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ANALYSIS OF AN ELASTOHYDRODYNAMIC LUBRICATED POINT CONTACT
(USER'S MANUAL)



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PREFACE

This technical report was prepared for the Lubrication Branch, Fuels and Lubricants Division, Aero Propulsion and Power Laboratory, Wright Research and Development Center (WRDC), Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The work herein was accomplished under Project 3048, Task 304806, Work Unit 30480619, "Bearing Research for Propulsion and Power Systems," for the period of April 1987 to April 1988, with Mr Lewis Rosado, WRDC/POSL, as project engineer.

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1.0 SCOPE

This report provides the numerical procedures and user's information for executing a PC-based computer program which calculates pressure, dimensions, and film thickness for an elastohydrodynamic (ehd) lubricated point contact. In addition, it provides the basic theoretical background and description of the computer codes and equations used.

1.1 PURPOSE

The purpose of this computer program is to simplify the task of calculating the descriptive characteristics of a general elastohydrodynamic lubricated point contact for a given set of input variables using a desktop PC.

The following descriptive characteristics of the contact are calculated:

- 1.1.1 The contact maximum and mean Hertzian stresses.
- 1.1.2 The contact ellipse dimensions.
- 1.1.3 The ehd isothermal minimum and central film thickness.
- 1.1.4 A thermal film thickness correction factor accounting for the effect of shear heating because of sliding and rolling.

1.2 INTRODUCTION

This report will aid the user in executing the ehd computer program described below and help him/her understand and interpret the results obtained. An easy step-by-step approach will be used, including a sample run of the program.

An abbreviated summary of each section outlined in this manual is described below:

Section 2.0: The technical background, historical overview, governing equations and notation are presented in this section.

Section 3.0: A general description of the computer program and its function is presented in this section.

Section 3.1: The program organization is described and explained. The number and name of subprograms with their respective functions are listed in this section.

Section 3.2: In this section the program logic flow is fully described. Interrelationship between subprograms is completely explained and the program flow chart is presented.

Section 3.3: The instructions for using the program are explained in this section. The procedures for installing, executing, and available options are presented in succession with a sample run of the program. Procedures for terminating and restarting the program are described and the outputs presented.

Section 4.0: The possible error messages are listed and described in this section. Recommendations on corrective action are included for each error message.

Section 5.0: In this section, all referenced material in this report is listed by author, title, and document number.

2.0 TECHNICAL BACKGROUND

When two rotating non-conformal surfaces are loaded together and a lubricant, such as oil, is added or injected between them, a very thin film is formed between the two bodies. This is commonly found in machine elements such as rolling bearings, gears, and cams. In such systems, very high pres-

asures can be generated in the contact region, thus causing the rubbing surfaces to deform elastically and the viscosity of the oil to increase many times over its normal value. These two effects enable the thin lubricant film to form and actually separate the two surfaces. This is referred to as an elastohydrodynamic (ehd) film. It is formed by the combination of the hydrodynamic action of the lubricant and the elastic properties of the rolling elements.

The thickness of the elastohydrodynamic lubricant film is one of the most important and critical parameters in defining the performance and reliability of a rolling element bearing. This governs the operation and life of the bearing, particularly when the lubricant film thickness approaches or becomes less than the average value of the surface roughness. This condition is determined by the film thickness ratio λ , where λ is defined as:

$$= h\lambda(\sigma_1^2 + \sigma_2^2)^{-\frac{1}{2}}, \sigma_1, \sigma_2 - \text{surface roughness of bodies 1 and 2.}$$

At values of $1 \leq \lambda \leq 2$, the ehd point contact is said to be operating under a mixed lubrication condition. At values of $\lambda < 1$, the point contact is said to be in a boundary lubrication condition. In this regime, asperity contact will occur at ball/race interface causing surface distress which in turn shortens the rolling contact fatigue life of the bearing [1]. In order to ensure that bearings and gears do not operate at these conditions, an understanding of the ehd lubrication process is required.

2.1 HISTORICAL OVERVIEW

One of the first solutions in predicting the film thickness between two rolling bodies was presented by Martin in 1916 [2]. Martin provided the first paper on line contact lubrication. Even though he failed to predict a correct film thickness by assuming the rolling elements as rigid bodies and the lubricant as an incompressible isoviscous fluid, his work initiated the

theoretical study of elastohydrodynamic lubrication of line contacts. It was not until 30 years later that Grubin and Vinogradova (1949) [3], actually made the first attempt to correctly analyze elastohydrodynamic lubrication. Their approach took into account the effects of elastic deformation and viscosity-pressure characteristics of the lubricant. In 1959, Dowson and Higginson [4] derived an empirical expression by solving the Reynolds and elasticity equations. They were the first to analyze the detailed film shape between lubricated rollers. Since then, numerous investigators have contributed to the understanding of ehd lubricant films. Archard and Cowking (1966) [5] gave the first step toward a theoretical solution of the ehd point-problem. Cheng (1970) [6] also derived a numerical solution for point-contact ehd lubrication by evaluating the deformation using the Hertz equation and then applying the Reynolds equation to the obtained geometry. In 1976, Hamrock and Dowson [7,8], presented a numerical solution for an isothermal ehd lubricated point contact. Their analysis required the simultaneous solution of the elasticity and Reynolds equations which was presented in their earlier work [9]. In the elasticity analysis, the contact zone was divided into equal rectangular areas and it was assumed that a uniform pressure was applied over each element.

The effects of temperature in frictionally heated contacts was first looked at by Blok [10, 11]. He introduced the idea of "flash" temperature and applied it to explain the failure mechanism in lubricated Hertzian contact. Later Chao and Sternlicht [12] calculated ehd contact temperatures by solving the Reynolds equation, the elasticity equation, and the energy equation. The present work is a result of a study of the nature of incomplete knowledge of the relationship between pressure, temperature, and shear stress in the process of ehd lubrication.

was developed by Cheng [13]. In his work, the viscous heating, the heat transfer within the lubricant film, and the heat transfer within the bearing surfaces are all taken into account. He found that viscous heating can considerably reduce the film thickness [14]. Recently, Wilson and Sheu [15] developed a thermal reduction factor that considered sliding effects. Their analysis was based on an improved thermal Reynolds equation. From this work and previous analyses, Cheng and Zhu [16] derived an empirical expression that includes the effect of contact pressure, rolling speed, and sliding on the thermal reduction of film thickness.

The computer program described in this report is based on the film thickness equations developed by Hamrock and Dowson [7, 8] and the thermal reduction factor developed by Cheng and Zhu [16].

