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FUZE GEAR TRAIN EFFICIENCY

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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WEAPON SYSTEMS LABORATORY
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This report describes the results of an analytical study of the point efficiencies of various types of fuze gear trains. Involute and clock-tooth profiles for two and three pass step-up gear meshes which operate in spin and nonspin environments are compared, and the differences explored. The conclusions of an investigation concerning the geometrical factors which influence the point efficiencies of multipass step-up gear trains are discussed. The analyses on which these results are based are given in detail.

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INTRODUCTION

The point efficiencies of various types of fuze related step-up gear trains were investigated and insights concerning the reasons for the resulting differences in these efficiencies are provided. The investigation also represents an application and extension of the tools furnished in Fuze Gear Train Analysis (FGTA) (ref 1).

The FGTA report (ref 1) deals primarily with the derivation of expressions and their subsequent computer formulation for point and cycle efficiencies of two and three pass step-up gear trains, with involute or clock gear teeth, which must operate in a spin environment. These programs are easily modified to simulate nonspin environments. In addition, derivations and computer programs are given for efficiency analyses of single pass involute and clock gear meshes which operate in nonspin environments. The report also contains a program for the design of the unity contact ratio involute meshes having unequal addenda, which were used in the study.

The present report gives the results of the efficiency comparisons between involute and clock gear two and three pass step-up gear trains which operate in spin and nonspin environments.

To perform these comparisons and to make their results as meaningful as possible, a number of preliminary tasks had to be carried out. Since no American standard for the design of clock tooth gear and pinion sets could be found, a computer program was written which uses British Standard No. 978 (ref 2). The three pass step-up gear trains were modeled after the M125A1 (brass) safety and arming device, and since no comparable two pass step-up train was initially available a two pass train with essentially the same step-up ratio was designed.

In order to simulate the randomness of the gear train assembly and to start the simulations with the worst possible starting conditions, the initialization parameters J_i have been introduced into the programs. These parameters make it possible to start the motion of any mesh anywhere between 0% and 100% of the total angle from earliest to latest tooth contact in a single tooth cycle of the driving gear. The worst starting condition for an involute mesh occurs at the start of approach action, i.e., when J_i equals zero. For a clock gear mesh it occurs at the end of the recess action when J_i equals unity.

To learn more concerning the geometrical factors which influence the point efficiencies of multipass step-up gear trains, additional analyses pertaining to compound gears and single pass meshes with involute and clock type teeth were performed. It was found that the distance of the line of action of the resultant force of the driving gear on the driven pinion from the friction circle, associated with the pinion pivot, is an important indicator of efficiency in step-up meshes. This distance, which depends on a number of parameters in addition to pivot radius and coefficient of friction, may be used as an optimization criterion in future work.

SUMMARY

Friction Circle and Efficiency of Single Gear and Pinion Combination

The concept of the friction circle was reviewed and related to the efficiency of a compound gear and pinion. The resulting expression, associated with this simple model in which the input force acts on the pinion while the equilibrating output force acts on the gear, indicated that the input-output efficiency is a function of the distance of the line of action of the input force from the friction circle. The larger this distance, the greater becomes this efficiency. Locking will occur if this distance becomes zero or the line of action passes inside the friction circle.

Efficiency Comparison Between Involute and Clock Gear Type Single Pass Step-up Gear Trains

Computer comparison of point efficiencies for increasingly severe friction conditions between involute and clock gear single pass step-up gear trains are presented here. Subsequently, analytical expressions for the distance of the line of action of the resultant force of the gear on the pinion from the pinion axis are given for both types of gearing and discussed. (The distance to the pinion axis, rather than the one to the friction circle was choosen for simplicity.)

Comparing the point efficiencies of the two types of gear trains revealed:

1. Regardless of the magnitude of the coefficient of friction, the point efficiency at initial contact, i.e., at the earliest possible position during approach action, is always higher for the clock gear mesh than for the involute mesh. This effect becomes especially pronounced for higher values of the coefficient of friction, when the involute mesh indicates a tendency to lock. This result may explain the greater tolerance of clock tooth trains when foreign material is unintentionally present.

2. The maximum point efficiencies of both types of meshes are essentially the same for a given coefficient of friction and occur at or near the pitch point.

3. The efficiencies of both types of meshes decrease during recess action w the greater decrease taking place in the clock gear configuration.

4. As a consequence of the above, the worst starting condition, i.e., the greatest danger of stalling due to a limited input moment and a high coefficient of friction, is associated with the beginning of approach action for involute meshes and the end for recess action for clock gear meshes.

The following conclusions were obtained from work performed concerning the distance of the line of action of the resultant force of the gear on the pinion from the pinion axis in involute meshes:

1. An increase of the coefficient of friction causes a decrease in this distance, becoming especially pronounced at initial contact if the approach angle is large.

2. The distance is generally smaller during approach action than during recess action.

3. An increase in the step-up ratio of a mesh in which the pinion remains the same causes a small decrease in the distance.

4. When the pitch radius of the pinion is large, this distance becomes larger.

5. An increase in the pressure angle of a given mesh decreases this distance from the line of action of the force to the pinion axis.

Comparing clock gear and involute meshes relative to the line of action of the force of the gear on the pinion from the pinion axis revealed:

1. Just as the point efficiency at initial contact is higher for the clock gear meshes than for involute meshes, regardless of the magnitude of the coefficient of friction, the distance is always larger for clock meshes at that instant. This difference in magnitude becomes more pronounced as the coefficient of friction increases.

2. The increase of the distance as approach action progresses is smaller for comparable clock meshes than for involute meshes. At the pitch point, the distance is essentially the same for both types of configurations. During recess, this distance decreases more for clock meshes than for involute meshes because the approach angle is larger in involute meshes while the reverse is true for the recess angle.

There is a proportional relationship between the distance of the line of action from the pinion axis and the point efficiency for any given contact condition, and, therefore, any geometrical change which increases this distance will also increase the point efficiency.

Since the point efficiency of involute meshes is only undesirable at the very beginning of the approach action, any modification which decreases contact before the pitch point, while maintaining an acceptable contact ratio, may produce gear meshes with generally higher point efficiencies than are found in clock gear meshes.

Efficiency Comparisons Between Involute and Clock Two and Three Pass Step-up Gear Trains in Spin and Nonspin Environments

The two pass trains were designed to have the same step-up ratio as the three pass trains and the newly introduced initialization parameters were used to obtain the worst possible starting conditions for all individual meshes.

The comparisons led to the following conclusions:

1. For a given mesh and spin condition there is no significant difference in the range of point efficiencies between involute and clock gears.

2. Without spin the two pass step-up trains are more efficient than the three pass trains.

3. With spin the three pass meshes are slightly more efficient than the two pass meshes.

4. All mesh point efficiencies are independent of the magnitude of the spin velocity.

Revision of Program INVOL3

A revised version, as well as an updated description of program INVOL3 which allows the determination of point and cycle efficiencies for three pass involute tooth step-up gear trains operating in a spin environment is given in appendix A. (All meshes have unity contact ratio.)

The original program was listed and described in detail in appendix C-3 of reference 1.

The present version of the program contains three initialization parameters J_i which allow the initial point of contact of each of the three meshes to be chosen arbitrarily. Further, for convenience and appropriate checking, certain gear and fuze parameters have been made part of the data and/or the output of the program. The data used in the new sample program are identical to those of the original sample program in reference 1. In order to obtain the worst starting conditions for an involute train, the three initialization parameters were set equal to zero in the sample program.

Revision of Program INVOL4

A revised version, as well as an updated description of program INVOL4 which allows the determination of point and cycle efficiencies for two pass involute tooth step-up gear trains operating in a spin environment is given in appendix B. (All meshes have unity contact ratio.)

The original program was listed and described in detail in appendix C-4 of reference 1.

The present version of the program contains two initialization parameters J_i which allow the initial point of contact of each of the two meshes to be chosen arbitrarily. Further, for reasons of convenience, and to allow appropriate checking, certain gear and fuze parameters have been made part of the data and/or the output of the program.

The data used in the new sample program differ from those used in reference 1. A new gear train, which has essentially the same step-up ratio as the three pass train, was designed. The gear parameters associated with this train were obtained with the help of program INVOL1 (originally given in appendix C-1, reference 1). The output of this program, one for each of the two meshes, is listed in appendix B. In order to obtain the worst possible starting conditions for an involute train, the two initialization parameters were set equal to zero in the sample program.

Design of Clock Tooth Gear and Pinion Set According to British Standard No. 978

Program BRITSTD for the design of clock tooth gear and pinion sets, according to British Standard No. 978 (ref 2), is given in appendix C. This program furnishes all necessary input parameters (i.e., gear and pinion dimensions) for programs CLOCK1 and CLOCK2, which are both listed in appendix F of reference 1, as well as the revised programs CLOCK3 and CLOCK4, which are given in appendixes D and E, respectively, of the present report.

The appendix also shows how to determine the center of curvature coordinates of the addendum radius of clock teeth with data from the standard. The associated computer program is listed in the appendix. In addition, five sample outputs are given. These furnish the input data for the sample runs of the revised programs CLOCK3 and CLOCK4.

Revision of Program CLOCK3

A revised version, as well as an updated description, of program CLOCK3, which allows the determination of point and cycle efficiencies for three pass clock tooth step-up trains operating in a spin environment is given in appendix D.

