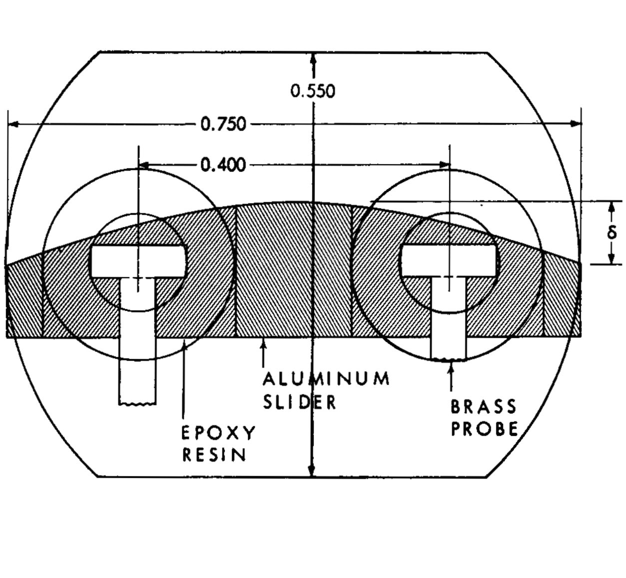
The initial experimental studies were made with pivoted slider bearings with plane surfaces operating on a 6-inch-diameter disk. The size and shape of the bearings used is shown in Fig. 1. The pivot was located 60 per cent of the bearing breadth (direction of surface motion) from the leading edge, and the bearing surfaces were hand-lapped until the surface profile was less than one light fringe (11.6 microinches) convex. This specification was arbitrary, but at this stage of the investigation it was believed that such a small deviation from a flat surface would have a negligible effect.

The performance of these bearings was rather inconsistent, but after sufficient data had been obtained, it became apparent that they might be separated into two groups, neither of which behaved as might be expected from available experimental data or theoretical work. A typical load-clearance curve for one group of bearings is shown in black in Fig. 2. This curve shows that the bearing load increased with decreasing film thickness until the minimum film thickness was about 340 microinches, and the load was 230 grams. At this point, an additional load of 10 grams caused the bearing to fail and contact the moving surface.

The majority of the bearings fell into the second group, and their behavior was even more unexpected than that of the first group. Figure 3 shows a load-clearance curve (in black) typical of this group of bearings. This curve reveals that these bearings behave much the same as those in the first group until a minimum film thickness of approximately 320 microinches is reached. At this point, the slope of the curve changes abruptly and a small increase in load causes a relatively large change in the clearance. In this case, an increase in load of 10 grams caused the minimum film thickness to decrease 85 microinches. After passing through this region, the slope changes abruptly again and the load can be increased without failure of the bearing. This plateau in the curve was most puzzling and at first was thought to be due to some peculiarity in the instrumentation used to measure the clearance. However, numerous tests proved conclusively that this behavior was characteristic of the bearings and was not caused by the particular experimental setup used in the tests.

At this point in the investigation, the numerical solution of the Reynolds equation became available. The first data obtained from the computer were for a flat slider bearing, similar to the bearings used in the experimental work. In Fig. 2, the curve in color is a load-clearance curve plotted from these data; the angle of inclination as a function of the minimum film thickness is also shown. These curves readily explain why some of the experimental bearings failed, even though the clearance between the slider and the moving surface was still relatively large. These curves show that the angle of the inclination be-

Figure 1 **Experimental slider configuration.**



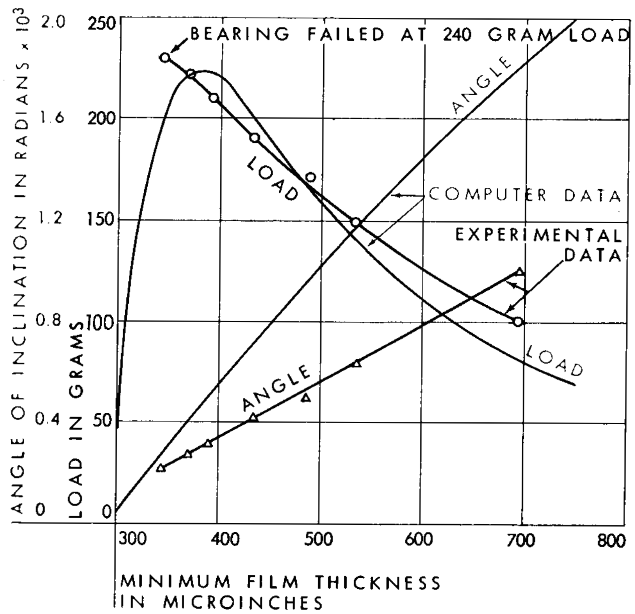


Figure 2 **Load and angle vs film thickness with pivot 0.075 in. behind center line, flat surface, and velocity of 2500 ips. Experimental data in black, computed data in color.**

comes zero while the bearing is still above the moving surface, and also that there are two clearances possible for a given load, one of the two being unstable. In the case of this particular slider, if the load is increased above 220 grams, the bearing becomes unstable and fails.

While the excellent correlation between the experimental and computer data explained the behavior of the bearings which failed, the plateau in the load-clearance curves of the majority of the bearings remained unexplained. The next step in the investigation was to determine whether the small amount of curvature permitted on the experimental bearing surfaces could be critical. In order to investigate this possibility, a solution for a slider with a 10-microinch convex surface was obtained from the computer. The computer curve for this bearing is shown in color in Fig. 3. An examination of the curve reveals that, contrary to expectations, as little as 10 microinches curvature has a significant effect on the bearing performance and causes the plateau in the load-clearance curve. As shown by the curve, the bearing behaves very much like the flat bearing until the film thickness is comparatively small and the angle of inclination approaches zero; at this point, an increase in the load causes a relatively large change in spacing. However, because of the convex surface, failure does not occur. When the clearance becomes small enough so that the slight curvature is significant relative to the film thickness, the bearing is again capable of supporting a load due to the wedge-shaped film created by the curvature. Although the slider continues to support a load after passing through the plateau, it should be noted that the film thickness becomes so small for any appreciable load that contact is likely to occur due to surface roughness.

Convex sliders

The instability of the flat sliders as discussed above suggested the possibility of a convex gliding surface. Since the load-carrying ability of a slider is dependent upon the formation of a wedge between the slider and the surface above which it is gliding, a convex slider appeared to be the answer, as a wedge would be formed regardless of the position assumed.

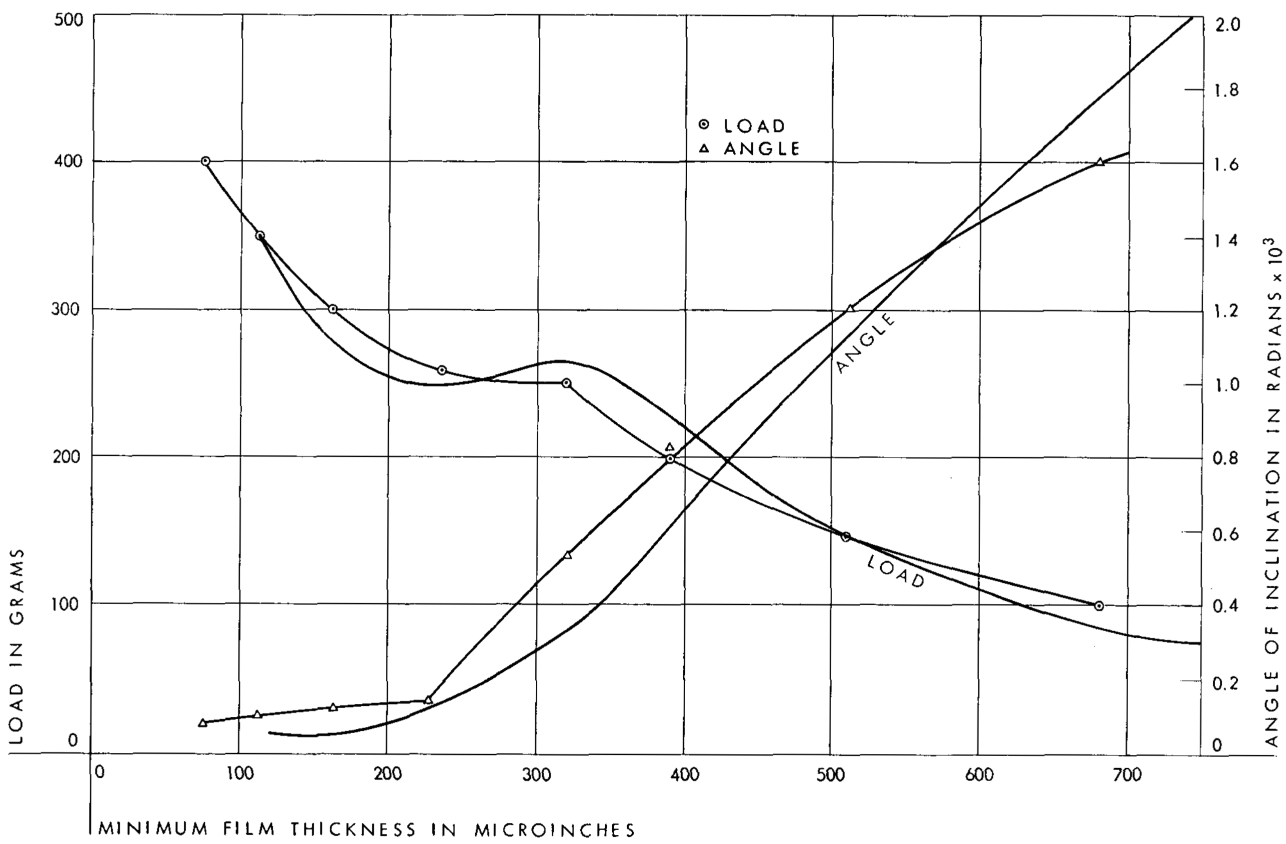
Cylindrical convex slider surfaces were manufactured by bending the slider so that the gliding surface is cylindrically concave and then lapping the gliding surface flat while the slider is in the bent position. Upon obtaining a flat surface, the slider is released from the bent position and assumes a convex cylindrical shape on the gliding surface. This procedure is discussed in more detail in Appendix 1. As shown in Fig. 1, the difference in elevation between the center of the slider and the ends is defined as the crown height.