2.2 NOMENCLATURE

E = modulus of elasticity, psi

ν = Poisson's ratio

$E' = 2/[(1-\nu_A^2)/E_A + (1 - \nu_B^2)/E_B]$, effective modulus of elasticity,
psi

F = normal applied load, lbs

a = semimajor axis of contact ellipse, mils

b = semiminor axis of contact ellipse, mils

$k = a/b$, elliptical eccentricity parameter

P_{max} = maximum Hertzian pressure, psi

P_{mean} = mean Hertzian pressure, psi

$P = P_{max}/E'$, dimensionless pressure

r_{AX} = radius of body A in rolling direction, inches

r_{BX} = radius of body B in rolling direction, inches

r_{AY} = radius of body A in crown direction, inches

r_{BY} = radius of body B in crown direction, inches

R_x = effective radius in rolling direction, inches

R_y = effective radius in crown direction, inches

u = surface velocity in x direction, in/sec

$u_{avg} = (u_A + u_B)/2$, average surface velocity, in/sec

$U = (\eta u_{avg})/E'R_x$, dimensionless speed parameter

$W = F/E'R_x^2$, dimensionless load parameter

$G = E'\alpha$, dimensionless material parameter

$H = h/R_x$, dimensionless film thickness

h_{min} = minimum film thickness, inches

h_{cen} = central film thickness, inches

ϕ_t = thermal reduction factor

$L = \eta \beta u_{avg}^2 / k_f$

α = pressure-viscosity coefficient, psi^{-1}

β = temperature-viscosity coefficient, $^{\circ}\text{F}^{-1}$

η = lubricant viscosity at temperature T , lb-sec/in^2

η_0 = lubricant viscosity at atmospheric pressure and temperature T_0 ,
 lb-sec/in^2

ρ = lubricant density, lb/ft^3

k_f = lubricant thermal conductivity, $\text{in-lb/sec-in-}^{\circ}\text{F}$

$S = 2 (u_B - u_A)/(u_A + u_B)$, slide-to-roll ratio

T = lubricant inlet temperature, °F

T_0 = reference temperature, °F

ν = kinematic viscosity, cS

η_k = dynamic viscosity, cp

D, I, J = viscosity and density constants

H_{minc} = corrected minimum film thickness (inches)

H_{cenc} = corrected central film thickness (inches)

SUBSCRIPTS:

A = solid A

B = solid B

X, Y = coordinate system

2.3 GOVERNING EQUATIONS

The equations used in the analysis for calculating film thickness were developed by Hamrock [7]. The expressions are given by,

$$h_{min} = 3.63U^{.68}G^{.49}W^{-.073}(1 - e^{-.68k})Rx$$

$$h_{cen} = 2.69U^{.67}G^{.53}W^{-.067}(1 - .61e^{-.073k})Rx$$

The speed parameter, U , is given by,

$$U = \frac{\eta_{avg}}{E'Rx}$$

where η is the atmospheric viscosity of the lubricant at the inlet temperature and can be expressed by the Roeland's viscosity equation as,

$$\eta = \eta_0 e^{-\beta(T-T_0)}$$

For military liquid lubricants, the viscosity equation used was

presented by Hampton and Butler [17] and is expressed as,

$$\nu = \exp (D+I \ln T+J/T) \quad (\text{cS})$$

To obtain the dynamic viscosity, the lubricant density must be known. Davis, Turner and Butler [18] developed a temperature - density relationship which can be expressed as,

$$\rho = D+IT+JT^2$$

where D, I, and J, are coefficients derived from experimental data.

The dynamic viscosity is now given by,

$$\eta_k = \nu \rho \quad (\text{cp})$$

or

$$\eta_k = \nu \rho / 6897600 \quad (\text{lb-sec/in}^2)$$

The dimensionless material parameter is simply,

$$G = E' \alpha$$

where E' is the effective modulus of elasticity and may be expressed as,

$$E' = 2 / ((1-\nu_A^2)/E_A + (1-\nu_B^2)/E_B)$$

and α is the pressure-viscosity coefficient of the lubricant.

The dimensionless load parameter can be determined from:

$$W = F/E'R_x^2$$

Here, F is the applied normal force, lbs, and R_x is the effective radius in the rolling direction and is given by,

$$R_x = \frac{r_{AX} \times r_{BX}}{r_{AX} + r_{BX}}$$

The elliptical eccentricity parameter, k , is defined by the ratio,

$$k = a/b$$

where a and b are the semimajor and semiminor axes of the contact ellipse, respectively and are given by:

$$a = 1000 C M$$

$$b = 1000 C N$$

Here

$$C = \frac{[3 \pi R F]^{1/3}}{2 E'}$$

and M, N are variables that

depend on the ratio R_x/R_y . The maximum Hertzian stress is therefore,

$$P_{max} = \frac{3F}{2\pi ab}$$

and the mean Hertzian stress is simply,

$$P_{mean} = P_{max}/1.5$$

These are all the parameters that define the isothermal film thickness given by Hamrock's equation. In order to consider thermal effects in the contact because of shear heating, the following thermal reduction factor was used in the analysis:

$$\phi_t = \frac{1 + 4.15 PL^{.42}}{1 + .241(1+2.42S^{.83})L^{.64}} \quad (\text{Cheng and Zhu [16]})$$

where,

$$L = \frac{\beta \eta u_{avg}^2}{k_f}$$

The temperature-viscosity coefficient can be determined by solving the Roeland's viscosity equation,

$$\beta = - \frac{\ln\left(\frac{\eta}{\eta_0}\right)}{(T - T_0)}$$

The dimensionless pressure, P , is given simply by,

$$P = P_{\max}/E'$$

and the slide/roll ratio is expressed as

$$S = 2(u_B - u_A)/(u_B + u_A)$$

The thermally corrected film thickness can now be calculated,

$$h_{\min c} = h_{\min} \times \phi_t$$

$$h_{\text{cenc}} = h_{\text{cen}} \times \phi_t$$

3.0 COMPUTER PROGRAM DESCRIPTION

The ehd computer program calculates pressure, contact dimensions, minimum and central film thickness for a general elastohydrodynamic point contact that experiences both rolling and sliding. Film thickness calculations can be expressed in terms of the isothermal solution, which in turn can be multiplied by a thermal correction factor to account for thermal effects because of fluid shear. Operating conditions can be input manually or can be read from an existing datafile. The program has the capability of calculating the variation in film thickness as a function of speed and slide-to-roll ratio. In addition to this, the program can also calculate film thickness with a constant rolling speed for each body as an input value. The program is written in BASIC language and is available for public use. All requests must be referred to WRDC/POSL, WPAFB OH 45433-6563.

3.1 PROGRAM ORGANIZATION

The ehd program is divided into one main program and eight subprograms. The subprograms are linked in a form that will permit overall execution of program.

The program names and their associated function and data file names are listed in Table 1. The data input comprises 10 elements of variable data and 8 to 13 run control variables which depend on the type of analysis to be made. These input data elements are continually stored in files each time the program is executed.