The original program was listed and described in appendix I-1 of reference 1.

The present version of the program contains three initialization parameters J_i which allow the initial point of contact of each of the three meshes to be chosen arbitrarily. Certain gear and pinion parameters have been added to the input as well as to the output of the program. The data used in the sample program are identical to those in reference 1 with respect to diametral pitch and number of teeth of the individual meshes. The specific tooth dimensions were obtained with the help of program BRITSTD. (See first three sets of outputs in appendix C.) In order to approximate the worst starting conditions for a clock tooth train, the three initialization parameters were set equal to 0.9 in the sample program.

Revision of Program CLOCK4

A revised version, as well as an updated description, of program CLOCK4, which allows the determination of point and cycle efficiencies of two pass clock tooth step-up gear trains operating in a spin environment is given in appendix E.

The original program was listed and described in appendix I-2 of reference 1.

The present version of the program contains two initialization parameters J_i which allow the initial point of contact of each of the two meshes to be chosen arbitrarily. Certain gear and pinion parameters have been added to the input as well as to the output of the program.

The data used in the new sample program differ from those used in reference 1. The new clock tooth train has the same step-up ratio, gear and pinion tooth numbers, and diametral pitches as were given to the new involute tooth two pass train (appendix B of the present report). The specific tooth dimensions were obtained with the help of program BRITSTD (fourth and fifth output sets in appendix C). In order to approximate the worst starting conditions for a clock tooth train, the two initialization parameters were set equal to 0.9 in the sample program.

FRICTION CIRCLE AND EFFICIENCY OF SINGLE GEAR AND PINION COMBINATION

Friction Circle

A free-body diagram of a single gear and pinion combination is shown in figure 1. The common pivot shaft has the radius ρ. This compound gear is driven in a clockwise direction by the input force F_i which acts on the pinion portion of the combination at distance a from the pivot axis O. Force F_o, at distance b from the pivot axis, is exerted by the next component of the gear train on the gear portion of the combination. The pivot bearing applies the reaction R on the pivot shaft. It consists of the normal component N and the tangential friction force component μN (where μ represents the coefficient of friction between pivot shaft and bearing). Since the friction force must oppose rotation, the vector sum

$$\bar{R} = \bar{N} + \overline{\mu N} \qquad (1)$$

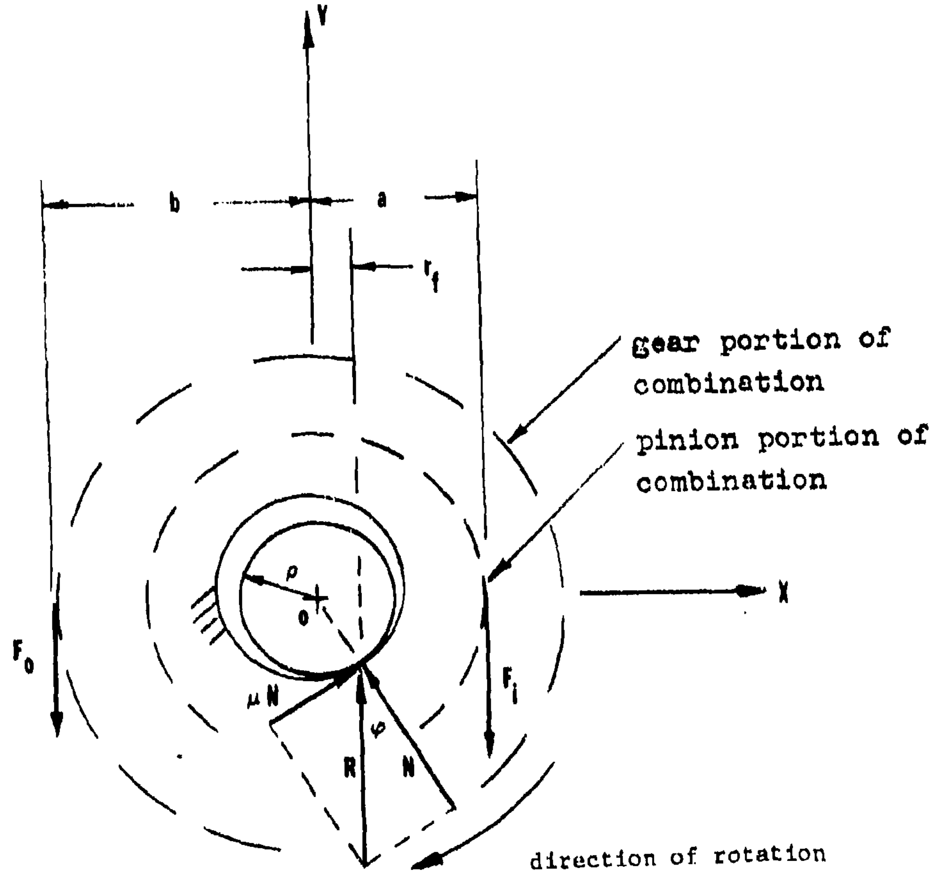

Figure 1. Free-body diagram of single gear and pinion combination

can only be satisified if the line of action of force R is located at the right hand side of the pivot center O. Varignon's theorem is used to determine the distance r_f of this line of action from the pivot axis. This theorem states that the moment of a force with respect to an axis equals the sum of the moments of the components of this force with respect to the same axis. Taking moments with respect to point O, one obtains for the forces R and μN:

$$r_f R = \rho \mu N \tag{2}$$

(Note that the normal component N exerts no moment about point O.) With

$$N = R\cos\phi, \quad \text{and} \tag{3}$$

$$\mu = \tan\phi \tag{4}$$

one obtains from equation 2,

$$r_f = \rho \sin\phi \tag{5}$$

This distance r_f represents the radius of the so-called friction circle and regardless of its direction, the bearing reaction R will always be tangent to this circle.

Efficiency of Single Gear and Pinion Combination

While figure 1 represents a simplified description of the loading condition of a single gear and pinion combination, since forces F_i and F_o are parallel, one may still obtain valuable insights concerning efficiency and locking from it.

To obtain the relationship between forces F_o and F_i, the following force and moment equilibrium conditions are used:

$$\sum F_y = 0: \quad -F_i - F_o + R = 0 \tag{6}$$

$$\sum M_o = 0: \quad bF_o - aF_i + r_f R = 0 \tag{7}$$

The moment equation 7 may be rewritten with the help of equation 6.

$$bF_o - aF_i + r_f(F_i + F_o) = 0 \tag{8}$$

The above furnishes the following expression for the output force F_o.

$$F_o = F_i\left(\frac{a - r_f}{b + r_f}\right) \tag{9}$$

Equation 9 may now be used to devise an efficiency expression. Assume that the combination gear rotates through a clockwise angle $\Delta\theta$.

The work done by force F_i is given by

$$W_i = F_i a \,\Delta\theta \tag{10}$$

The work of force F_o becomes for the same rotation

$$W_o = -F_i b \,\Delta\theta \left(\frac{a - r_f}{b + r_f}\right) \tag{11}$$

The efficiency η may now be found from the ratio of the output to the input work. Thus,

$$\eta = \left|\frac{W_o}{W_i}\right| = \frac{1 - \frac{r_f}{a}}{1 + \frac{r_f}{b}} \tag{12}$$

The following conclusions concerning the efficiency of single gear and pinion combinations are drawn from equation 12:

1. The friction circle radius r_f should be as small as possible.

2. The distance b should be as large as possible. This generally offers no difficulty in step-up gear trains since force F_o is applied to the gear portion of the combination which has a relatively large pitch radius.

3. Most importantly, the distance a should be as large as possible. This condition is critical in step-up gear trains since force F_i acts on the pinion portion of the combination and the associated distance a is never very large.

Equation 12 shows that friction locking may occur when $a \leq r_f$, i.e., when the line of action of the force on the pinion passes either tangent to or inside of the friction circle.

EFFICIENCY COMPARISONS BETWEEN INVOLUTE AND CLOCK GEAR TYPE SINGLE PASS STEP-UP GEAR TRAINS

To make the conclusions of the comparisons more general, the influence of the position of the line of action of the force of the gear on the pinion, with respect to the pinion pivot, on the mesh efficiencies is discussed for both types of gearing.

Efficiencies of Single Pass Step-up Gear Meshes with Involute and Clock Gear Type Teeth

Point efficiency comparisons between similar involute and clock gear type meshes are given in table 1. The involute mesh was designed with the help of computer program INVOL1 (ref 1). The efficiency computations for the involute mesh were obtained from computer program INVOL2 (ref 1). Computer program BRITSTD, which is listed and discussed in appendix C forms the basis of the design of the clock gear train. The efficiency computations of this single step-up mesh were made with computer program CLOCK2 (ref 1).

Both types of meshes have the following data in common:

P_d = 44, diametral pitch

N_G = 48, number of teeth of gear

N_P = 8, number of teeth of pinion

ρ_N = 0.060 in. (0.152 cm), pivot radius of gear (also subscript 1)

ρ_n = 0.030 in. (0.076 cm), pivot radius of pinion (also subscript 2)

The coefficient of friction is varied from $\mu = 0.1$ to $\mu = 0.8$.