The experimental work performed with these convex sliders not only verified that the wedge significantly improved the stability, but also showed that it increased the load-carrying ability considerably. Most of the tests were run using sliders with the same length-to-breadth ratio (L/B) but varying crown heights. The dimensions of this slider are shown in Fig. 1. The range of the tests included minimum film thicknesses from approximately 50 to 600 microinches ($67\times 10^{-6}<h_m/B<800\times 10^{-6}$) and disk surface speeds from 1000 to 2500 inches per second at the bearing center line.

At the crown heights up to approximately 200 microinches, the performance is very sensitive to variations in the crown height. In other words, the load for a given minimum film thickness (or the film thickness for a given load) varies greatly over a small range of crown height. This explains why the presumed flat sliders previously discussed were unpredictable and the data obtained were next to impossible to correlate. Unless extreme care is taken when lapping the surface flat, there is usually a small amount of curvature, nearly always convex, which will cause a variation in performance from one slider to another.

At crown heights greater than 200 microinches, the performance is considerably less sensitive to crown height, and the maximum load capacity for a given film thickness (or a maximum film thickness for a given load) is reached where the crown height is approximately 350

Figure 3 **Load and angle vs film thickness where pivot is 0.075 in. behind center line, surface is flat within 11.6 microinches, and velocity is 2500 ips. Experimental data in black. Computed data in color is for a 10-microinch convex surface with a breadth of 0.6 in. and a length of 0.55 in.**



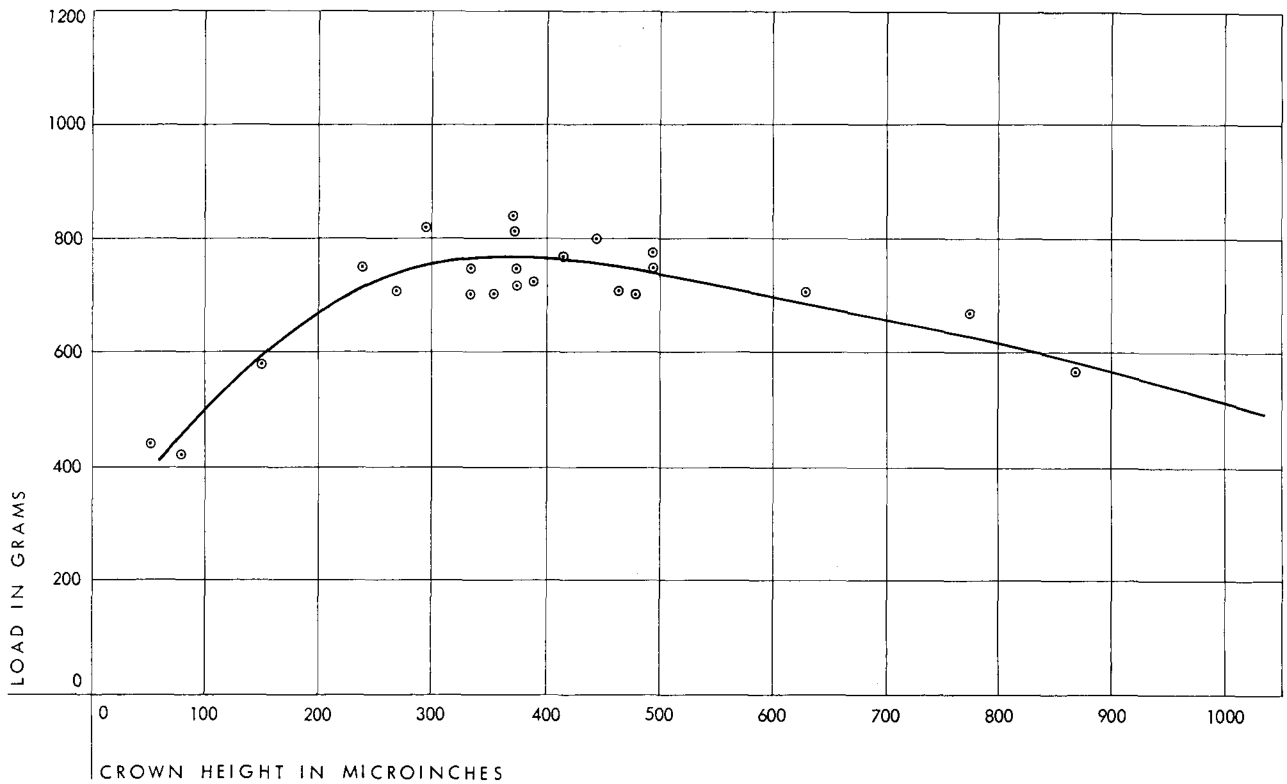


Figure 4 **Load vs crown height for a minimum film thickness of 250 microinches, a velocity of 2500 ips and with the pivot located 0.075 in. behind the center line. Data are experimental.**

microinches. Above this value, the load capacity slowly decreases with increasing crown height.

Figure 4 shows load plotted against crown height for a minimum film thickness of 250 microinches. Figure 5 shows minimum film thickness plotted against crown height for loads of 400, 600, and 800 grams. These two curves show the effect of crown height quite clearly and indicate that an optimum crown height for these sliders is between 300 and 400 microinches, since both the maximum load capacity and minimum sensitivity to crown-height variation occur in this range.

Experimental runs were made to establish the reproducibility of data from one slider to another in this optimum crown-height range. The crown heights on these sliders varied from 305 to 385 microinches. The test data show that the minimum film thickness for a load of 500 grams at a speed of 2500 inches per second is 328 ± 13 microinches, a variation of ± 4 per cent. Other loads produce similar variations.

Variation in crown height has a pronounced effect on the angle of inclination. For a given minimum film thickness the angle of inclination increases with increasing crown height.

The equivalent spring stiffness or slope of the load-clearance curve (for a given load and speed) also reaches a maximum at a crown height of around 350 microinches. An empirical relation may be easily recognized by plotting load against film thickness on log paper and thereby obtaining an equation. A straight line satisfactorily approximates the equivalent spring stiffness at the point of interest.

The equivalent spring stiffness is on the order of 4 grams per microinch or about 8800 pounds per inch at a film thickness of 250 microinches and a speed of 2500 inches per second. Since the mass of the slider is approximately 2 grams and that of the associated mounting equipment is about 12 grams, one would expect an undamped natural frequency, under the above conditions, between 2000 and 4500 cycles per second. This would not be a natural frequency in the true sense of the word, because of the nonlinearity of the spring rate. No experimental work was done to determine this natural frequency.

As explained above, the convex slider is more stable than the flat slider and, as shown by Fig. 6, has no maximum on the load-clearance curve. One might infer from this that there is no limit to its load-carrying capacity. Roughness of the slider and the disk surfaces do limit the load, however, since intermittent contact is made with an apparent gap existing between the disk and the slider. For example, it was found that on a disk that was ground to an average surface roughness of 12 to 14 microinches, intermittent contact occurred when the slider was operating approximately 200 microinches above the mean surface. Hand polishing of the disk with crocus cloth reduced this contact point to a film thickness