3.2 PROGRAM LOGIC FLOW

The overall logic flow for the ehd computer program is shown in Fig. 1. On execution, the main program SH requests input for the material properties of the rolling contact bodies. The subprogram VISC is then called and the lubricant properties and operating temperatures are entered. The geometry of the rolling contact bodies and the applied load are entered during execution of the subprogram HERTZ. Finally, the Hertzian pressures and contact dimensions are calculated. All the input and calculated data are stored in their respective files for later access during execution. The main program, SH, is called and the load and material parameters for film thickness calculations are computed and stored in a file. At this point, the only parameter left to be calculated for the isothermal film thickness is the speed parameter. SH then prompts the user to determine if the speed of the rolling contact bodies is to remain constant. If so, SH calls subprogram CONSTANT, the speed of both bodies is entered and the isothermal film thickness is

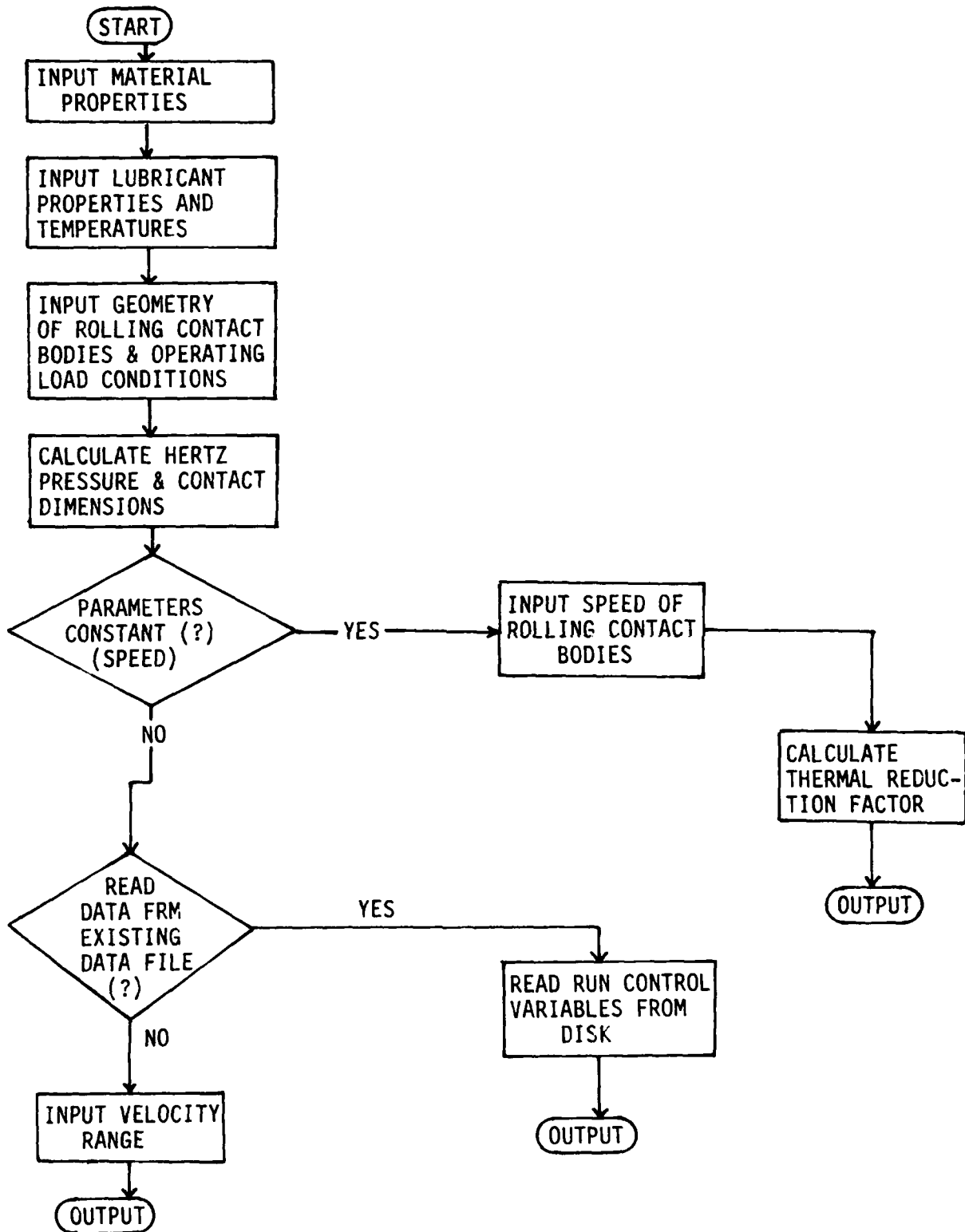


Figure 1. Logic Flow Chart.

calculated. The subprogram THERMO is then linked and the lubricant thermal properties entered. Finally the slide/roll ratio, thermal reduction factor, and the thermally corrected film thickness are calculated by the subprogram CONSCALC. The subprogram OUT is called and a hardcopy of both isothermal and thermally corrected solutions are printed.

If the speed is to be varied, THERMO will prompt the user for establishing the mode in which the speed range is to be input. Two modes exist; the user can manually input the operating speed limits through the keyboard or the operating speed conditions can be read by the program directly from an existing file. If the user is to specify the speed range, THERMO will call the subprogram LIMITS and the operating speed range is entered for both rolling contact bodies. A hardcopy is then printed showing the variation in film thickness as a function of average rolling speed. In addition, the thermal reduction factor and slide/roll ratio are also printed as a function of average rolling speed. Results are stored in a user specified file for further use, such as plotting.

If the operating speed conditions are to be read directly from a file, THERMO would call subprogram READAT. READAT will prompt the user to insert the floppy diskette containing the data into the specified disk drive. The user enters the filename to be accessed and READAT performs the calculations and printouts of the resulting data and stores this data in a user specified file for later use.

TABLE 1. Program Names

<u>PROGRAM</u>	<u>FUNCTION</u>	<u>DATAFILE NAMES</u>
SH	Main program, input material properties, determines logic of analysis to be made	PROP, E01, FTC, CONS4
VISC	Input lubricant properties and operating temperatures	LUBE1, LUBE2, LUBE3, BEALPH
HERTZ	Input geometry of rolling contact bodies. Input operating load condition	HER, GEOM, RX, HERZ
CONSTANT	Input operating speed conditions of rolling contact bodies. Calculates film thickness for constant speed mode.	CONSPD
THERMO	Input thermal conductivity of lubricant. Determines between generating data and reading data from existing file.	PHITA
CONSCALC	Calculates thermal reduction factor and film thickness for constant speed mode.	CONDAT, CONDAT3
OUT	Output for isothermal and thermal solution of analysis for constant speed mode.	
LIMITS	Input operating speed limits, sliding velocity range and number of data points for varying speed mode. Calculates thermal reduction factor, film thickness and slide/roll over the specified range. Outputs results (film thickness, Hertz pressure, slide/roll, thermal reduction factor, geometry, avg. rolling speed.	

Table 1. Program Names (cont.)

<u>PROGRAM</u>	<u>FUNCTION</u>	<u>DATA FILE NAMES</u>
READAT	Reads run control variables from existing datafile in varying speed mode. Outputs results (film thickness, thermal reduction factor, slide/roll, avg. rolling speed, operating conditions.	