The specific data for the involute mesh, as designed by INVOL1 to have unequal addenda and unity contact ratio, are as follows:

θ = 20° the pressure angle

R_p = 0.54545 in. (1.3854 cm) r_p = 0.09091 in. (0.2309 cm) (pitch radii)

R_b = 0.51256 in. (1.3019 cm) r_b = 0.08543 in. (0.2170 cm) (base circle radii)

R_o = 0.55609 in. (1.4125 cm) r_o = 0.10985 in. (0.2790 cm) (outside radii)

The specific data for the clock gear mesh, as obtained with the help of program BRITSTD, are given by:

R_p = 0.54545 in. (1.3854 cm) r_p = 0.09091 in. (0.2309 cm) (pitch radii)

a_G = 0.54157 in. (1.3756 cm) a_P = 0.09083 in. (0.2307 cm) (positions of centers of curvature)

Table 1. Comparison of single pass step-up gear efficiencies as functions of coefficient of friction with nonzero pivot radii. (Obtained with programs INVOL2 and CLOCK2)

	Clock tooth shape efficiency			Involute tooth shape efficiency		
Coefficient of friction (μ)	Initial contact point (ε_p)	Maximum point (ε_p)	Final contact point (ε_p)	Initial contact point (ε_p)	Maximum point (ε_p)	Final contact point (ε_p)
0.1	0.933	0.956	0.883	0.900	0.954	0.919
0.2	0.866	0.913	0.785	0.796	0.912	0.846
0.3	0.800	0.872	0.700	0.688	0.874	0.781
0.4	0.734	0.833	0.626	0.576	0.834	0.721
0.5	0.668	0.796	0.562	0.460	0.806	0.666
0.6	0.602	0.760	0.505	0.340	0.776	0.615
0.7	0.536	0.726	0.455	0.214	0.748	0.568
0.8	0.471	0.693	0.409	0.084	0.722	0.525

ρ_G = 0.04886 in. (0.1241 cm) ρ_P = 0.01591 in. (0.0404 cm) (radii of tooth curvature)

t_G = 0.03608 in. (0.0916 cm) t_p = 0.02382 in. (0.0605 cm) (tooth thicknesses at pitch circles)

Similar efficiency comparisons for the same meshes are given in table 2. To illustrate the effects of tooth contact friction only, the pivot radii ρ_N and ρ_n were made equal to zero.

Both tables show maximum point efficiencies and point efficiencies for the earliest possible contact of the meshes (at the maximum angles of approach), as well as for the final contact, when a new set of teeth is about to come into engagement.

The data for tables 1 and 2 are derived from the typical outputs of program INVOL2 and CLOCK2 which are shown in tables 3 and 4, respectively.

Conclusions of Efficiency Comparisons

Inspection of table 1 permits the following conclusions:

1. Regardless of the magnitude of the coefficient of friction, the point efficiency ϵ_p at initial, i.e., earliest possible, contact is always higher for the clock gear mesh than for the involute mesh. This effect becomes especially pronounced for higher values of the coefficient of friction, when the involute mesh indicates a tendency to lock. This result may explain the greater tolerance of clock tooth type trains for the presence of foreign material during assembly.

2. Both involute and clock gear point efficiencies increase steadily after initial contact has been made and until maximum point efficiency is reached. The rate of increase of efficiency is much greater for the involute mesh (tables 3 and 4).

3. The maximum point efficiencies of both mesh types are essentially the same for a given coefficient of friction. They occur when the contact point betweeen gear and pinion coincides with the line connecting their pivots. Since in this position there is no relative velocity between the contacting surfaces of the teeth, there is also no friction force.

4. The efficiencies of both mesh types decrease steadily after the maximum has been reached at pitch point contact. The rate of this decrease is much less pronounced for the involute mesh. The latest possible contact efficiency of the involute mesh is higher than that of the clock gear (table 1). Therefore, if one can design a modified involute step-up mesh which avoids contact before the pitch point as much as possible and still has an acceptable contact ratio, it may show higher efficiencies than a comparable clock gear mesh.

Table 2. Comparison of single pass step-up gear efficiencies as functions of coefficient of friction with zero pivot radii. (Obtained with programs INVOL2 and CLOCK2)

	Clock tooth shape efficiency			Involute tooth shape efficiency		
Coefficient of friction (μ)	Initial contact point (ε_p)	Maximum point (ε_p)	Final contact point (ε_p)	Initial contact point (ε_p)	Maximum point (ε_p)	Final contact point (ε_p)
0.1	0.977	1.000	0.929	0.947	0.999	0.964
0.2	0.954	0.999	0.867	0.890	0.999	0.930
0.3	0.930	0.998	0.812	0.830	0.998	0.899
0.4	0.906	0.998	0.765	0.765	0.998	0.870
0.5	0.881	0.997	0.722	0.697	0.997	0.843
0.6	0.856	0.997	0.684	0.623	0.996	0.818
0.7	0.831	0.996	0.650	0.545	0.995	0.795
0.8	0.804	0.996	0.619	0.460	0.994	0.773

Table 3. Typical output of program INVOL2 for table 2

```
GEAR PITCH RADIUS (CAPRP) = .54545   PINION PITCH RADIUS (RP) = .09091

GEAR OUTSIDE RADIUS (CAPRO) = .55609   PINION OUTSIDE RADIUS FOR UNITY CONTACT RATIO (ROFIN) = .10985

PRESSURE ANGLE IN DEGREES (THETAD) = 20.00

GEAR PIVOT RADIUS (RHOCAPN) = .060   PINION PIVoT RADIUS (RHON) = .030

COEFFICIENT OF FRICTION (MU) = .10

RANGE DIVISOR (K) = 50

                    0

ALPHAD = 16.61   S = 1.0    POINTEF = .8996
ALPHAD = 16.76   S = 1.0    POINTEF = .9014
ALPHAD = 16.91   S = 1.0    POINTEF = .9033
ALPHAD = 17.06   S = 1.0    POINTEF = .9051
ALPHAD = 17.21   S = 1.0    POINTEF = .9070
ALPHAD = 17.36   S = 1.0    POINTEF = .9088
ALPHAD = 17.51   S = 1.0    POINTEF = .9106
ALPHAD = 1[illegible].66   S = 1.0    POINTEF = .9125
ALPHAD = [illegible].81   S = 1.0    POINTEF = .9143
ALPHAD = 17.96   S = 1.0    POINTEF = .9162
ALPHAD = 18.11   S = 1.0    POINTEF = .9180
ALPHAD = 18.26   S = 1.0    POINTEF = .9199
ALPHAD = 18.41   S = 1.0    POINTEF = .9217
ALPHAD = 18.56   S = 1.0    POINTEF = .9236
ALPHAD = 18.71   S = 1.0    POINTEF = .9254
ALPHAD = 18.86   S = 1.0    POINTEF = .9273
ALPHAD = 19.01   S = 1.0    POINTEF = .9291
ALPHAD = 19.16   S = 1.0    POINTEF = .9310
ALPHAD = 19.31   S = 1.0    POINTEF = .9328
ALPHAD = 19.46   S = 1.0    POINTEF = .9347
ALPHAD = 19.61   S = 1.0    POINTEF = .9366
ALPHAD = 19.76   S = 1.0    POINTEF = .9384
ALPHAD = 19.91   S = 1.0    POINTEF = .9403
ALPHAD = 20.06   S = 1.0    POINTEF = .9421
ALPHAD = 20.21   S = 1.0    POINTEF = .9440
ALPHAD = 20.36   S = 1.0    POINTEF = .9459
ALPHAD = 20.51   S = 1.0    POINTEF = .9477
ALPHAD = 20.66   S = 1.0    POINTEF = .9496
ALPHAD = 20.81   S = 1.0    POINTEF = .9515
ALPHAD = 20.96   S =-1.0    POINTEF = .9541
ALPHAD = 21.11   S =-1.0    POINTEF = .9524
ALPHAD = 21.26   S =-1.0    POINTEF = .9506
ALPHAD = 21.41   S =-1.0    POINTEF = .9489
ALPHAD = 21.56   S =-1.0    POINTEF = .9471
ALPHAD = 21.71   S =-1.0    POINTEF = .9454
ALPHAD = 21.86   S =-1.0    POINTEF = .9437
ALPHAD = 22.01   S =-1.0    POINTEF = .9420
ALPHAD = 22.16   S =-1.0    POINTEF = .9402
ALPHAD = 22.31   S =-1.0    POINTEF = .9385
ALPHAD = 22.46   S =-1.0    POINTEF = .9368
ALPHAD = 22.61   S =-1.0    POINTEF = .9350
ALPHAD = 22.76   S =-1.0    POINTEF = .9333
ALPHAD = 22.91   S =-1.0    POINTEF = .9316
ALPHAD = 23.06   S =-1.0    POINTEF = .9299
ALPHAD = 23.21   S =-1.0    POINTEF = .9281
ALPHAD = 23.36   S =-1.0    POINTEF = .9264
ALPHAD = 23.51   S =-1.0    POINTEF = .9247
ALPHAD = 23.66   S =-1.0    POINTEF = .9230
ALPHAD = 23.81   S =-1.0    POINTEF = .9212
ALPHAD = 23.96   S =-1.0    POINTEF = .9195
```