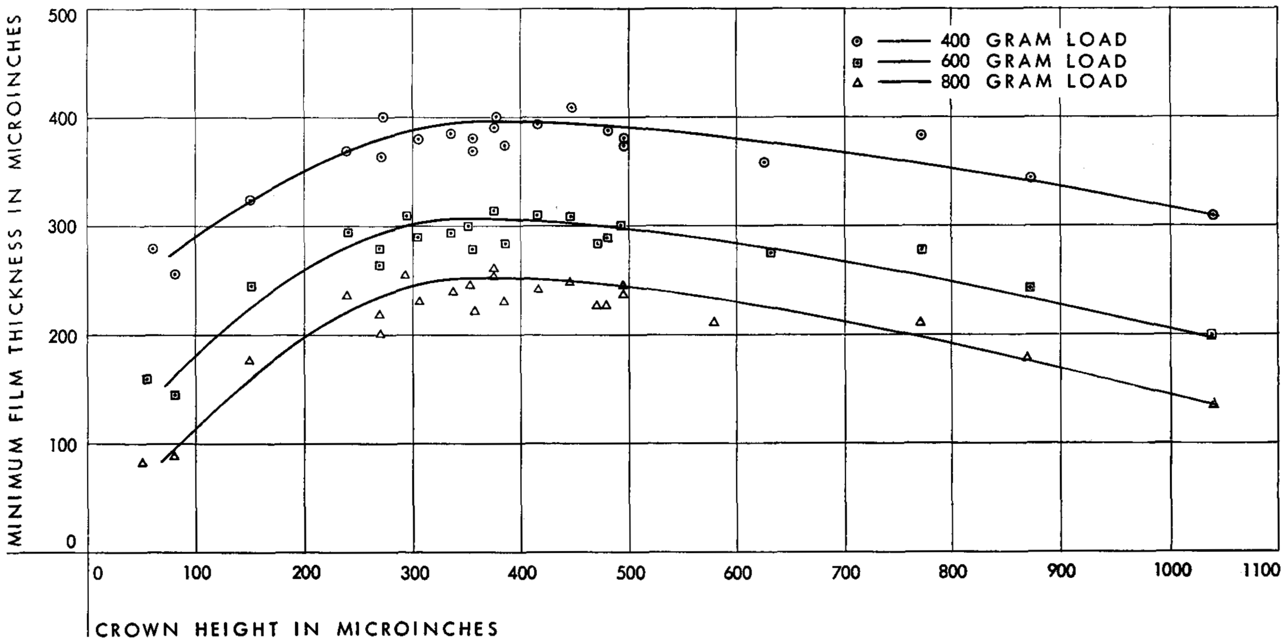
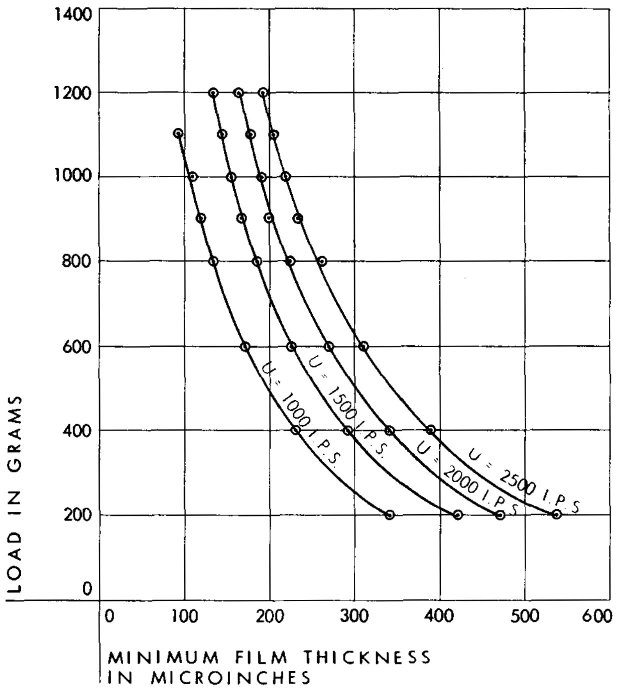


Figure 5 **Film thickness vs crown height for a velocity of 2500 ips, and with pivot located 0.075 in. behind the center line. Data are experimental.**

Figure 6 **Load vs film thickness for a crown height of 375 microinches, and pivot located 0.075 in. behind the center line. Data are experimental.**



in the neighborhood of 125 microinches. Experimentation with disks having average surface roughness of 30 and 52 microinches yielded similar results, although the contact height before hand polishing varied considerably. Except for specific tests investigating the effect of surface roughness, disks lapped to an average surface roughness of 3 to 5 microinches were used, and contact occurred only when the minimum film thickness was under 100 microinches.

Tests were run at speeds of 1000, 1500, 2000, and 2500 inches per second, and the results indicate that the variation in the film thickness with speed for a given load is nearly linear. The data also reveal that this variation in film thickness with speed increases as the crown height increases.

For convenience of manufacture and mounting, the large majority of data were taken using sliders that had rounded ends, as shown in Fig. 1. This shape was inconvenient for use in the computer solution, so a rectangular slider that was approximately equivalent was used for comparison. Good qualitative agreement was obtained as indicated by Fig. 7. The maximum on this load - crown height curve is at a crown height of approximately 250 microinches as compared to 350 microinches for the experimental curve. Two possible reasons for this difference are apparent. The first is the fact that the loading of the experimental sliders was such that, under test, the slider would tend to straighten out, thus reducing the crown height. An upper bound for the flattening under load may be obtained by assuming the slider to deflect as a simple beam. In this case the decrease in crown height for the condition of the abovementioned curve would be approx-

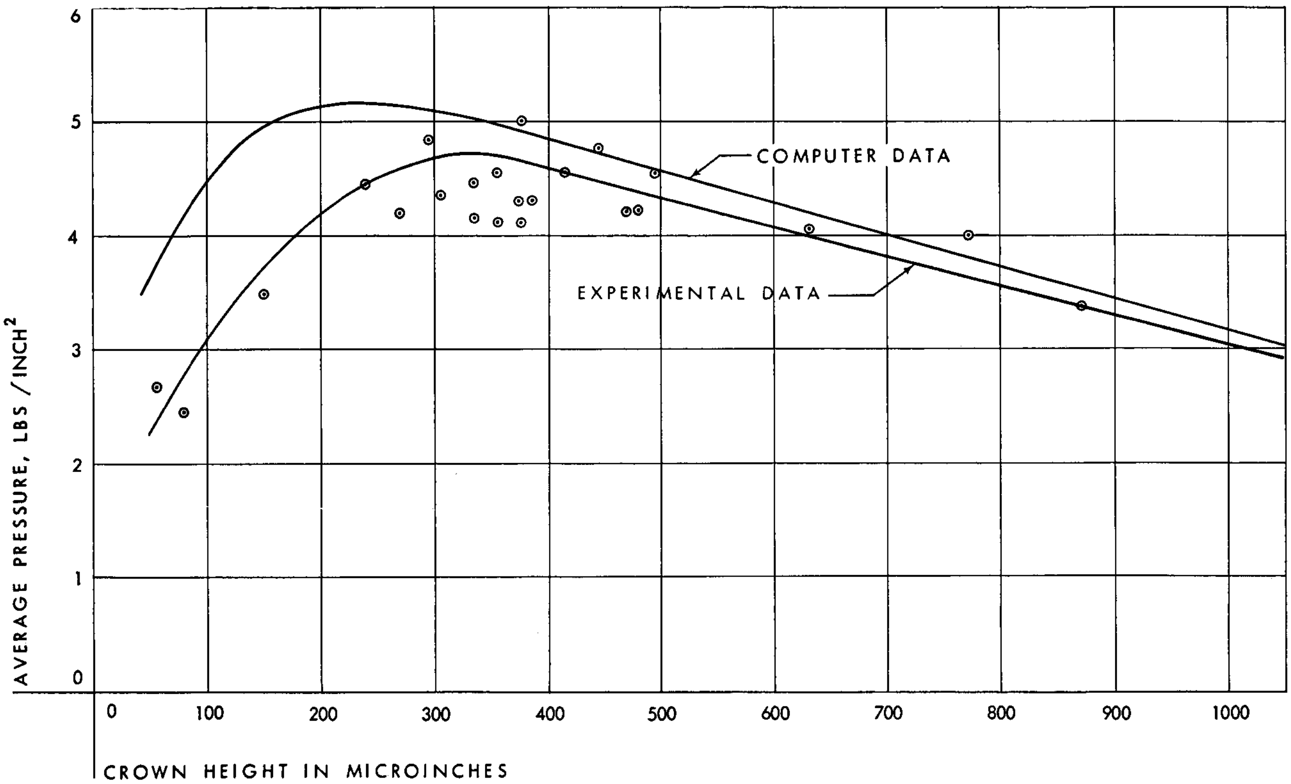


Figure 7 **Load vs crown height for a minimum film thickness of 250 microinches, a velocity of 2500 ips, and with pivot located 0.075 in. behind the center line.**

imately 10 per cent of the crown height. Secondly, the two sliders were of different length and perhaps the plot should be load against the ratio crown height/length. Taking a dimensional-analysis approach would also indicate this as a possibility. Indeed, in this case if the experimental crown height of 350 microinches is divided by the breadth of the experimental slider, and the 250-microinch crown height is divided by the breadth of the computer slider, the agreement is excellent. However, with this in mind, several sizes and shapes of sliders were run on the computer. In each case, the maximum in the load - crown height curve (film thickness constant) occurred at approximately the same crown height and not the same crown height/length ratio as would be expected from the above information. No effort was made to verify this experimentally.

For more exact comparison between computer and experimental results, a slider with identical geometry was investigated from both viewpoints. This slider was 0.4 inch long and 0.625 inch in breadth (direction of motion) and had a crown height of 415 microinches. As shown in Fig. 8, agreement between the two is excellent.