3.3 USER'S INFORMATION

This section is a detailed description of how to use the ehd program. Topics in this section include instructions for loading and executing the program and a discussion of the output data for a sample case. The information is intended to be sufficient to permit a user to successfully run the program and interpret the results.

3.3.1 INSTALLING THE PROGRAM

The ehd program is written in the BASIC language and is executable on a Zenith 100-PC using the Z-DOS operating system. The main program and all subprograms are stored on one floppy diskette with the following file names:

SH.BAS
VISC.BAS
HERTZ.BAS
THERMO.BAS
CONSTANT.BAS
CONSCALC.BAS
LIMITS.BAS
OUT.BAS
READAT.BAS

We recommend the following procedure be used when executing the program:

- a. Turn on the computer and set the default drive to A.
- b. Insert the Z-BASIC diskette into drive A and enter Z-BASIC (refer to your Z-BASIC manual if necessary).
- c. Insert the ehd model diskette into drive A.

Now you are ready to load and execute the program.

3.3.2 EXECUTING THE PROGRAM

To illustrate program execution, the film thickness between a 1-inch-diameter steel ball and a flat sapphire disk will be calculated using MIL-L-7808 as the lubricant operating at an inlet temperature of 200°F. All possible cases will be analyzed and explained: constant speed, varying speed and reading data from an existing file.

Once the diskette containing the ehd model is inserted into drive A, it may be executed as follows:

- a. Load "SH"
- b. RUN

The program should begin by prompting the user with the following:

"DO YOU WANT TO CHANGE MATERIAL PROPERTIES (Y/N)? (POISSONS RATIO AND MODULUS OF ELASTICITY OF ROLLING CONTACT BODIES)"

SH will always begin this way. Since no material properties are yet stored in the properties file (PROP), the user should enter 'yes' or 'Y' and the following will appear on the screen:

ENTER THE FOLLOWING:

POISSONS RATIO OF BODY A

Here the user should enter Poisson's ratio of one of the two bodies. The user should always recall which of the two bodies was chosen as body A and B for later reference. The format to be used when entering numeric data is basically the same as when entering data into any other computer system. For example, 30E + 6 equals 30×10^6 or 30,000,000, and 30E - 6 equals 30×10^{-6} or 0.00003. Integers are entered as whole numbers and fractions as decimal numbers. Choosing the steel ball as body A and the sapphire disk as body B, enter 0.29 for Poisson's ratio of body A and 0.34 for body B.

After entering these values the program will prompt:

ELASTIC MODULUS OF BODY A (PSI)

The user should enter Young's modulus of elasticity for body A and B in psi. In this example, enter 30E+6 for body A and 54E+6 for body B. The material properties are now stored in the PROP file and will not have to be re-entered unless the user decides to change these properties. Changes can be made by entering 'yes' or 'Y' when prompted at the beginning of the execution of SH.

After the material properties have been entered and stored, the following prompt from the subprogram VISC will appear on the screen:

IS LUBRICANT AND INLET TEMPERATURE THE SAME AS PREVIOUS (Y/N)?

If lubricant properties and inlet temperature are the same as previously, the user will enter 'Y'. The user should note that both lubricant type and inlet temperature must be the same as before in order for this to hold true. Initially, no lubricant properties are stored, so the user will enter 'N'. After responding, the following prompt will be displayed:

IS LUBRICANT MIL-L-7808 (Y/N)?

If the lubricant to be used in the analysis is MIL-L-7808, enter 'yes' or 'Y' and the program will automatically access the lubricant properties. The user will then enter the lubricant inlet temperature in degrees F. Enter 200 for the sample case. The inlet viscosity and temperature-viscosity coefficient of the lubricant are then calculated and displayed as follows:

LUBRICANT MIL-L-7808

REF VISC (CS) 4.36914

INLET VISC (CS) 3.558109

BETA 1.016671E-02

ENTER PRESSURE-VISCOSITY COEFFICIENT (IN²/LBM)

The user must enter the pressure-viscosity coefficient of the lubricant with the specified units (enter 7E-5 for the sample).

If the lubricant is not MIL-L-7808, the viscosity must then be entered manually. There are three ways to input the lubricant properties manually and these are listed below:

- a. Inlet lubricant viscosity is known.
- b. Temperature-viscosity coefficient is known.
- c. Two viscosities at their respective temperatures are known.

Each will be discussed in detail.

3.3.2.1 KNOWN LUBRICANT INLET VISCOSITY

The subprogram VISC has the capability of providing the user with a number of useful methods in determining or accessing lubricant properties. Practically any type of lubricant can be analyzed if the properties are known. In this section one of the methods of specifying the lubricant properties is described.

If the lubricant inlet viscosity is known, the user must specify so when prompted:

IS INLET VISCOSITY OF LUBRICANT KNOWN (Y/N)?

The inlet viscosity and the inlet lubricant temperature are then entered in centiStokes and degrees Fahrenheit, respectively. At this point the user is prompted for entering a reference viscosity, which is defined as a value at atmospheric pressure and at a reference temperature. The reference temperature should be near the inlet temperature. In this particular program, the reference temperature should be within \pm five percent of the inlet temperature. This allows the program to calculate the temperature-viscosity coefficient of the lubricant at the inlet conditions using the Roeland's equation discussed earlier. Figure 2 shows a typical viscosity-temperature curve. The temperature-viscosity coefficient is simply the slope of a line tangent to the curve at a point equal to the inlet condition. For example, if T_{inlet} is 210°F and n_{inlet} is 3.5cS, then T_{ref} can