Table 4. Typical output of program CLOCK2 for table 2

```
CAPRP = .59545   RP = .03891   AG = .54157   AP = .09083 RHO1 = .0600   RHO2 = .0300   DELGD =   3.2624   DELPD =   2.5246

RHOG = .04086   RHOP = .01591                           PHIDOT =  1.0                  GAMMPD =  10.0881   ALPHPD =   7.5641

TG = .03609   TP = .02382                               K =  50.

NG = 48.   NP =  8.                                     MU =  .10

PHID = 176.2813   PSID =    3.5816   PSIDOT = -6.0220   SR =-1.0   ETAGRD =  90.1036   ETAPRD =  98.0623   POINTEF =  .933
PHID = 176.4313   PSID =    2.5994   PSIDOT = -6.0072   SR =-1.0   ETAGRD =  90.0900   ETAPRD =  96.9964   POINTEF =  .935
PHID = 176.5813   PSID =    1.6993   PSIDOT = -5.9948   SR =-1.0   ETAGRD =  90.0997   ETAPRD =  95.9560   POINTEF =  .937
PHID = 176.7313   PSID =     .9008   PSIDOT = -5.9847   SR =-1.0   ETAGRD =  90.1326   ETAPRD =  94.9405   POINTEF =  .939
PHID = 176.8813   PSID =  359.9038   PSIDOT = -5.9766   SR =-1.0   ETAGRD =  90.1886   ETAPRD =  93.9494   POINTEF =  .941
PHID = 177.0313   PSID =  359.0878   PSIDOT = -5.9705   SR =-1.0   ETAGRD =  90.2676   ETAPRD =  92.9824   POINTEF =  .943
PHID = 177.1813   PSID =  358.1125   PSIDOT = -5.9661   SR =-1.0   ETAGRD =  90.3696   ETAPRD =  92.0392   POINTEF =  .945
PHID = 177.3313   PSID =  357.2178   PSIDOT = -5.9634   SR =-1.0   ETAGRD =  90.4944   ETAPRD =  91.1194   POINTEF =  .946
PHID = 177.4813   PSID =  356.3235   PSIDOT = -5.9621   SR =-1.0   ETAGRD =  90.6422   ETAPRD =  90.2228   POINTEF =  .948
PHID = 177.6313   PSID =  355.4291   PSIDOT = -5.9622   SR =-1.0   ETAGRD =  90.8128   ETAPRD =  89.3491   POINTEF =  .950
PHID = 177.7813   PSID =  354.5347   PSIDOT = -5.9636   SR =-1.0   ETAGRD =  91.0063   ETAPRD =  88.4981   POINTEF =  .952
PHID = 177.9313   PSID =  353.6400   PSIDOT = -5.9660   SR =-1.0   ETAGRD =  91.2226   ETAPRD =  87.6697   POINTEF =  .954
PHID = 178.0813   PSID =  352.7449   PSIDOT = -5.9695   SR =-1.0   ETAGRD =  91.4619   ETAPRD =  86.8638   POINTEF =  .955
PHID = 178.2313   PSID =  351.8491   PSIDOT = -5.9737   SR = 1.0   ETAGRD =  91.7240   ETAPRD =  86.0803   POINTEF =  .956
PHID = 178.3813   PSID =  350.9527   PSIDOT = -5.9787   SR = 1.0   ETAGRD =  92.0092   ETAPRD =  85.3190   POINTEF =  .954
PHID = 178.5313   PSID =  350.0555   PSIDOT = -5.9843   SR = 1.0   ETAGRD =  92.3173   ETAPRD =  84.5799   POINTEF =  .952
PHID = 178.6813   PSID =  349.1574   PSIDOT = -5.9904   SR = 1.0   ETAGRD =  92.6484   ETAPRD =  83.8629   POINTEF =  .950
PHID = 178.8313   PSID =  348.2583   PSIDOT = -5.9969   SR = 1.0   ETAGRD =  93.0026   ETAPRD =  83.1681   POINTEF =  .948
PHID = 178.9813   PSID =  347.3583   PSIDOT = -6.0035   SR = 1.0   ETAGRD =  93.3799   ETAPRD =  82.4954   POINTEF =  .947
PHID = 179.1313   PSID =  346.4573   PSIDOT = -6.0103   SR = 1.0   ETAGRD =  93.7804   ETAPRD =  81.8448   POINTEF =  .945
PHID = 179.2813   PSID =  345.5552   PSIDOT = -6.0170   SR = 1.0   ETAGRD =  94.2040   ETAPRD =  81.2164   POINTEF =  .943
PHID = 179.4313   PSID =  344.6522   PSIDOT = -6.0235   SR = 1.0   ETAGRD =  94.6509   ETAPRD =  80.6101   POINTEF =  .941
PHID = 179.5813   PSID =  343.7482   PSIDOT = -6.0298   SR = 1.0   ETAGRD =  95.1209   ETAPRD =  80.0262   POINTEF =  .939
PHID = 179.7313   PSID =  342.8423   PSIDOT = -6.0566   G = .08892   SF = 1.0   ETAGFD =  96.0625   POINTEF =  .937
PHID = 179.8813   PSID =  341.9316   PSIDOT = -6.0856   G = .08830   SF = 1.0   ETAGFD =  97.1232   POINTEF =  .935
PHID = 180.0313   PSID =  341.0168   PSIDOT = -6.1114   G = .08771   SF = 1.0   ETAGFD =  98.1880   POINTEF =  .933
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PHID = 180.6313   PSID =  337.3269   PSIDOT = -6.1785   G = .08558   SF = 1.0   ETAGFD = 102.4779   POINTEF =  .925
PHID = 180.7813   PSID =  336.3995   PSIDOT = -6.1858   G = .08511   SF = 1.0   ETAGFD = 103.5553   POINTEF =  .923
PHID = 180.9313   PSID =  335.4713   PSIDOT = -6.1891   G = .08467   SF = 1.0   ETAGFD = 104.6334   POINTEF =  .921
PHID = 181.0813   PSID =  334.5436   PSIDOT = -6.1883   G = .08425   SF = 1.0   ETAGFD = 105.7118   POINTEF =  .919
PHID = 181.2313   PSID =  333.6151   PSIDOT = -6.1834   G = .08385   SF = 1.0   ETAGFD = 106.7897   POINTEF =  .917
PHID = 181.3813   PSID =  332.6882   PSIDOT = -6.1744   G = .08348   SF = 1.0   ETAGFD = 107.8656   POINTEF =  .915
PHID = 181.5313   PSID =  331.7630   PSIDOT = -6.1611   G = .08314   SF = 1.0   ETAGFD = 108.9418   POINTEF =  .913
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PHID = 182.1313   PSID =  328.0914   PSIDOT = -6.0661   G = .08205   SF = 1.0   ETAGFD = 113.2133   POINTEF =  .905
PHID = 182.2813   PSID =  327.1840   PSIDOT = -6.0320   G = .08185   SF = 1.0   ETAGFD = 114.2708   POINTEF =  .903
PHID = 182.4313   PSID =  326.2820   PSIDOT = -5.9938   G = .08167   SF = 1.0   ETAGFD = 115.3227   POINTEF =  .901
PHID = 182.5813   PSID =  325.3861   PSIDOT = -5.9517   G = .08153   SF = 1.0   ETAGFD = 116.3687   POINTEF =  .899
PHID = 182.7313   PSID =  324.4967   PSIDOT = -5.9057   G = .08141   SF = 1.0   ETAGFD = 117.4081   POINTEF =  .896
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PHID = 183.0313   PSID =  322.7401   PSIDOT = -5.8025   G = .08126   SF = 1.0   ETAGFD = 119.4647   POINTEF =  .892
PHID = 183.1813   PSID =  321.8740   PSIDOT = -5.7456   G = .08123   SF = 1.0   ETAGFD = 120.4808   POINTEF =  .890
PHID = 183.3313   PSID =  321.0166   PSIDOT = -5.6854   G = .08123   SF = 1.0   ETAGFD = 121.4882   POINTEF =  .888
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PHID = 183.6313   PSID =  319.3302   PSIDOT = -5.5554   G = .08131   SF = 1.0   ETAGFD = 123.4746   POINTEF =  .883
```

The results of efficiency computations for involute and clock gear meshes with zero pivot radii (table 2) show the same general tendencies as were found for the configurations of table 1. In addition, it confirms the well-known rule of making the pivot radii as small as possible in order to assure high point efficiencies.

Position of Line of Action of Force of Gear on Pinion in Involute and Clock Gear Meshes

The section on efficiency of single gear and pinion combination showed that to avoid locking and to improve the efficiency of a single compound gear and pinion it is desirable to have the line of action of the input force pass as far as possible from the friction circle and with that from the pivot of the pinion. The following provides some insights concerning the position of this line of action in involute and clock gear meshes during the various phases of contact. It is intended to serve as a starting point for future work on mesh efficiency improvement.

Position of Line of Action of Force of Gear on Pinion in an Involute Mesh

The force of the gear on the pinion, together with the associated line of action, as it appears during both approach and recess, is shown in figure 2. F_a represents the contact force during approach and F_r is the same force during recess. As indicated in the figure, the direction of the friction force component μF is reversed as contact changes from approach to recess. It is to be recalled that this is due to a similar change in the direction of the relative velocity between the gear and pinion contact points. Since the relative velocity is zero when contact occurs at the pitch point, the friction component also vanishes at that instant. (For a discussion of the above concepts see appendix A-1 (ref 1). The normal component F of the contact force retains its direction throughout the complete cycle of motion.