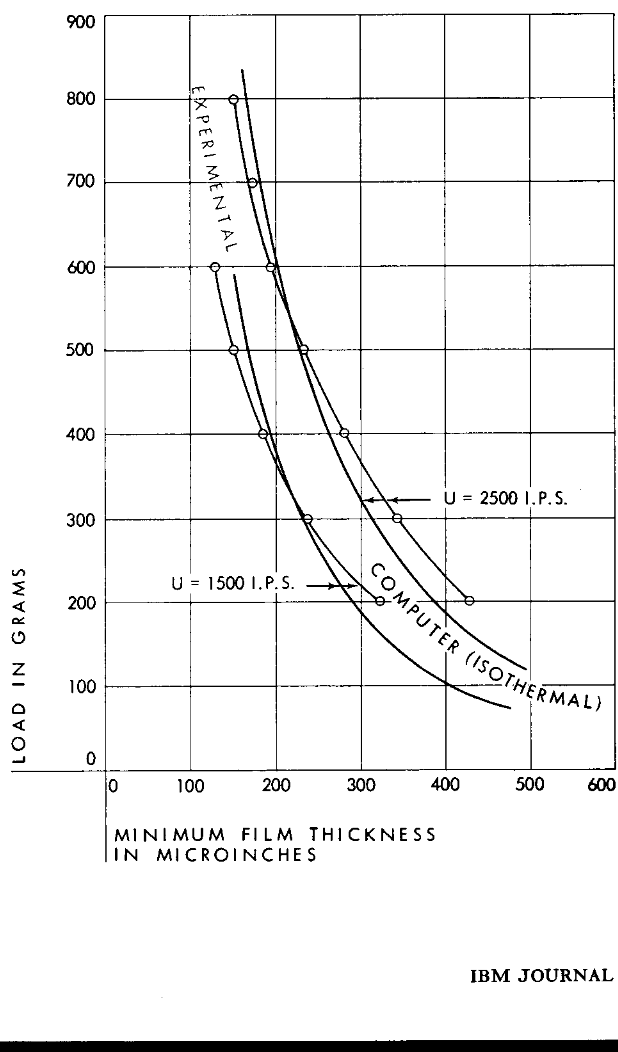


Figure 8 **Load vs minimum film thickness for a crown height of 415 microinches, a breadth of 0.625 in., a length of 0.400 in., and with pivot located 0.075 in. behind the center line.**

The agreement between the experimental and computer data is slightly better for isothermal flow than for adiabatic flow. The load capacity of the adiabatic slider is greater at film thickness below 350 microinches, and the difference becomes larger as the film thickness decreases.

Investigation of the effect of varying the location of the pivot revealed that for the chosen shape, the optimum pivot location is 62 per cent of the breadth from the leading edge and that small deviations from this location do not seriously affect the performance. A few experimental runs were made and, because of the agreement between the experimental and computer work, the computer results were used without extensive verification. Graphs showing the effect of pivot location using computer data are available.[2]

The process used to manufacture the convex sliders inherently produces a cylindrical surface, and therefore no experimental work was done to determine the effect of side curvature (curvature in the direction normal to the direction of motion). The influence of this parameter on the load capacity of slider with a crown height of 350 microinches was investigated on the computer, and the results are shown in Fig. 9. This curve indicates that a small amount of side curvature does not seriously injure the performance. However, a spherical slider of the dimensions shown on the graph would have a side curvature of about 295 microinches, and in this case, the load capacity is only 61 per cent of the load capacity of a cylindrical slider.

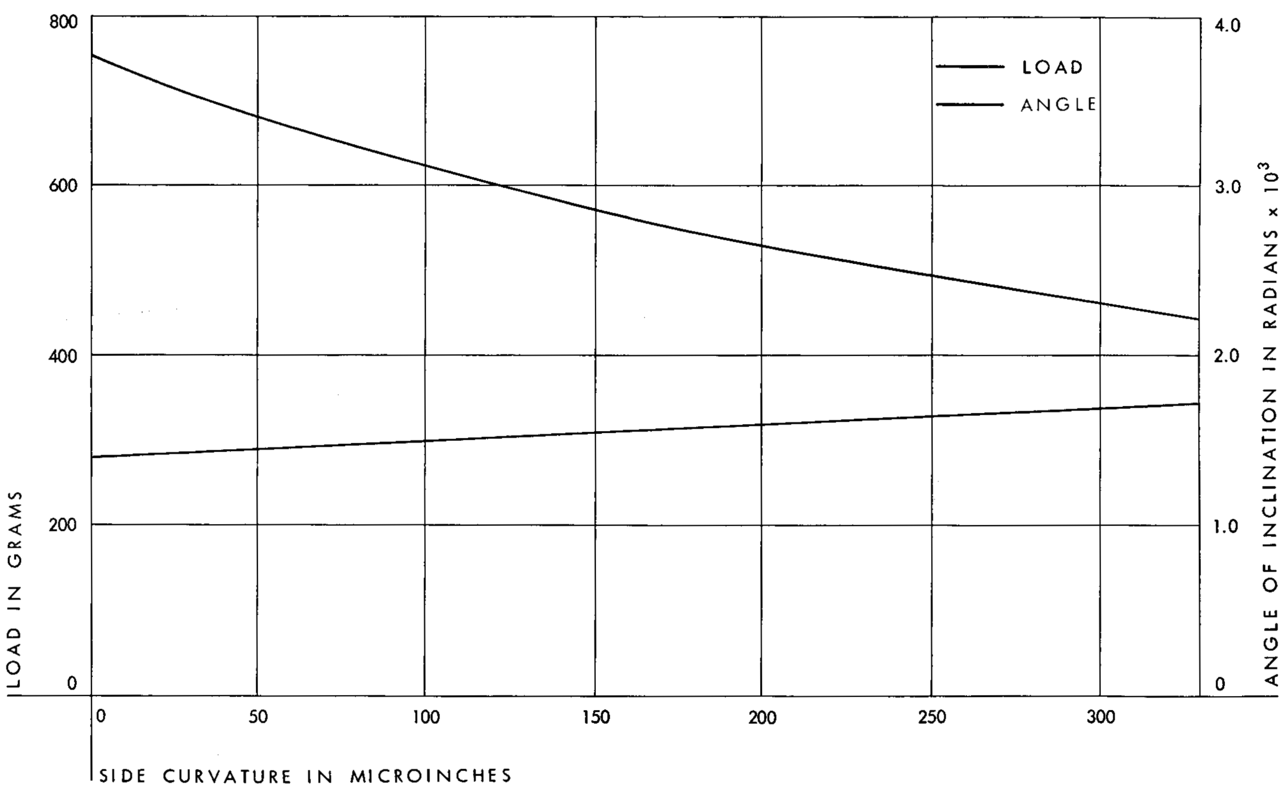
Some sort of design data that would be readily available for use would be most desirable in order to know in advance some of the characteristics of any proposed slider. Because of the many variables involved, it is rather difficult to reduce the necessary information to a few all-encompassing charts. Two examples derived from computer data are shown in Figs. 10 and 11. One of these shows the operating characteristics of a group of sliders with a given crown height, operating at 2500 inches per second and a film thickness of 250 microinches. The second shows the necessary geometry for a slider to operate at a film thickness of 250 microinches, a speed of 2500 inches per second, and a load of 500 grams. Charts similar to these could be made for any desired film thickness, load or speed. Obviously, there are many combinations of these variables.

Experimental setup

Figure 12 is a partial side view of the experimental setup, showing most of the components described below.

A six-inch lapped disk was mounted on a spindle that was belt driven by a variable speed, ⅓ hp, dc shunt motor. Speeds up to 12,000 revolutions per minute were possible with this arrangement. The disk was leveled by use of leveling screws from below and runout observed

Figure 9 **Load and angle vs side curvature for a minimum film thickness of 250 microinches, a crown height of 350 microinches, a breadth of 0.6 in., a length of 0.55 in., a velocity of 2500 ips, and with pivot located 0.075 in. behind the center line. Data are computed.**