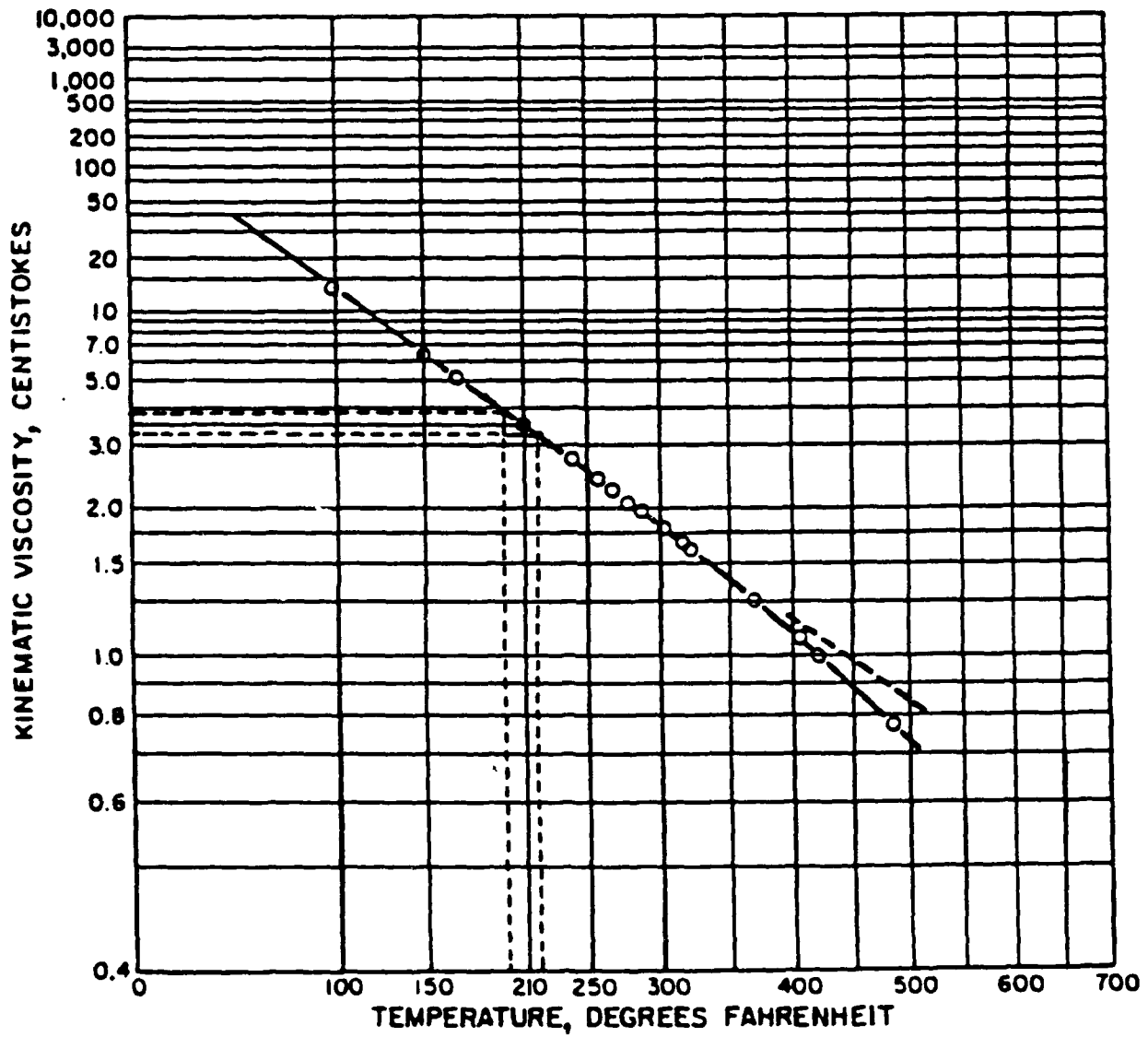


Figure 2. Viscosity-Temperature Plot for 0-68-17

be 200°F or 220°F. Thus, η_{ref} is then 3.8 cS or 3.25 cS depending on which T_{ref} is used. Therefore, the temperature-viscosity coefficient given by

$$\beta = \frac{-\ln \frac{\eta_{ref}}{\eta_{inlet}}}{T_{ref} - T_{inlet}}$$

becomes

$$\beta = \frac{-\ln \frac{3.25}{3.5}}{220-210} = .0074$$

Finally, the lubricant density in gm/cc and identification name or number are entered.

3.3.2.2 KNOWN TEMPERATURE-VISCOSITY COEFFICIENT

If the inlet viscosity is unknown, but the temperature-viscosity coefficient is known, the user shall specify so when prompted:

IS TEMP-VISC COEFFICIENT KNOWN (Y/N)?

The temperature-viscosity coefficient, reference temperature, reference viscosity, and inlet temperature are then entered. With these values, the inlet viscosity can now be calculated. (See Section 2.3).

3.3.2.3 USING TWO KNOWN VISCOSITIES AND THEIR RESPECTIVE TEMPERATURES

If neither inlet viscosity nor temperature-viscosity coefficient are known, then one choice remains. The user must enter two known viscosities of the lubricant and their respective temperatures. The inlet temperature must fall between these two temperatures. For example,

T1 = 150°F, T2 = 200°F, Tinlet = 160°F. The temperature-viscosity coefficient can now be calculated and used to obtain the inlet viscosity. Finally the lubricant density and identification are entered. For all three possible methods discussed above, the pressure-viscosity coefficient will have to be entered manually. The calculation of this pressure-viscosity coefficient is beyond the scope of this program.

3.3.2.4 GEOMETRY AND LOAD

Once the lubricant properties are entered, calculated, and stored in their respective files, the subprogram HERTZ is called and the geometry of the system is defined. The user will be prompted:

IS GEOMETRY OF SYSTEM TO BE ANALYZED THE SAME AS PREVIOUS
(Y/N)?

Since the geometry is yet to be defined and stored in the GEOM file, the user shall enter 'no' or 'N'. The following will appear on the screen:

ENTER RADIUS OF BODY A IN ROLLING DIRECTION (IN)

Here the user must recall which of the two bodies was chosen as body A and enter its radius in the rolling direction. For concave surfaces, the radius values must be entered as negative numbers. For the sample being analyzed enter 0.5 for the radius in the rolling direction of body A. The radius of body B in the rolling direction is then entered when the following appears:

ENTER RADIUS OF BODY B IN THE ROLLING DIRECTION (IN)

Enter 999 (flat disk) for the sample. Next, the radius of both bodies in the crown direction are entered when the following prompts appear on the screen:

ENTER RADIUS OF BODY A IN THE CROWN DIRECTION (IN)

ENTER RADIUS OF BODY B IN THE CROWN DIRECTION (IN)

Enter 0.5 for body A and 999 for body B.

The system is now defined as a ball on a flat disk. These values are now stored and the program will prompt:

ENTER APPLIED NORMAL FORCE (LBS)

The applied load is entered in pounds (Enter 10 lbs for the sample). The Hertzian profile will then appear on the screen as

P_{MAX} = 149846.9 . P_{MEAN} = 99897.91 PSI

A = 5.644771 B = 5.644771

Where P_{MAX} and P_{MEAN} are the maximum and mean Hertz pressure, respectively, and A and B are the semimajor and semiminor contact ellipse dimensions in MILS.

The system is now completely defined in terms of geometry, material and lubricant properties. All values are stored in their respective files and now SH will prompt the user as follows:

ENTER NUM. OF CHOICE

(1) CONSTANT SPEED

(2) VARYING SPEED

1 OR 2 _____

We will first consider the first choice which will maintain the speed constant and calculate the output for this condition. Enter 1.

3.3.2.5 CONSTANT SPEED

The program will prompt the user for the speed conditions of both bodies as follows:

ENTER SPEED OF BODY A (IN/SEC)

For the sample we are analyzing, enter 400 for the speed of body A.

ENTER SPEED OF BODY B (IN/SEC)

Enter 500 for body B. Units must be in inches per second.

If the lubricant is not MIL-L-7808, the program will prompt the user for the thermal conductivity of the lubricant in the specified units. If MIL-L-7808 is the lubricant used, the program will calculate the results and the following will appear on the screen:

PREPARE PRINTER FOR OUTPUT OF RESULTS

ENTER 'R' WHEN READY

The user will adjust the paper in the printer and enter R when ready. The user will then enter any number (no greater than 99) for the system to be analyzed. This number is solely for identification purposes and comes in handy when comparing a number of different systems.