The distance of the line of action of the resultant force from the pinion pivot O_n is smaller during most of the approach motion than it is during recess motion (fig. 2). The symbols r_{Ma} and r_{Mr} are used for this distance during approach and recess, respectively, while r_{Mp} is used for pitch point contact. The following gives analytical expressions for these terms and discusses possible ways of maximizing them:

1. Distance r_{Ma} During Approach Motion

The distance of the line of action from point O_n may be determined with the help of Varignon's theorem, i.e., the sum of the moments of the forces F and μF with respect to point O_n equals the moment of the resultant F_a with respect to the same point. Thus, vectorially

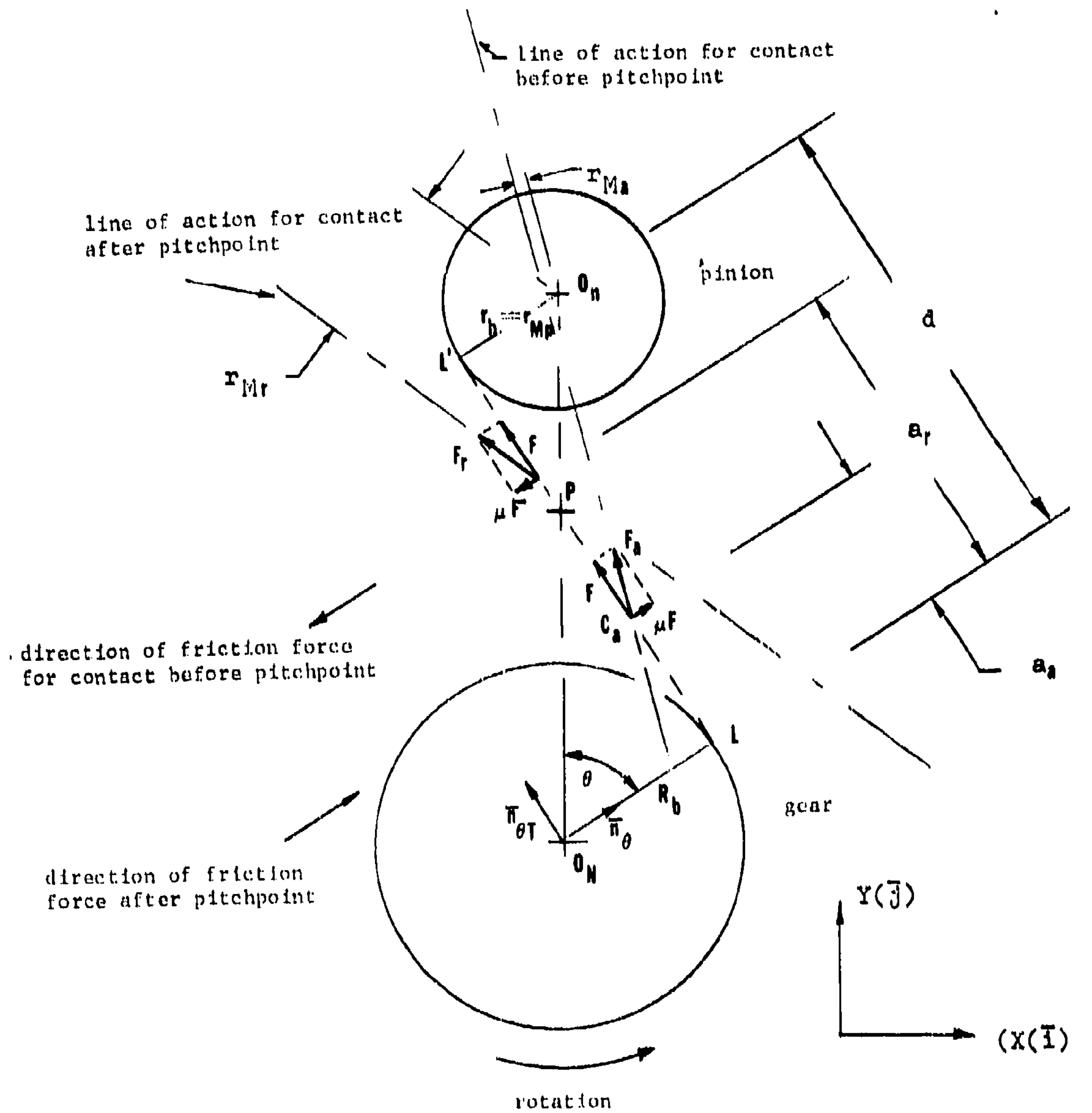

Figure 2. Line of action of force of gear on pinion in an involute step-up mesh

$$\bar{r}_{Ma} \times \bar{F}_a = [-r_b \bar{n}_\theta + (d-a_a)(-\bar{n}_{\theta_T})] \times [F\bar{n}_{\theta_T} + \mu F \bar{n}_\theta] \qquad (13)$$

where

μ = coefficient of friction between teeth

F_a = resultant force during approach, equal to $F\sqrt{1+\mu^2}$

F = normal component of resultant force

μF = friction component of resultant force

r_b = pinion base radius

d = distance $\overline{LL'}$ (fig. 2)

a_a = distance from point L to gear and pinion contact point C_a during approach. ($a_a < LP$)

$$\left.\begin{aligned} \bar{n}_\theta &= \sin\theta \bar{i} + \cos\theta \bar{j} \\ n_{\theta_T} &= -\cos\theta \bar{i} + \sin\theta \bar{j} \end{aligned}\right\}^{1}$$

When equation 13 is solved for the moment arm r_{Ma}, which represents the perpendicular distance from the line of action to point O_n, one obtains the following scalar quantity:

$$r_{Ma} = \frac{r_b - \mu(d - a_a)}{\sqrt{1 + \mu^2}} \qquad (14)$$

For greater insight the above expression is rewritten with the help of

r_b = $r_p \cos\theta$, where r_p is the pinion pitch radius

d = $(R_p + r_p)\sin\theta$, where R_p is the gear pitch radius

a_a = $K_a R_p \sin\theta$, where $K_a = \overline{C_a L}/\overline{LP} < 1$ since the length $\overline{C_a L}$ is less than the distance $\overline{LP}$. The closer the contact of gear and pinion to point L along line LP, the smaller is K_a

---

[1]See equations A-4 and A-5 of reference 1 for these unit vectors. θ is the pressure angle.

Thus, one obtains for equation 14

$$r_{Ma} = \frac{r_p}{\sqrt{1 + \mu^2}} \{\cos\theta - \mu\sin\theta \, [\, 1 + \frac{R_p}{r_p} (1 - K_a)] \, \} \tag{15}$$

2. Distance r_{Mp} for Contact at the Pitchpoint

Since there is no friction component when contact takes place at the pitch point, the distance r_M becomes

$$r_{Mp} = r_b = r_p \cos\theta \tag{16}$$

3. Distance r_{Mr} During Recess Motion

For contact during recess, the sign of the friction component $\mu F \bar{n}_\theta$ in equation 13 must be reversed. Also since contact is now made after the pitch point, the distance from point L to the contact point (not specifically called out in fig. 2) becomes

$$a_r = K_r R_p \sin\theta$$

where

$$K_r > 1$$

The resulting scalar expression has the form

$$r_{Mr} = \frac{r_p}{\sqrt{1 + \mu^2}} \{\cos\theta - \mu\sin\theta \, [\, \frac{R_p}{r_p} (K_r - 1) - 1] \, \} \tag{17}$$

If the above is expressed similar to equation 14, it becomes

$$r_{Mr} = \frac{r_b + \mu \, (d - a_r)}{\sqrt{1 + \mu^2}} \tag{18}$$

4. Conclusions for Involute Meshes

Equations 15 through 17 and the data in tables 5 and 6 were used to draw the following conclusions concerning the distance r_M of the line of action of the resultant force of the gear on the pinion from the pinion pivot:[2]

For All Contact Conditions.

1. The larger the pitch radius of the pinion, the larger becomes the distance r_M and with that the less becomes the danger of locking or of obtaining excessively low efficiencies according to equation 12. (Note that the symbol r_M now replaces the symbol a in this expression. Further, it must be understood that equations 15 and 17 are not valid for contact at the pitch point.)

2. With the exception of a short distance, at the beginning of recess motion, an increase of the coefficient of friction decreases the distance r_M. (Compare columns III and IV of table 5.)

3. For otherwise fixed conditions an increase in the step-up ratio R_p/r_p generally causes a small decrease in the distance r_M.

4. For equal distances along the line LL' before and after the pitch point (fig. 2), i.e., for $K_a = 1 - x$ and $K_r = 1 + x$, the distance r_M is always smaller for the approach case. (Compare values for $K_a = 0.8$ and $K_r = 1.2$ in all columns of table 5. Similar information is contained in all rows of table 6.)

5. For otherwise fixed conditions, the distance r_M decreases as the pressure angle is increased (table 6).

For Contact During Approach. For any given configuration, the factor K_a should be as close to unity as possible in order to avoid excessively small values of r_{Ma}. This implies that initial contact between the gear and the pinion should be near the pitch point, i.e., the angle of approach should be small.

It is to be noted that r_{Ma} is always less than r_b which represents its value at the pitch point (equation 16 and columns III, IV and V of table 5).

For Contact During Recess. For any set of fixed conditions the maximum value of r_M is reached shortly after the pitch point is passed. This maximum value of r_{Mr} is larger than the associated distance r_{Mp} at the pitch point. This maximum

[2] The distance from the pinion friction circle gives direct information concerning the possibility of locking. Any conclusions concerning mesh efficiency must also take the distance of this line of action from the gear pivot into account.