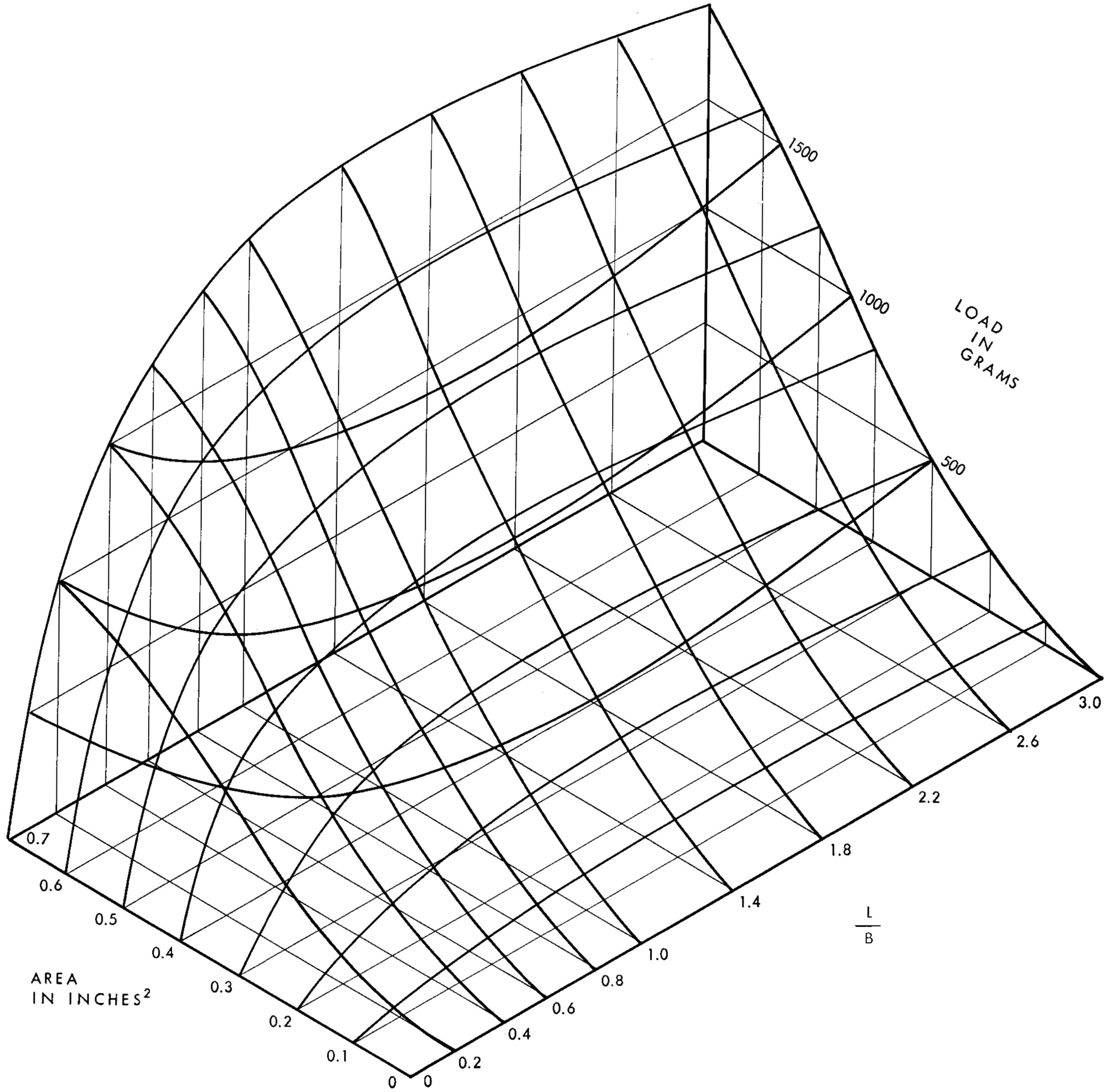


Figure 10 **Load-shape profile for a crown height of 250 microinches, a minimum film thickness of 250 microinches, a velocity of 2500 ips and with pivot located 62.5 per cent from the leading edge.**

on a dial indicator. Runout was limited to less than 0.0001 inch total indicator reading. A separate test after the sliders were better understood indicated that disk runout on the order of 0.001 inch caused no measurable variation in spacing at the speeds used in the investigation.

The sliders were mounted in gimbals so that they were free to pivot in both directions. They could, therefore, seek their own equilibrium position under any operating conditions. A thin leaf spring held this assembly in place over the disk. The spring was chosen so that it would hold the slider above the disk when not loaded, but required only a small load to bring it down to the operating position. The load was applied by means of a torsion bar with an arm to push down on the leaf spring at the correct position for applying the load. The load was applied by hanging weights on a cord around a loading wheel on the end of the torsion bar.

Two small brass probes potted in epoxy in the slider were used to determine the film thickness at each of two points. These were potted so they did not touch the aluminum slider and were not exposed on the bottom side of the slider. Variation in film thickness caused a change in

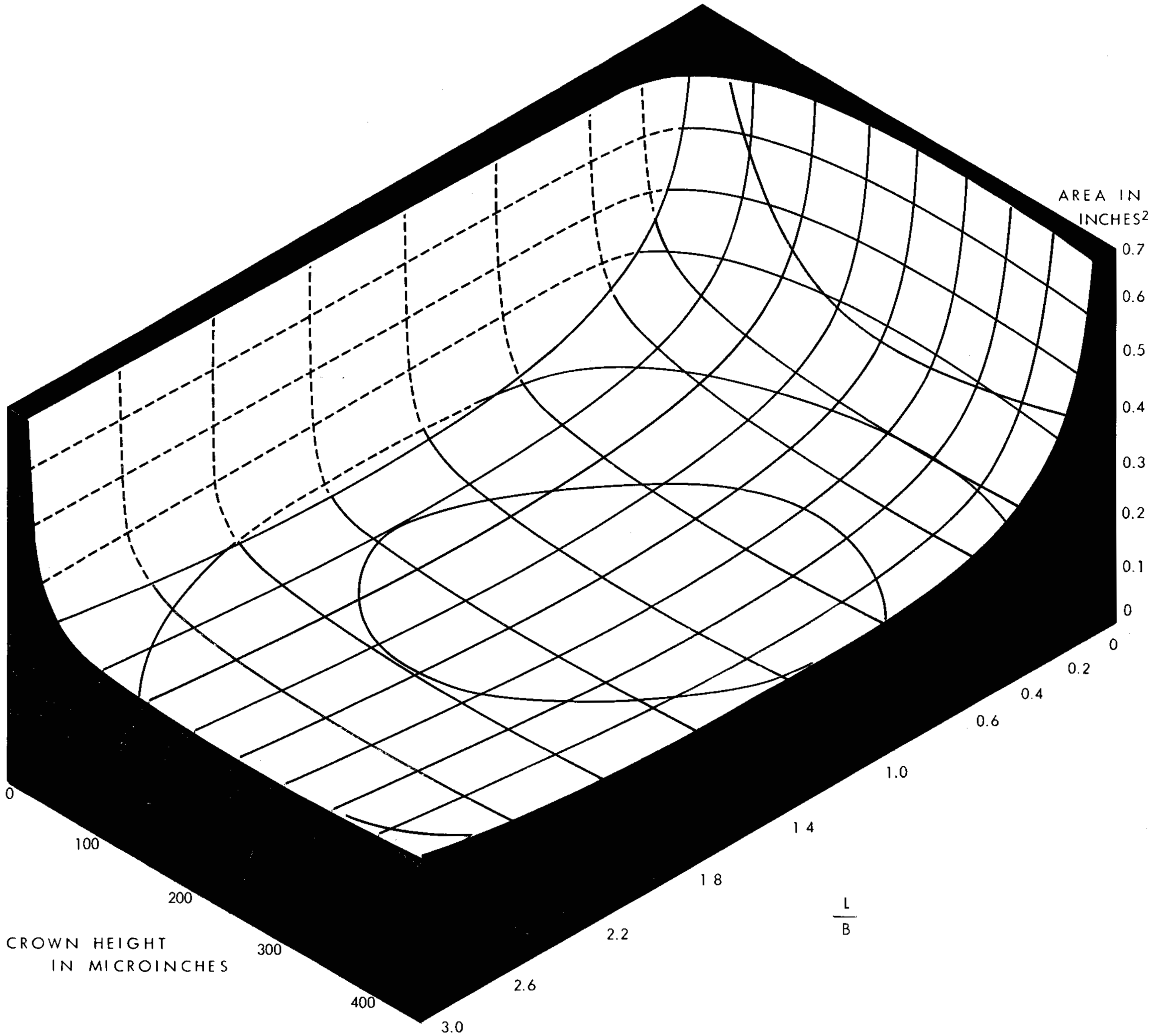


Figure 11 **Geometry for a minimum film thickness of 250 microinches, a velocity of 2500 ips, a load of 500 grams, and with pivot located 62.5 per cent from the leading edge.**

the capacitance between the probe and the disk, which was translated into a change in voltage output by a Decker Delta Unit.[3]

A small voltage (1.5 v) was applied between the slider and the disk. An oscilloscope was used to detect this voltage whenever the slider contacted the disk. This method indicated contact at a clearance somewhat greater than that at which actual physical contact occurred due to the breakdown of the air at very small clearances. With 1.5 volts across the gap, apparent contact would be indicated at 25 to 50 microinches above actual contact.