3.3.2.6 VARYING SPEED

In this section a sample case will be analyzed using varying speed conditions. The same values for geometry, lubricant, and material properties will be used as in the previous case. Load SH as discussed in Section 3.3.2 and execute. Since no changes will be made to the geometry, materials, and lubricant properties, the user should state so when prompted to change these. When the subprogram HERTZ is reached, enter the applied load after defining the system geometry as discussed in Section 3.3.2.4. Enter 10 lbs for the sample. The Hertzian profile will be displayed as discussed before and the following will then appear on the screen:

ENTER CHOICE NUM

(1) CONSTANT SPEED

(2) VARYING SPEED

1 OR 2 _____

Enter choice 2 for varying speed and the following prompt will be displayed:

DO YOU WANT TO GENERATE YOUR OWN DATA VARYING SPEED?

At this point the user has two choices, he/she can specify a speed range for each of the two bodies by establishing a maximum and minimum limit or he can access an existing file which contains the operating speed conditions. Both will be discussed in detail in the following sections.

3.3.2.6.1 GENERATING YOUR OWN DATA

If the user decides to generate data by specifying the speed limits, he/she would state so when prompted. The subprogram LIMITS will then be called and the following will appear on the screen:

ENTER NUMBER OF DATA POINTS

The user will enter any integer ranging from 2 to N. This number will define the number of calculations the loop in the program will undergo (enter 15 for the sample case). The speeds of both bodies will then be entered as follows:

ENTER INITIAL VELOCITY OF BODY A (IN/SEC)

(Enter 430 for the sample)

ENTER FINAL VELOCITY OF BODY A (IN/SEC)

(Enter 650 for the sample)

ENTER INITIAL VELOCITY OF BODY B (IN/SEC)

(Enter 817 for the sample)

ENTER FINAL VELOCITY OF BODY B (IN/SEC)

(Enter 0 for the sample)

The operating speed range has been defined and the program will calculate the results N times through the specified range. The program loop is organized in the following form:

FOR I = 1 TO N

UA(I+1) = (UFA-UIA)/N + UA(I)

UB(I+1) = (UFB-UIB)/N + UB(I)

UAVG(I) = (UA(I)+UB(I))/2

.
. .
. .
. .

NEXT I

Where, UFA and UIA are the final and initial velocities of body A, respectively and UFB and UIB are the final and initial velocities of body B, respectively. The speed of both bodies will be varied through increments determined by the final and initial speed of both bodies, and by the number, N, assigned by the user.

The program will set UA(1) AND UB(1) equal to the initial speed of body A and B, respectively.

For the sample being analyzed:

$$\text{UIA} = 430 \qquad \text{UA}(1) = 430$$

$$\text{UFA} = 650 \qquad \text{UB}(1) = 817$$

$$\text{UIB} = 817$$

$$\text{UFB} = 0$$

FOR I = 1 TO 15

$$\text{UA}(2) = (650-430)/15 + 430$$

$$\text{UB}(2) = (0-817)/15 + 817$$

$$\text{UAVG}(1) = (430 + 817)/2$$

.
. .
. .

NEXT I

After entering the speed limits for both bodies, the user will adjust the paper in the printer for the hardcopy output of the results. The printer will first print the input variables and operating conditions of the system and then the screen will display the following:

ENTER FILENAME FOR STORAGE OF DATA

The user will enter any alphanumeric or numeric filename for storing the results which remain to be printed. These results will be saved in matrix form in this file for later use. The program will then resume printing the results.

3.3.2.6.2 READING DATA FROM EXISTING FILE

This section will aid the user to execute and use the ehd program as a powerful tool for analyzing data acquired from an ehd or traction test rig. The user may prefer to generate data by having the program read the operating speeds of both bodies directly from an existing file. Such a method is currently used in an optical ehd test rig located in the Aero Propulsion and Power Laboratory at Wright-Patterson AFB, Ohio (Fig. 3). This test rig basically simulates the ehd lubricated point contact found typically in ball bearings [19]. It consists of a 1-inch-diameter polished steel ball which is driven at varying speeds on a 4-inch-diameter sapphire disk. The point contact formed by loading the lubricated ball against the disk is observed by means of a microscope. The interferometric pattern observed under static conditions is the classic "Newton's ring" (Fig. 4) formation. Upon rotating the disk by means of a variable speed electric motor, a lubricant film is formed between ball and disk, and the central region of the interference pattern changes color. Prior calibration of this film thickness to color relation allows the film thickness to speed

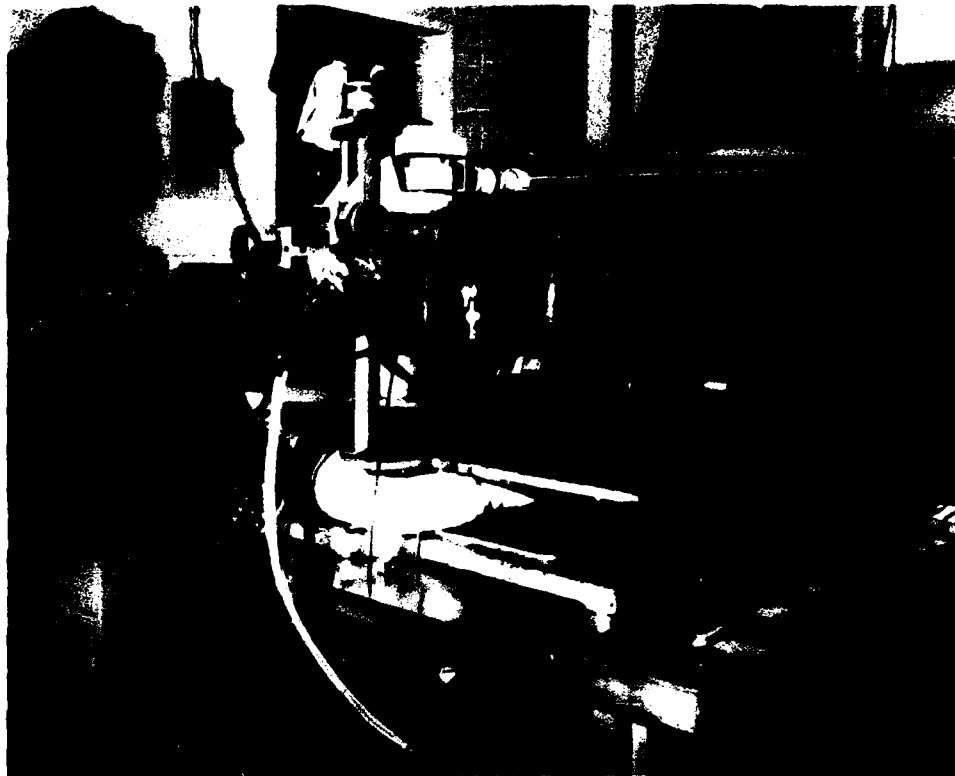


Figure 3. Aero Propulsion and Power Laboratory Optical EHD Test Rig.