Table 5. Distance r_M of line action from pinion axis according to equations 15 through 17 [for pressure angle $\theta = 20°$]

I Approach factor K_a	II Recess factor K_r	III Distances r_{Ma}, r_{Mp}, r_{Mr} for $\mu = 0.1$ $R_p/r_p = 6$	IV Distances r_{Ma}, r_{Mp}, r_{Mr} for $\mu = 0.3$ $R_p/r_p = 6$	V Distances r_{Ma}, r_{Mp}, r_{Mr} for $\mu = 0.1$ $R_p/r_p = 8$
0.4	-	0.778 r_p	0.448 r_p	0.737 r_p
0.6	-	0.819	0.566	0.792
0.8	-	0.860	0.684	0.846
0.9	-	0.880	0.749	0.873
0.95	-	0.891	0.772	0.887
Pitch point	-	0.934 $r_p = r_b$	0.934 r_p	0.934 r_p
-	1.001	0.968	0.997	0.969
-	1.01	0.966	0.993	0.966
-	1.10	0.949	0.939	0.942
-	1.20	0.928	0.880	0.914
-	1.40	0.880	0.762	0.860

Table 6. Influence of pressure angle on distance r_M according to equations 15 through 17 [for $\mu = 0.1$, $R_p/r_p = 6$]

Pressure angle θ (degrees)	Approach distance r_{Ma} ($K_a = 0.9$)	Pitch point distance r_{Mp}	Recess distance r_{Mr} ($K_r = 1.1$)
14	0.927 r_p	0.970 r_p	0.975 r_p
16	0.913	0.961	0.967
18	0.897	0.951	0.958
20	0.880	0.940	0.948
22	0.863	0.927	0.937
24	0.844	0.913	0.925

value increases with an increase in the coefficient of friction (conclusion no. 2 above).

Position of Line of Action of Force of Gear on Pinion in a Clock Gear Mesh

Distance r_{Mrd} for Round on Round Phase of the Motion

The normal force F of the gear on the pinion, together with the friction force μF for a typical contact condition during the round on round phase of the motion is shown in figure 3. While the normal force always has the direction of the unit vector $\overline{n}_\lambda$, the direction of the friction force depends on the direction of the relative velocity $\overline{V}_{S/T}$, between the contact point S of the gear and the contact point T of the pinion (fig. 3). Equation E-50 (ref 1) shows that the sense of this friction force may be obtained with the signum function $s_R = V_{S/T}/|V_{S/T}|$. The friction force with a positive s_R is shown in figure 3.

Varignon's theorem was used to determine the distance r_{Mrd} of the line of action of the resultant force F_{rd} from the pinion pivot O_n, i.e.,

$$\overline{r}_{Mrd} \times \overline{F}_{rd} = (a_p\overline{n}_p - \rho_p\overline{n}_\lambda) \times (F\overline{n}_\lambda + \mu s_R\, F\overline{n}_{N\lambda}) \qquad (19)$$

where

F_{rd} = $F\sqrt{1 + \mu^2}$

a_p = O_nC_p, the distance from the pivot to the center of curvature of the pinion profile

ρ_p = radius of curvature of pinion profile

$\overline{n}_p$ = $\cos(\psi - \delta_p)\,\overline{i} + \sin(\psi - \delta_p)\,\overline{j}$, see equation E-4 (ref 1)

$\overline{n}_\lambda$ = $\cos\lambda\,\overline{i} + \sin\lambda\,\overline{j}$, see equation E-2 (ref 1)

$\overline{n}_{N\lambda}$ = $-\sin\lambda\,\overline{i} + \cos\lambda\,\overline{j}$, see equation E-3 (ref 1)

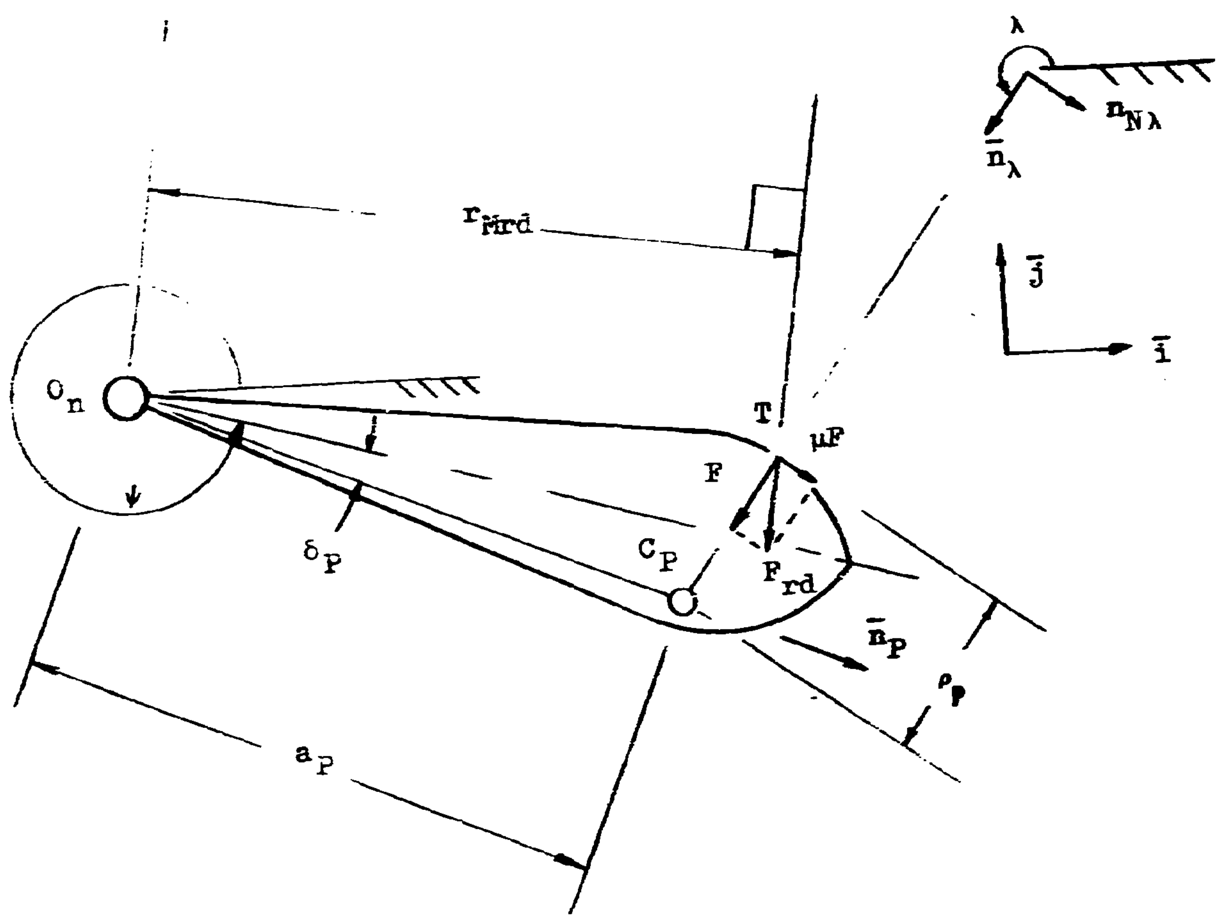

Figure 3. Position of line of action of force of gear on pinion in round on round phase of motion of clock gear mesh (gear not shown)

When equation 19 is solved for the absolute value of the moment arm r_{Mrd}, one obtains

$$r_{Mrd} = \frac{1}{\sqrt{1 + \mu^2}} \left\{ a_p \left[\sin(\lambda - \psi + \delta_p) + \mu s_R \cos(\lambda - \psi + \delta_p) \right] - \mu s_R \rho_p \right\} \qquad (20)$$

Distance r_{Mf} for Round on Flat Phase of the Motion

The normal force F of the gear on the pinion, together with the associated friction force μF for a typical contact condition during the round on flat phase of the motion is shown in figure 4. This contact is made at point T of the radial pinion flank which is at a distance g from the pinion pivot O_n. The normal force always has the negative direction of the unit vector $\bar{n}_{NF}$ (equation E-22, ref 1), while the friction force has the direction of the unit vector $\bar{n}_F$ (eq E-23, ref 1) at all times.