Measurements and test procedure

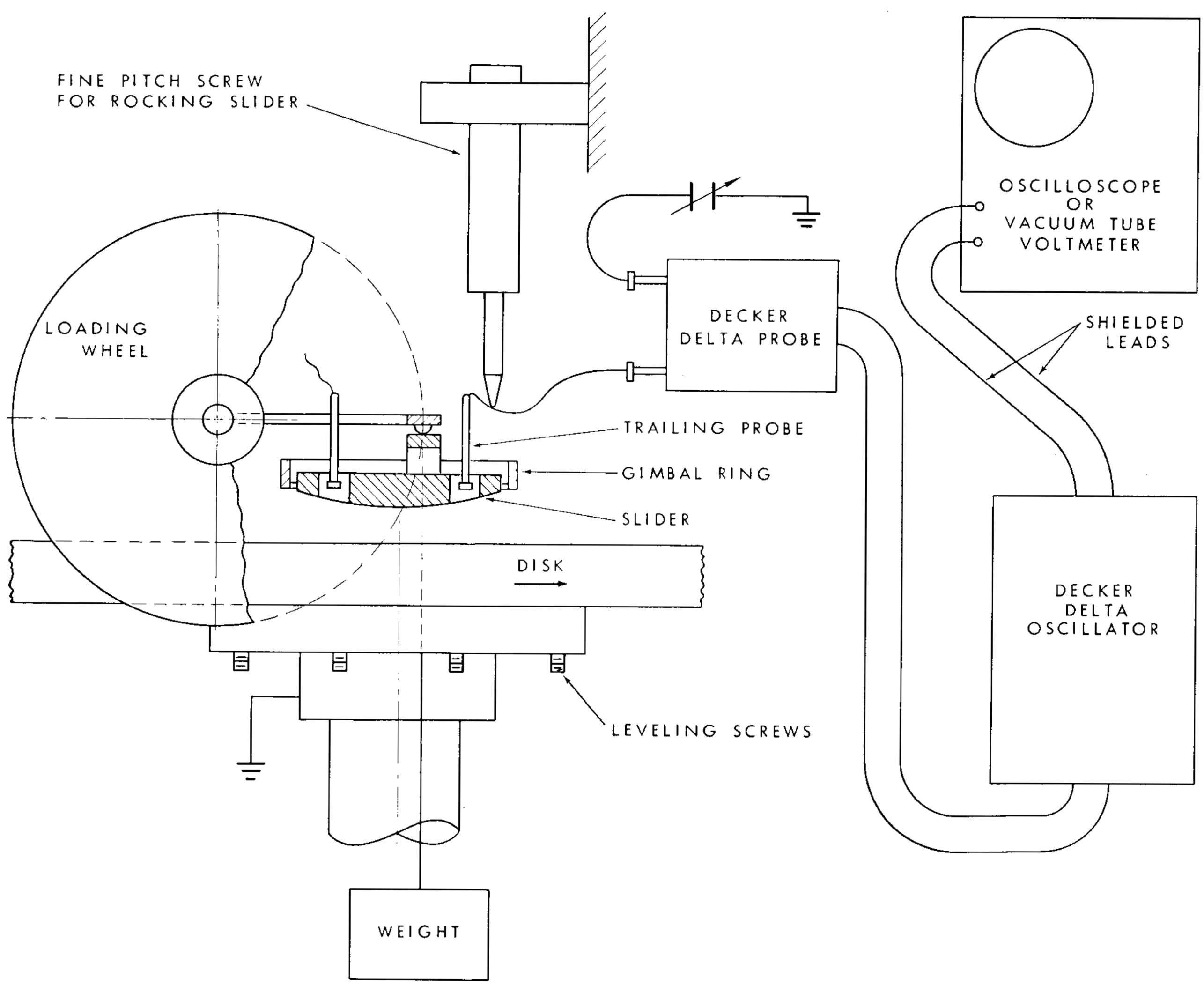
The surface profile of each slider was determined from the number of interference fringes which appeared when the bearing was placed under an optical flat in monochromatic light. While the surface profile of flat and slightly convex sliders could easily be determined by visual inspection, it was difficult to count accurately the interference fringes for crown heights greater than 100 microinches. For this reason, photographs (see Fig. 13) were taken of the fringe pattern on each slider, which made it possible to determine accurately the surface profile by counting the interference fringes on the photographs. A more complete discussion of this technique is given in Appendix 3.

Two Decker Delta transducers were used to measure the clearance at the leading and trailing probes simultaneously. The output voltage of each Decker unit was observed on a separate vacuum tube voltmeter. The Decker units were calibrated by observing the output voltage when the sliders were at accurately known distances from the disk surface. A reading was also obtained with the slider in contact with the disk. This was possible because of the 0.003- to 0.005-inch layer of plastic which covered the probes and insulated them from the disk. The bearings were spaced at known distances from the disk surface by inserting thin shims between the slider and the disk. Holes, slightly larger than the probe diameter, were cut in the shims which were placed under the slider so that the holes were directly beneath the probes. Because of the presence of these holes, the shims had no effect on the capacitance between the probe and the disk. The disk and slider surfaces were thoroughly cleaned before each reading, and at least three readings were taken with each shim. The shim thicknesses ranged from 350 to 1980 microinches and were measured with a Pratt and Whitney "Sigmatic" Comparator which has a least count of 20 microinches. Samples of the shim material were also sent to the National Bureau of Standards, which verified the thickness measurements.

Both Decker units were calibrated simultaneously when flat sliders were tested, as the entire bearing surface was the same distance from the disk during calibration. However, a different procedure was required when calibrating with convex sliders. Because of the curved surface, it was necessary to calibrate each transducer separately by rocking the slider on its curved surface until the probe which was being calibrated was at the lowest point on the slider. This position was attained by observing the voltmeter while rocking the bearing. The rocking of the slider was done with a fine-pitch screw as shown in Fig. 12. By this procedure, voltage readings were obtained with the slider in contact with the disk and for four shim thicknesses. These values were then used to plot a calibration curve for each probe.

The experimental procedure for both the flat and convex sliders was essentially the same. The tests were run

Figure 12 **Air slider experimental setup.**



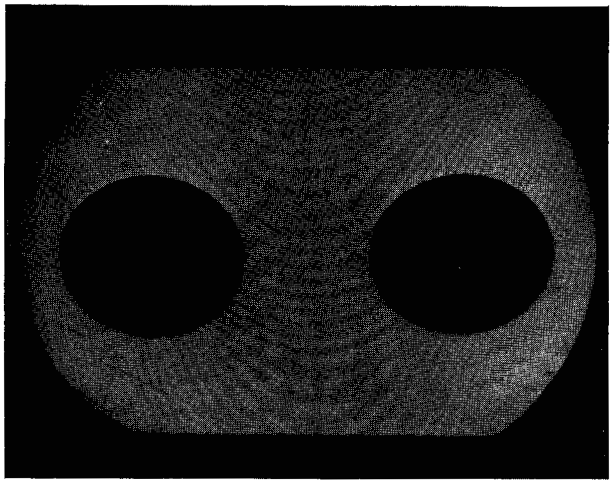


Figure 13 **Interference fringes indicating the curvature of an experimental slider surface.**

with disk surface speeds at the bearing centerline of 1000, 1500, 2000, and 2500 inches per second. The flat slider tests were started with a load of 50 grams, which was increased in small increments until failure occurred or until the trailing probe clearance was between 50 and 100 microinches. The initial load applied to the convex sliders was 200 grams in most instances, and the load was increased in increments of 100 or 200 grams until the minimum clearance was from 100 to 150 microinches. The maximum load applied on any convex slider was 1400 grams, which was usually sufficient to bring the minimum clearance below 150 microinches. Two spacing measurements were taken for each load, one as the bearing was being loaded and the second as the bearing was being unloaded. These two values were then averaged. In general, it was found that the clearances were smaller when the slider was being unloaded than when loading. This difference in clearance was largest at the leading probe, indicating that the angle of inclination was smaller when the load was being diminished. This variation was attributed to a small amount of friction in the bearing pivots. At the conclusion of each test, the calibration was rechecked, and if any changes had occurred the test was rerun. The angle of inclination and minimum film thickness were calculated from the measured film thickness at the lead and trail probes. The minimum film thickness is always at the trailing edge of a flat slider and is easily computed from the lead and trail probe clearances. Determination of the minimum film thickness is complicated when the slider has a convex surface profile, as the location of the minimum film thickness varies with the angle of inclination. The method used to compute the magnitude and location of the minimum film thickness for convex sliders is given in Appendix 2.

The work done by C. Handen[4] on air-lubricated slider bearings at the IBM Research Center in Poughkeepsie was of considerable aid in setting up the instrumentation of this investigation.

Appendix 1: Method of manufacturing convex sliders

The process used to manufacture the convex sliders for this investigation is relatively simple and the results were very satisfactory. This method essentially reduces the problem of making convex surfaces to one of making flat surfaces.

The process consists of applying a force at the center of the slider with a spring and bending fixture such as is shown in Fig. 14. The surface is then lapped flat while the slider is held in a bent position by the fixture. After the surface has been lapped flat, the slider is removed from the fixture, and assumes its original unbent form. The result is a cylindrical convex surface of the same curvature as the concave surface to which the slider was bent before lapping.

The surface obtained by this method is comparable to the elastic curve of a simple beam, loaded at the center, for which

$$\delta(x)=(Px/48EI)(3B^2-4x^2) \qquad 0 \leqq x \leqq B/2\,, \tag{4}$$

where δ = deflection, P = applied force, I = moment of inertia, E = modulus of elasticity, and B = breadth.

At $x=B/2$, the deflection has been defined as the crown height. At this point,

$$\delta=PB^3/48EI\,. \tag{5}$$

To normalize the location dimensions, let $x=XB$. Then,

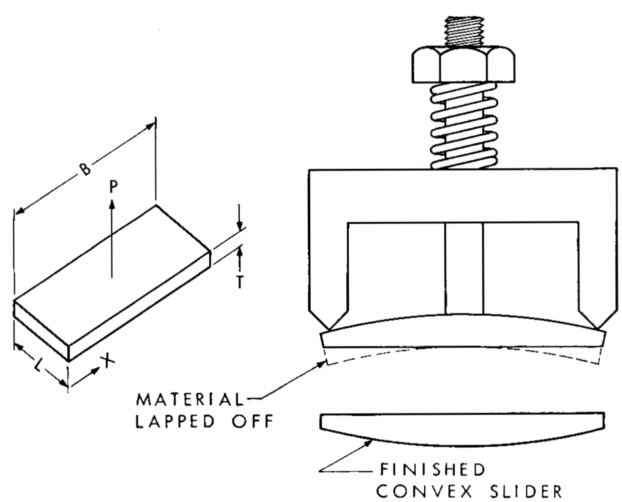
$$\delta(X)=(PB^3/48EI)X(3-4X^2)\,. \tag{6}$$

Any point on the curve can now be expressed in terms of the crown height.

$$\delta(X)/\delta=X(3-4X^2)\,. \tag{7}$$

Figure 15 is a graph of this equation which shows for comparison some points measured on the surface of a slider manufactured by the method described above, and the surface profile used in the computer solution. (See

Figure 14 **Method of producing convex slider from flat block dimensioned as shown at left.**



Appendix 3 for method of measuring surface profile.)