Figure 4. Typical Elastohydrodynamic Point Contact.

characteristic of the lubricant to be determined. Temperature and applied load are also parameters that affect film thickness and therefore affect the observed color of the interference pattern. The lubricated ball is mounted on a shaft so that it can be independently driven by a variable speed electric motor. Ball and disk speeds are independently varied causing a surface speed difference between them. This, in turn, produces a traction force across the lubricant film. The data obtained, which includes ball speed, disk speed, lubricant temperature, applied load and traction force, are then recorded and stored directly using an HP 9826 computer and HP 3497A data acquisition/control unit. Photos of the interferometric pattern are taken simultaneously during operation of the test rig (Fig. 4). These are taken at different ball-disk speed conditions and at various temperatures and loads. The data are then transferred to the Z-DOS operating system which permits easy access to the ehd program. The theoretical film thickness is calculated utilizing the program and then compared to the experimental values obtained from the photographs.

3.3.2.6.3 TRANSFERRING DATA

In order to successfully execute the ehd program in this mode, the data obtained from the test rig must be correctly formatted and structured in the following form:

NUMBER OF DATA POINTS, N
LUBRICANT IDENTIFICATION, (Alphanumeric)
BALL RADIUS, (INCHES)
DISK RADIUS, (INCHES)
LOAD, (LBS)

LUBRICANT TEMPERATURE, (°F)	
AVERAGE ROLLING SPEED, (IN/SEC)	
BALL SPEED (RPM)	DISK SPEED (RPM)
.	.
.	.
.	.
.	.

TO N

These data should be delivered on a floppy diskette formatted with a Z-DOS system. The user will execute SH following the procedures discussed in Sections 3.3.2 through 3.3.2.6. After the following prompt is displayed on the screen:

```
DO YOU WANT TO GENERATE YOUR OWN DATA VARYING SPEED  
(Y/N)?
```

the user should enter 'N'. This will call the subprogram READAT. READAT will open all the files containing input variable data and operating conditions which were stored during the execution of SH. Next, the following will be displayed:

```
INSERT DATAFILE DISK (CONVERTED TO RPM) INTO DISK DRIVE  
'A'. ENTER 'R' WHEN READY
```

The user will remove the ehd program main diskette from disk drive 'A' and insert the diskette containing the test rig data discussed earlier. When ready, the user should enter 'R'. The files stored in the diskette will then be displayed helping the user to identify the file to be accessed. The program will then prompt the user:

```
ENTER FILENAME OF DATAFILE TO BE ACCESSED
```

The user will enter the filename, which should be one of the files displayed. READAT will access this file and the screen will display:

ADJUST PAPER IN PRINTER FOR HARDCOPY OF RESULTS

ENTER 'R' WHEN READY

A hardcopy of the input data will be printed (see section 3.3.5.2), and the following will appear on the screen:

INSERT DISKETTE FOR STORING RESULTS IN DISK DRIVE B

ENTER 'R' WHEN READY

The user should insert a Z-DOS formatted diskette into the specified disk drive. Enter 'R' and READAT will access the data in disk drive 'A' and perform calculations. Results will be simultaneously hardcopy printed and stored in disk drive 'B'. The user should label the diskette in disk drive 'B' as 'Film Thickness Results'. Included in the data file will be the identifying parameters such as load, temperature, average rolling speed, and lubricant used. Results can now be plotted using this diskette and any plotting software package such as "GRAFTALK".

3.3.3 TERMINATING THE PROGRAM

If during normal operation of the program, the user wishes to stop execution, press the 'CTRL' key and the 'C' key simultaneously. This will immediately 'break' or stop execution. The following will appear on the screen:

BREAK IN LINE [NUMBER]

Where line [number] identifies the last statement read or executed before terminating.

3.3.4 RESTARTING THE PROGRAM

In order to re-execute the program from the very beginning, the user shall load SH as discussed in Section 3.3.2 and enter 'RUN'. Follow instructions explained in Sections 3.3.2 through 3.3.2.6.

If by any means, the user accidentally enters a faulty value for any of the input variables, the user should press the CTRL key and the 'C' key simultaneously as discussed in Section 3.3.3. After the 'BREAK IN LINE [NUMBER]' message appears, the user should type and enter 'RUN'. This will execute the subprogram which is currently in memory, prompting the user for the last set of input variables which had been entered before. The user can now proceed entering the correct values.

3.3.5 OUTPUT FOR CONSTANT SPEED

The results obtained when executing the program in the constant speed mode are shown in Table 2. The output consists of input variable data and calculated values. The input variable data is divided into two sections: input values and geometry. The input values consist of the speeds of both bodies, the applied load, and lubricant inlet temperature. The geometry consists of the radii of the bodies in both crown and rolling directions. The calculated values are the results of the analysis. These include the Hertzian profile, lubricant viscosity, slide/roll, thermal reduction factor, and film thickness. The units are as shown.

3.3.6 OUTPUT WHEN VARYING SPEED

In the varying speed mode, the output is similar to the constant speed mode with the difference that the slide/roll, thermal reduction factor, and film thickness are presented as a function of speed.

When generating your own data, the format of the output is as shown in Table 3. The output consists of the operating conditions, which include the applied load and inlet lubricant temperature, the geometry of the

system, the Hertz profile, lubricant properties, and the speed limits of both bodies. The film thickness, both isothermal and thermally corrected, slide/roll and thermal reduction factor are then printed as a function of the average rolling speed.

When the ehd program reads data from an existing file, the output is structured in the same form as when generating the data, discussed above. The results shown in Table 4 were obtained from the optical ehd test rig described in Section 3.3.2.6.2. The output includes operating conditions, geometry of the system, Hertz profile, lubricant characteristics, and calculated values. The calculated values consist of both isothermal and thermally corrected film thickness, thermal reduction factor, and slide/roll ratio. These values are printed as a function of average rolling speed.