Since friction force, μF, does not exert a moment about the pivot point, O_n, the moment of the resultant force, F_f, at the distance r_{Mf}, must be equal to the moment of force F at the distance g. Thus,

$$\bar{r}_{Mf} \times \bar{F}_f = g\bar{n}_F \times F(-\bar{n}_{NF}) \qquad (21)$$

where, again

$$F_f = F \sqrt{1 + \mu^2}$$

When equation 21 is solved for the absolute value of the moment arm r_{Mf}, one obtains

$$r_{Mf} = \frac{g}{\sqrt{1 + \mu^2}} \qquad (22)$$

Distance r_{MP} for Contact on the Line of Centers (Pitch Point)

When contact points S and T coincide with the line of centers, i.e., the line connecting the gear and pinion pivots, the relative velocity $\bar{V}_{S/T}$ vanishes as it changes directions. The clock gear computer programs indicate the passing of the contact points through the line of centers by a change of sign of the signum parameter. Such a change of sign of the parameter s_R between the angles $\phi = 178.0813°$ and $\phi = 178.2313°$ while the mesh is in the round on round phase of the motion is shown in table 4. Since all presently examined clock gear

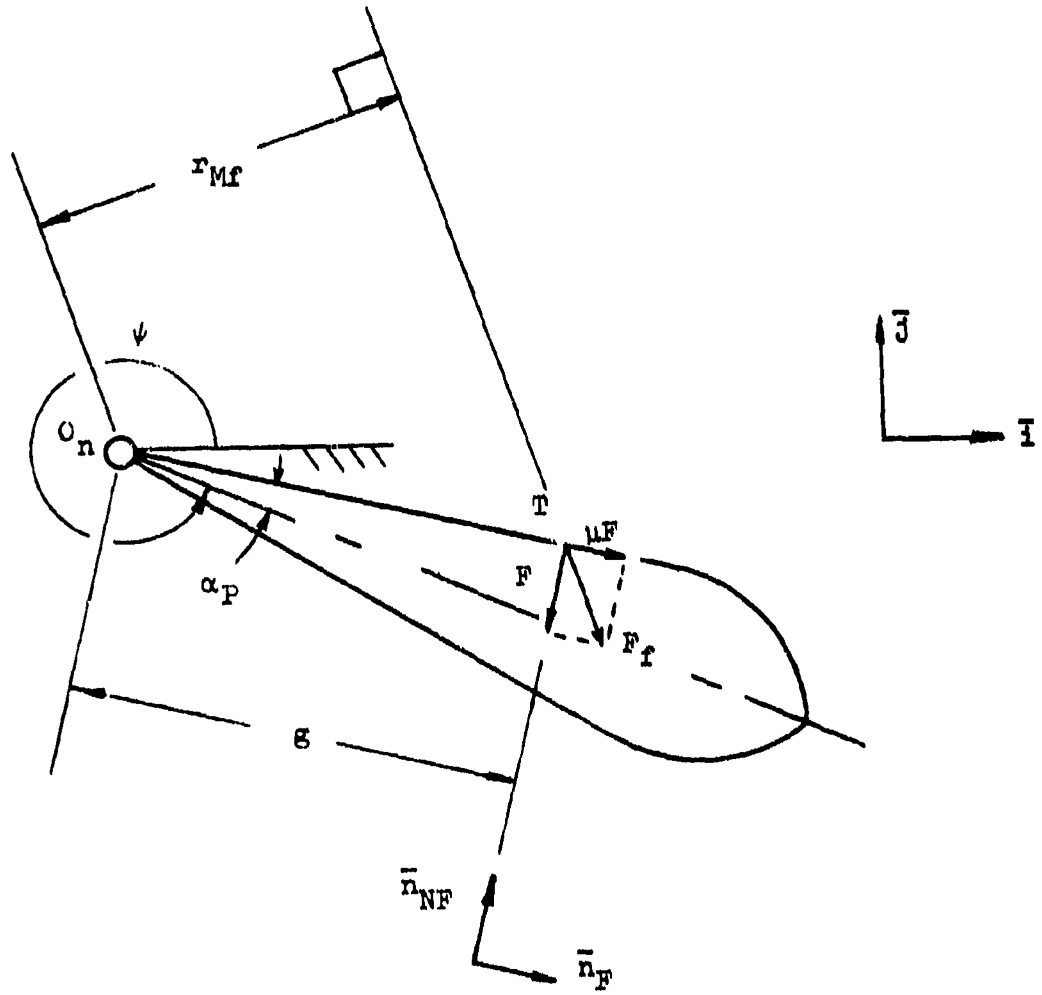

Figure 4. Position of line of action of force of gear on pinion in round on flat phase of motion of clock gear mesh

meshes show centerline contact during the round on round phase of motion, the derivation for the distance of the line of action from the pinion pivot must use the round on round parameters of equations 19 and 20.

With $\bar{V}_{S/T} = 0$, the friction component μF vanishes and the normal force F becomes the resultant force of the gear on the pinion (fig. 3). The normal distance r_{Mp} of force F from the pinion pivot may be obtained by setting $\mu = 0$ in equation 20. This furnishes

$$r_{Mp} = a_p \sin (\lambda - \psi + \delta_p) \tag{23}$$

As previously, the absolute value of r_{Mp} is desired.

Comparison of Line of Action Distances r_M for Clock and Involute Type Meshes

Comparison of the distances of the lines of action of resultant forces of the gear on the pinion from the pinion pivots for comparable clock gear and involute type meshes which operate with coefficients of friction of 0.1 and 0.8 is shown in table 7.

The gear and pinion sets are those described in the section on single pass step-up gear meshes with involute and clock gear type teeth and which form the bases of tables 3 and 4. Both have a diametral pitch of 44 and the numbers of the teeth of the gears and the pinions are 48 and 8, respectively.

The computations for the involute gear mesh are based on equations 14, 16, and 18. Specific parameters for the evaluation of these expressions are as follows:

$$r_b = r_p \cos\theta = 0.09091 \cos 20 = 0.08543 \text{ in. } (0.2170 \text{ cm})$$

$$d = (R_b + r_b)\tan\theta = (0.51255 + 0.08543) \tan 20$$

$$= 0.21764 \text{ in. } (0.5528 \text{ cm})$$

The distances a_a and a_r are computed with the help of equation A-203 (ref 1), i.e.,

$$a_a, a_r = R_b \alpha \tag{24}$$

Table 7 Comparison of line of action distances r_M for clock gear and involute meshes

Contact angle (deg)	Distance r_M for μ = 0.1				Distance r_M for μ = 0.8			
	Clock mesh		Involute mesh		Clock mesh		Involute mesh	
	In. (cm)	Eq no.	In. (cm)	Eq no.	In. (cm)	Eq no.	In. (cm)	Eq no.
0.00	0.0864 (0.2195)	20	0.0781 (0.1984)	14	0.0523 (0.1328)	20	0.0235 (0.0597)	14
0.90	0.0883 (0.2243)	20	0.0789 (0.2004)	14	0.0589 (0.1496)	20	0.0286 (0.0726)	14
1.80	0.0891 (0.2263)	20	0.0797 (0.2024)	14	0.0640 (0.1626)	20	0.0336 (0.0853)	14
1.80	Pitch point 0.0907 (0.2304)	23	(*)		Pitch point 0.0907 (0.2304)	23	(*)	
1.95	0.0911 (0.2313)	20	0.0798 (0.2029)	14	0.0768 (0.1951)	20	0.0334 (0.0848)	14
3.30	0.0889 (0.2259)	20	0.0810 (0.2057)	14	0.0700 (0.1778)	20	0.0420 (0.1067)	14
3.45	0.0885 (0.2248)	22	0.0812 (0.2062)	14	0.0694 (0.1763)	22	0.0428 (0.1087)	14
4.244	(*)		Pitch point 0.0854 (0.2169)	16	(*)		Pitch point 0.0854 (0.2169)	16
4.39	(*)		0.0879 (0.2233)	18	(*)		0.0853 (0.2167)	18
6.90	0.0802 (0.2037)	22	0.0861 (0.2187)	18	0.0634 (0.1610)	22	0.0712 (0.1808)	18
7.35	0.0809 (0.2055)	22	0.0853 (0.2167)	18	0.0635 (0.1613)	22	0.0687 (0.1745)	18

* = not computed

The angle α for any position of the involute mesh may be obtained from table 3. What is referred to as contact angle in table 7 is obtained from the formulation

$$\text{Contact angle} = \alpha - 16.61^\circ \tag{25}$$

where 16.61° represents the earliest possible contact angle of the involute mesh. The total angle of rotation of the gear for one cycle of contact is obtained from the difference between the initial and final angles, i.e., 23.96° - 16.61° = 7.35°. By way of the change of sign of the signum parameter, the pitch point contact for this mesh occurs between α = 20.81° and 20.96° (table 3). A more precise computation, according to equation A-216 (ref 1), gives the value of 20.854° for this angle.

The computations for the clock gear mesh are based on equation 20 for the round on round phase of motion and on equation 22 for the round on flat phase. The pitch point computations, i.e., when the contact points are located on the line of centers, make use of equation 23.

Table 4 furnishes the following required parameters:

a_P = 0.09083 in. (0.2307 cm)

ρ_P = 0.01591 in. (0.0404 cm)

δ_P = 2.524°

In addition, table 4 shows that round on round contact starts when ϕ = 176.2813° and that contact coincides with the line of centers shortly after ϕ = 178.0813°. The latter is indicated by the change of sign of the signum parameter s_R. The round on flat phase of the motion begins at ϕ = 179.7313° and ends at ϕ = 183.6313°.

Similar to equation 25, the contact angle for the clock gear mesh is determined by way of

$$\text{Contact angle} = \phi - 176.2813^\circ \tag{26}$$

The total angle of rotation of the gear for one contact cycle is again 7.35°. The values of the variables ψ, s_R and g, which are needed for the various computations, may also be found in table 4. The necessary values of the angle λ are shown in table 8.