In order to obtain the information given in this article, the performance of convex sliders over a large range of crown heights (54 to 1038 microinches) was investigated. The curved surfaces on these sliders were obtained by lapping the surface flat before bending so that the deflection could be measured as the slider was bent concave. This method is useful for producing sliders with various crown heights for experimental purposes, but a simpler method can be used to make a number of bearings with approximately the same crown height. In this case there is no need to lap the surface flat before bending. It is only necessary to apply the same load to each slider and then lap flat. Since the moment of inertia is $LT^3/12$, Eq. (5) for the crown height can be written as

$$\delta = PB^3/4LT^3\,, \tag{8}$$

where L is the length of the slider perpendicular to the direction of motion, and T is the thickness. In this instance, B is the distance between the supports on the bending fixture. Variations in any of these factors will, of course, affect the crown height obtained, and therefore variation in the load and modulus must be considered as well at the tolerances on the slider dimensions. When tolerances are included, Eq. (8) can be written as

$$\delta' = \frac{(P\pm p)(b\pm B)^3}{4(E\pm e)(L\pm l)(T\pm t)^3}\,. \tag{9}$$

From Equations (8) and (9) the ratio of the desired curvature to that which will be produced due to the effect of the tolerances can be obtained, and omitting terms containing b^2, b^3, t^2, and t^3, the resulting equation is

$$\frac{\delta'}{\delta} \cong \frac{\left(1\pm\frac{p}{P}\right)\left(1\pm\frac{3b}{B}\right)}{\left(1\pm\frac{e}{E}\right)\left(1\pm\frac{l}{L}\right)\left(1\pm\frac{3t}{T}\right)}\,. \tag{10}$$

This equation indicates that variations in the slider thickness and the length between supports on the bending fixture will have the greatest effect on the crown height and, therefore, must have the smallest tolerances. Some reasonable tolerances on the dimensions of a slider similar to those used in the experimental work might be

$$B\pm b = 0.750\pm 0.002\,, \qquad L\pm l = 0.550\pm 0.005\,,$$

$$T\pm t = 0.115\pm 0.002\,, \qquad e = 0.05E\,.$$

As pointed out in the text, the slider performance is practically the same for any crown height between 300 and 400 microinches. Using the dimensions and tolerances given above, and assuming the most unfavorable combinations of tolerances, the allowable variation in the applied load P for a crown height of 350 microinches ± 50 microinches can be computed from Eq. (10). The result is that for the conditions specified, a 5 per cent variation in the load can be tolerated.

In order to check the feasibility of making a number of sliders by this method, with crown heights between 300 and 400 microinches, a group of 7 sliders were lapped with approximately the same load applied to each slider. The crown heights which were produced on these sliders ranged from 305 to 385 microinches. The specific crown height produced on each individual slider is available in an internal IBM report[2] which includes a tabulation of all the experimental data taken during this investigation.

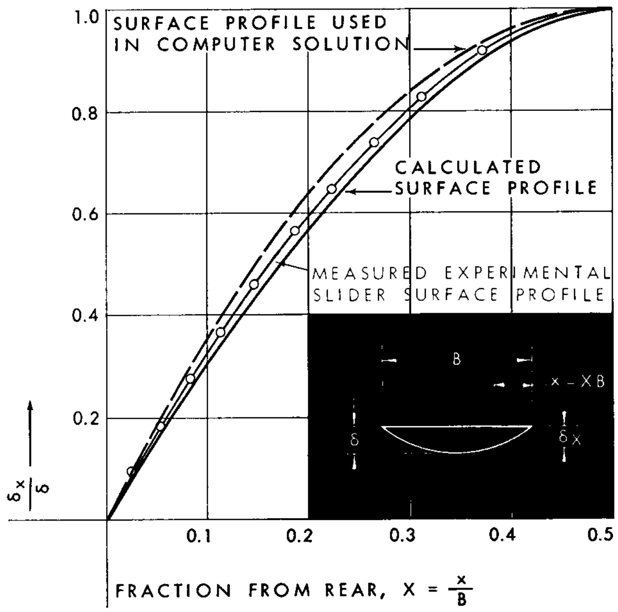


Figure 15 **Measured, calculated, and computed convex surface profile.**

Appendix 2: Magnitude and location of the minimum film thickness for convex sliders

The angle of inclination assumed by a slider is a function of the load, speed, pivot location, and crown height. Since there is a variation in the angle, it is obviously impossible to locate the probe so that it is always at the point of minimum film thickness. Therefore, it is necessary to compute the magnitude and location of the minimum film thickness from the lead and trail probe film thickness and the slider geometry.

The geometry of the system is shown in Fig. 16. The slider shape, $\delta(X)$, is known relative to the indicated coordinate system (see Appendix 1). We see that the location of the minimum film thickness is at the point where the surface of the slider is parallel to the surface of the disk. In other words, where the magnitude of the slope of the slider surface is equal to the angle of inclination of the slider. Thus

$$\alpha = (h_l - h_t)/d \qquad (\alpha \text{ is small so } \tan\alpha \approx \alpha)\,. \tag{11}$$

Equating the angle to the slope of the slider surface,

$$(h_l - h_t)/d = \delta/B(3-12X_m^2)\,. \tag{12}$$

For the experimental slider, $d=2/5$ in. and $B=3/4$ in. and (10) becomes

$$(h_l - h_t)\,\delta = 8/15(3-12X_m^2)\,. \tag{13}$$

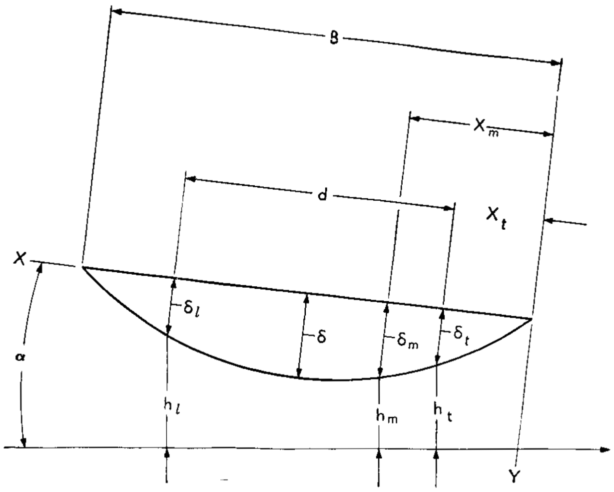


Figure 16 **Geometry of slider system.**

From this we can solve for X_m, which is the fraction of the breadth from the trailing edge to the point of minimum film thickness. This is shown plotted in Fig. 17.

Referring again to the sketch (Fig. 16), and remembering that α is very small, we can write:

$$h_t+\delta_t+B(X_m-X_t)\alpha=h_m+\delta_m\,. \tag{14}$$

Knowing $\delta(X)=\delta X(3-4X^2)$ and also that for the experimental slider $X_t=0.233$, we can solve Eq. (14) in terms of X:

$$(h_t-h_m)/\delta=X_m(3-4X_m{}^2)-0.65 \\ -(X_m-0.233)(3-12X_m{}^2)\,. \tag{15}$$

We could plot this directly, but it is more convenient to plot $(h_t-h_m)/\delta$ against $(h_l-h_t)/\delta$, since this involves only the experimental data and makes it unnecessary to calculate X_m or obtain it from another graph. This curve is also shown in Fig. 17. It is possible for the angle to become so large that there is no point where the gliding surface and the disk are parallel. In this case, the minimum film thickness is at the trailing edge and its magnitude is directly proportional to the angle. The beginning of this portion of the curve and its slope is shown where $(h_l-h_t)/\delta>1.6$ on Fig. 17.

Let us now take some representative values from the experimental data and compute (h_t-h_m) and X_m. For one of the experimental runs, the maximum value of (h_l-h_t) is 635 microinches and the slider crown height is 496 microinches. Using these values and Fig. 15 we find that (h_t-h_m) is 0.25 microinches and X_m is 0.222. The minimum value of (h_l-h_t) for this run is 425 microinches, and the corresponding values for (h_t-h_m) and X_m are 21 microinches and 0.339.

Appendix 3: Measurement of the curvature of convex sliders

The observation and measurement of the curvature of the convex sliders with crown heights between 50 and 1000 microinches presented a rather interesting problem. This problem was solved by using a monochromatic light with an optical flat and observing the interference patterns caused by the curvature.

If one places an optical flat on the surface to be measured so that a thin, wedge-shaped film of air is formed, alternate dark and bright lines will appear (assuming the surface is polished enough to reflect light). Each dark line follows a path where the distance between the optical flat and the surface is constant. A dark line will appear wherever this distance is an odd multiple of one-half the wavelength of the monochromatic light. Under the conditions described above, if the surface is flat, parallel straight lines perpendicular to the direction of the wedge will appear. If the surface is not flat, the lines will follow some curved path indicating where the distance between the optical flat and surface is constant. This characteristic can be used to measure the amount of curvature by the following technique.