TABLE 2. OUTPUT FOR CONSTANT SPEED MODE

SYSTEM 1

INPUT VALUES:

SPEED OF BODY A (IN/SEC)= 400
 SPEED OF BODY B (IN/SEC)= 500
 AVG ROLLING SPEED (IN/SEC)= 450
 LOAD (LBS)= 10
 INLET OIL TEMPERATURE ,DEG. F, DEG. CELSIUS 200 93.33334

GEOMETRY:

RADIUS OF BODY A IN THE ROLLING DIRECTION .5 INCHES
 RADIUS OF BODY B IN THE ROLLING DIRECTION 999 INCHES
 RADIUS OF BODY A IN THE CROWN DIRECTION .5 INCHES
 RADIUS OF BODY B IN THE CROWN DIRECTION 999 INCHES

CALCULATED VALUES:

MEAN HERTZIAN PRESSURE (PSI) 102103
 MAX. HERTZIAN PRESSURE (PSI) 153154.4 A B
 SEMIMAJOR & SEMIMINOR AXIS OF CONTACT ELLIPSE 5.583486 5.583486 MILS
 THERMAL RED. FACTOR= .9424321
 SLIDE/ROLL RATIO (%)= 22.22222

LUBRICANT MIL-L-7808
 INLET LUBRICANT VISCOSITY (CS) , (LB-SEC/IN^2) 3.558109 4.625191E-07
 LUBRICANT DENSITY (GM/CC) .89662

ISOTHERMAL PREDICTED FILM THICKNESS

HMIN= 4.051312E-06 INCHES
 HCENTRAL= 7.014834E-06 INCHES

CORRECTED FILM THICKNESS (THERMAL RED. FACTOR CONSIDERED)

HMIN= 3.818087E-06 INCHES
 HCENTRAL= 6.611004E-06 INCHES

TABLE 3. OUTPUT FOR VARYING SPEED MODE
(USER SPECIFIED SPEED RANGE)

OPERATING CONDITIONS

LOAD (LBS) 10
INLET LUBRICANT TEMPERATURE , DEG. F 200

GEOMETRY:

RADIUS OF BODY A IN THE ROLLING DIRECTION .5 INCHES
RADIUS OF BODY B IN THE ROLLING DIRECTION 999 INCHES
RADIUS OF BODY A IN THE CROWN DIRECTION .5 INCHES
RADIUS OF BODY B IN THE CROWN DIRECTION 999 INCHES

HERTZ PROFILE:

MAX. HERTZIAN STRESS (PSI) 153154.4
MEAN HERTZIAN STRESS (PSI) 102103
SEMIMAJOR & MINOR CONTACT ELLIPSE A B MILS
5.583486 5.583486

LUBRICANT MIL-L-7808
LUBRICANT INLET VISCOSITY (CS) 3.558109
LUBRICANT DENSITY (GM/ML) .89662

INITIAL VELOCITY OF BODY A (IN/SEC) 430
FINAL VELOCITY OF BODY A (IN/SEC) 650
INITIAL VELOCITY OF BODY B (IN/SEC) 817
FINAL VELOCITY OF BODY B (IN/SEC) 0

NUMBER OF DATA POINTS 15

AVG. ROLL. SPD. (IN/SEC)	THERM. RED. FACTOR	SLIDE/ROLL	ISOTHERMAL MIN.	FLM. THKNSS CENTRAL	CORRECTED MIN	FLM. THKNSS CENTRAL (MICRO-INCHES)
623.50	0.8721	-0.6207	5.0571	8.7278	4.4103	7.6115
603.60	0.8855	-0.5266	4.9468	8.5402	4.3805	7.5626
583.70	0.8995	-0.4261	4.8353	8.3505	4.3492	7.5111
563.80	0.9141	-0.3186	4.7225	8.1587	4.3168	7.4577
543.90	0.9296	-0.2031	4.6085	7.9646	4.2842	7.4041
524.00	0.9469	-0.0789	4.4932	7.7681	4.2546	7.3556
504.10	0.9524	0.0551	4.3765	7.5692	4.1680	7.2086
484.20	0.9392	0.2002	4.2582	7.3677	3.9991	6.9194
464.30	0.9287	0.3577	4.1384	7.1634	3.8432	6.6524
444.40	0.9197	0.5293	4.0170	6.9562	3.6945	6.3978
424.50	0.9119	0.7169	3.8937	6.7459	3.5508	6.1518
404.60	0.9051	0.9231	3.7687	6.5324	3.4109	5.9123
384.70	0.8990	1.1505	3.6416	6.3153	3.2740	5.6777
364.80	0.8937	1.4028	3.5124	6.0945	3.1392	5.4469
344.90	0.8891	1.6842	3.3810	5.8697	3.0061	5.2189

TABLE 4. OUTPUT FOR VARYING SPEED MODE
(READING RUN CONTROL VARIABLES FROM EXISTING FILE)

OPERATING CONDITIONS

LOAD (LBS) 10
 INLET LUBRICANT TEMPERATURE , DEG. F 120
 RADIUS OF BODY A IN THE ROLLING DIRECTION (INCHES..) .5
 RADIUS OF BODY B IN THE ROLLING DIRECTION 999
 RADIUS OF BODY A IN THE CROWN DIRECTION .5
 RADIUS OF BODY B IN THE CROWN DIRECTION 999
 MAX. HERTZIAN STRESS (PSI) 153154.4
 MEAN HERTZIAN STRESS (PSI) 102103
 SEMIMAJOR & SEMIMINOR CONTACT DIMENSIONS (MILS) A B
 5.583486 5.583486
 LUBRICANT MIL-L-7808
 LUBRICANT INLET VISCOSITY (CS) 9.688721
 LUBRICANT DENSITY (GM/ML) .9285752

ROLL.SPEED (IN/SEC)	SLIDE/ROLL (%)	THERMO.RED.FAC.	ISOTHERMAL FILM THICK.		THERMALLY CORRECTED FILM THICK.	
			MIN.	CENTRAL	MIN.	CENTRAL
			(MICRO-IN)			
268.782	21.93412	.92468	5.775	9.948	5.340	9.199
268.779	21.93946	.92468	5.775	9.948	5.340	9.199
268.788	21.94546	.92467	5.775	9.948	5.340	9.199
268.730	21.95478	.92468	5.775	9.947	5.340	9.197
268.783	21.89540	.92472	5.775	9.948	5.341	9.199
269.129	21.68411	.92485	5.780	9.957	5.346	9.208
269.515	21.38242	.92506	5.786	9.966	5.352	9.219
270.066	20.93280	.92538	5.794	9.980	5.362	9.235
270.611	20.48936	.92571	5.802	9.993	5.371	9.251
271.223	19.98994	.92608	5.811	10.008	5.381	9.269
271.756	19.51860	.92645	5.819	10.022	5.391	9.284
272.397	19.01143	.92683	5.828	10.037	5.402	9.303
272.763	18.61150	.92719	5.833	10.046	5.409	9.315
273.382	18.11701	.92757	5.842	10.062	5.419	9.333
274.206	17.58410	.92795	5.854	10.082	5.433	9.356
274.882	17.06390	.92836	5.864	10.099	5.444	9.375
275.355	16.62576	.92874	5.871	10.110	5.453	9.390

4.0 ERROR MESSAGES

<u>ERROR</u>	<u>DESCRIPTION</u>	<u>CORRECTIVE PROCEDURES</u>
(1) ?Redo from Start	This message appears when a non-numeric value has been given to a numeric variable.	The user should press the 'CTRL' key and the 'C' key simultaneously. Type and enter 'RUN' The user may now proceed to enter the correct values.
(2) Division by Zero	Appears when a zero has been assigned to a non-zero input variable or when a carriage return has been entered when prompted for a numeric key. This message also appears if the operation results in zero being raised to a negative power.	(Follow the same procedures as for error # (1)).

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