Set the flat on the surface so the wedge is formed in a known direction as shown in Fig. 18a. If the surface is curved, a curved pattern will appear as shown. A line can now be drawn across the pattern perpendicular to the direction of the wedge. Every time this line crosses an interference line it indicates that the surface elevation has changed one-half the wavelength of the monochromatic light under which this is being observed. (It is necessary that the line be perpendicular to the wedge in order to eliminate film thickness variation due to the angle of the optical flat.) By this means, we can actually plot the contour across the surface. This work was all done with a light whose wavelength is 23.2 microinches, thereby giving a contour line for every 11.6 microinches change in elevation.

The crown height can be determined by counting the number of interference lines crossed between the center and either end of the slider. Actually, the average of both sides should be used since it is difficult to get the contact point for forming the wedge exactly at the center of the slider. If the crown height is around 50 microinches, there will be 4 or 5 lines in the ⅜ of an inch from the center to the end of the experimental slider. These can be readily counted with the naked eye. If the crown height is above 10 or 15 interference lines, however, the count becomes more difficult. Taking photographs of the fringe patterns made the task of counting the lines relatively simple. However, the use of a camera introduced another problem. In order for the change in surface elevation between successive fringe lines to be exactly one-half of the wavelength of the light being used, the light source and the observer must be located so that the light always travels perpendicularly to the optical flat. This was physically impossible when using the camera, and it was necessary to take the photographs from an angle.

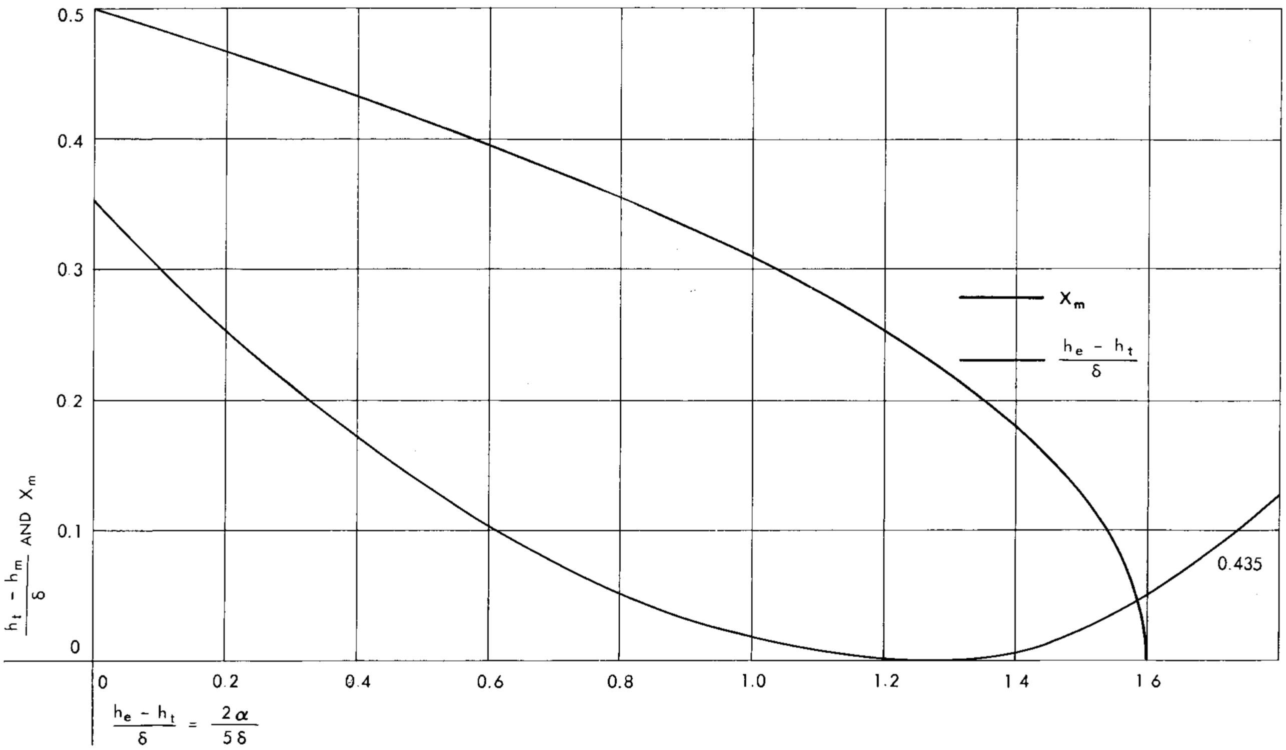


Figure 17 **Chart for determining the location and magnitude of the minimum film thickness from the lead and trail probe film thickness. The angle of inclination, α, is in radians, the crown height, δ, is in inches, the lead probe film thickness, h_l, is in inches, trail probe film thickness, h_t, is in inches, minimum film thickness, h_m, is in inches and X_m is the location of h_m as a fraction of breadth from trailing edge.**

The following is the derivation of a correction factor that enables one to observe the lines from an angle and correct the observation.

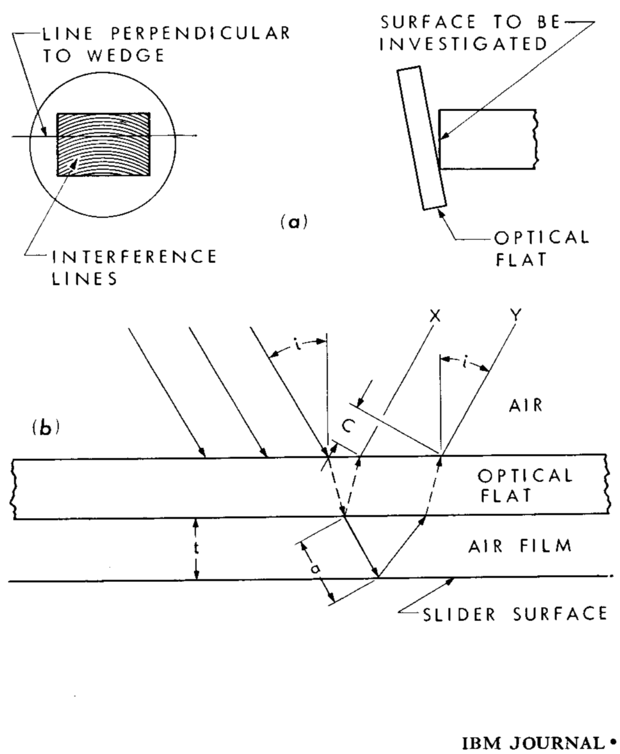
In order to get the dark lines, one must observe simultaneous rays that are half a wavelength out of phase, thereby cancelling one another. This phase shift is accomplished by a combination of phase shift due to reflection and the additional path length. Figure 18b shows the effect of observation from an angle.

It will be noted that reflected light ray, Y, has travelled farther than X. This difference in path length is $2a-C$. The observed light rays, then, would be at least this much out of phase with one another. There is a second factor that is different in the two paths. Ray X is travelling in a medium of high index of refraction and is partially reflected at a surface of lower index while Y is travelling in a medium of low index of refraction and is reflected at a surface of higher index of refraction. The first is unchanged in phase but the latter is shifted by half a wavelength. The total phase difference between the two is then

$$\Delta = 2a - C + (\lambda/2). \tag{16}$$

From the geometry we see that $C = 2a\sin^2 i$ and $a = t/\cos i$. Therefore,

Figure 18 **Method and geometry for determining surface flatness.**



$$\Delta = 2t\cos i + (\lambda/2)\,. \tag{17}$$

As stated before, the interference lines appear when one ray is half a wavelength out of phase with the other, i.e.,

$$\Delta = (\lambda/2)(2n-1) \tag{18}$$

for interference lines to appear. Solving Eqs. (17) and (18) for t reveals

$$t = \lambda(n-1)/2\cos i\,. \tag{19}$$

Inspection of the above equation reveals that when the fringe pattern is observed from an angle, the change in height between successive fringe lines is not half a wavelength, but half a wavelength divided by the cosine of the angle of incidence.

List of symbols

B = Breadth of bearing in direction of surface motion
h = Film thickness
h_l = Lead probe film thickness
h_m = Minimum film thickness
h_t = Trail probe film thickness
L = Length of slider normal to direction of surface motion
n = Polytropic gas expansion factor
p = Pressure
U = Velocity of moving surface
X = Location along breadth of slider, fraction from rear
X_m = Location of minimum film thickness, fraction from rear
x, y, z = Rectangular coordinate axes
α = Angle of inclination of slider
δ = Crown height
ρ = Density of gas
μ = Coefficient of viscosity

References

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2. R. K. Brunner, J. M. Harker, K. E. Haughton, and A. G. Osterlund, "A Gas Film Lubrication Study: Experimental Investigation of Pivoted Slider Bearings" *IBM Technical Report* No. 02,13.042.001, June 9, 1958.
3. Decker Aviation Corporation, Philadelphia, Pa.
4. C. Handen, "An Investigation of Air-Lubricated Shoes for High-Density Magnetic Drum Head Applications," *IBM Research Report* No. RC-4, January 1, 1957.

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