Table 8. Angles ψ (PSID) and λ (LAMDAD) as functions of angle ϕ(PHID) for same clock gear mesh of table 2

φ	ψ	λ
PHID = 176.2813	PSID = 3.5016	LAMDAD = 262.9153
PHID = 176.4313	PSID = 2.5994	LAMDAD = 263.0789
PHID = 176.5813	PSID = 1.6993	LAMDAD = 263.2192
PHID = 176.7313	PSID = .8008	LAMDAD = 263.3363
PHID = 176.8813	PSID = 359.9038	LAMDAD = 263.4303
PHID = 177.0313	PSID = 359.0078	LAMDAD = 263.5013
PHID = 177.1813	PSID = 358.1125	LAMDAD = 263.5493
PHID = 177.3313	PSID = 357.2178	LAMDAD = 263.5744
PHID = 177.4813	PSID = 356.3235	LAMDAD = 263.5767
PHID = 177.6313	PSID = 355.4291	LAMDAD = 263.5561
PHID = 177.7813	PSID = 354.5347	LAMDAD = 263.5126
PHID = 177.9313	PSID = 353.6400	LAMDAD = 263.4462
PHID = 178.0813	PSID = 352.7449	LAMDAD = 263.3570
PHID = 178.2313	PSID = 351.8491	LAMDAD = 263.2448
PHID = 178.3813	PSID = 350.9527	LAMDAD = 263.1097
PHID = 178.5313	PSID = 350.0555	LAMDAD = 262.9516
PHID = 178.6813	PSID = 349.1574	LAMDAD = 262.7705
PHID = 178.8313	PSID = 348.2583	LAMDAD = 262.5662
PHID = 178.9813	PSID = 347.3583	LAMDAD = 262.3389
PHID = 179.1313	PSID = 346.4573	LAMDAD = 262.0885
PHID = 179.2813	PSID = 345.5552	LAMDAD = 261.8148
PHID = 179.4313	PSID = 344.6522	LAMDAD = 261.5180
PHID = 179.5813	PSID = 343.7482	LAMDAD = 261.1980

The specific choices of the contact angles in table 7 are based on the various regime changes. Thus,

C.A. = 0°	represents initial contact
C.A. = 1.80°	represents near pitch point contact for the clock gear mesh. (Both equations 20 and 23 are evaluated with the associated data.)
C.A. = 3.45°	represents the beginning of the round on flat phase of the motion of the clock gear mesh.
C.A. = 4.244°	represents pitch point contact for the involute mesh.
C.A. = 6.90°	represents contact at the minimum of the distance g for the clock gear mesh.
C.A. = 7.35°	represents final contact for both meshes.

Computations are omitted whenever no significant changes occur.

Conclusions of Comparison of Distances r_M

The results of table 7 were used to show that the differences in point efficiencies between clock gear and involute meshes, for a given coefficient of friction, are reflections of the associated differences in the magnitudes of the distances r_M.

1. Just as the point efficiency at initial contact is higher for the clock gear mesh than for the involute, regardless of coefficient of friction, the distance r_M is also always larger for the clock mesh at that instant. This difference in magnitude becomes more pronounced as the coefficient of friction is increased.

2. The magnitude of r_M increases after the initial contact in both types of meshes until the pitch point is reached, or until shortly after the pitch point is passed. Parallel increases of point efficiencies, with maxima at or soon after the pitch point may be found in tables 3 and 4.

3. At the pitch point, r_M is independent of the coefficient of friction. The associated value of r_M is somewhat larger for the clock gear mesh. The pitch point is reached after 1.80° of gear rotation, after initial contact, in the clock gear mesh of table 7, while 4.24° of gear rotation for the involute mesh is required. Thus, the angle of approach of the clock mesh is considerably smaller.

4. Just as the point efficiencies of both meshes decrease steadily after the maxima have been reached, there is a continuous decrease in the magnitudes of the associated r_M. For a given coefficient of friction, this decrease is smaller for the involute mesh.

Since, according to equation 22, r_M is proportional to the round on flat phase distance g near the end of contact, the above efficiency decrease may possibly be controlled by increasing the minimum value of g by an appropriate redesign of the tooth.

Any change in geometry which increases the magnitude of the distance r_M will also increase the point efficiency of the mesh.

EFFICIENCY COMPARISONS BETWEEN INVOLUTE AND CLOCK GEAR TYPE TWO AND THREE PASS STEP-UP TRAINS WITH AND WITHOUT SPIN

The physical configurations and the associated analyses are those of the FGTA (ref 1). The two pass and three pass configurations are shown in figures 5 and 6, respectively.

The point efficiency computations for the involute tooth type trains were obtained with the help of programs INVOL3 and INVOL4. The programs CLOCK3 and CLOCK4 supplied the point efficiencies of the clock tooth type trains.

As discussed earlier, the above programs were modified by the introduction of the initialization parameters J_i. These parameters make it possible to vary the initial points of contact of the individual meshes, and with that allow the determination of that starting configuration of a given train which results in the lowest point efficiency. Investigation showed that the worst starting condition for an involute tooth type train occurs when all meshes make their initial contact at the earliest possible point during approach motion. For clock tooth type trains the worst starting condition is associated with a configuration where all meshes have their motion initiated as late as possible during recess motion. (This has been shown to be true for single pass meshes in the section entitled Efficiency Comparisons between Involute and Clock Gear Type Single Pass Step-up Gear Trains.)

The involute as well as the clock tooth type two pass step-up gear trains were designed with a step-up ratio of 47.265 in order to be comparable to the three pass trains which have a step-up ratio of 47.25 and whose configurations are identical with that of the M125A1 (brass) safing and arming mechanism.

The essential parameters of all fuze gear trains and the specific conditions of the associated computer programs follow. Subsequently, the results of the efficiency comparisons are shown in table 9 and figure 7.

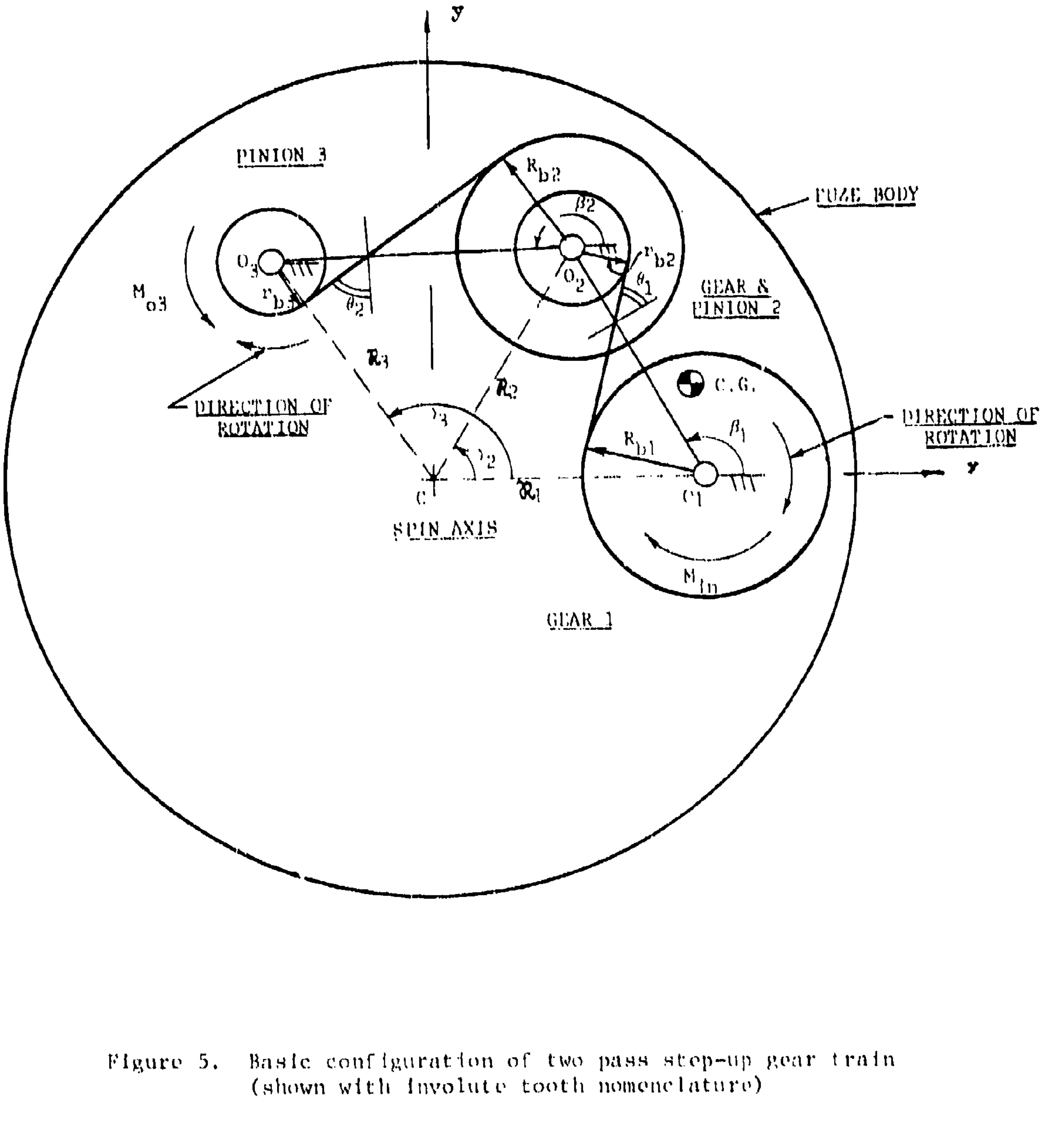

Figure 5. Basic configuration of two pass step-up gear train (shown with involute tooth nomenclature)

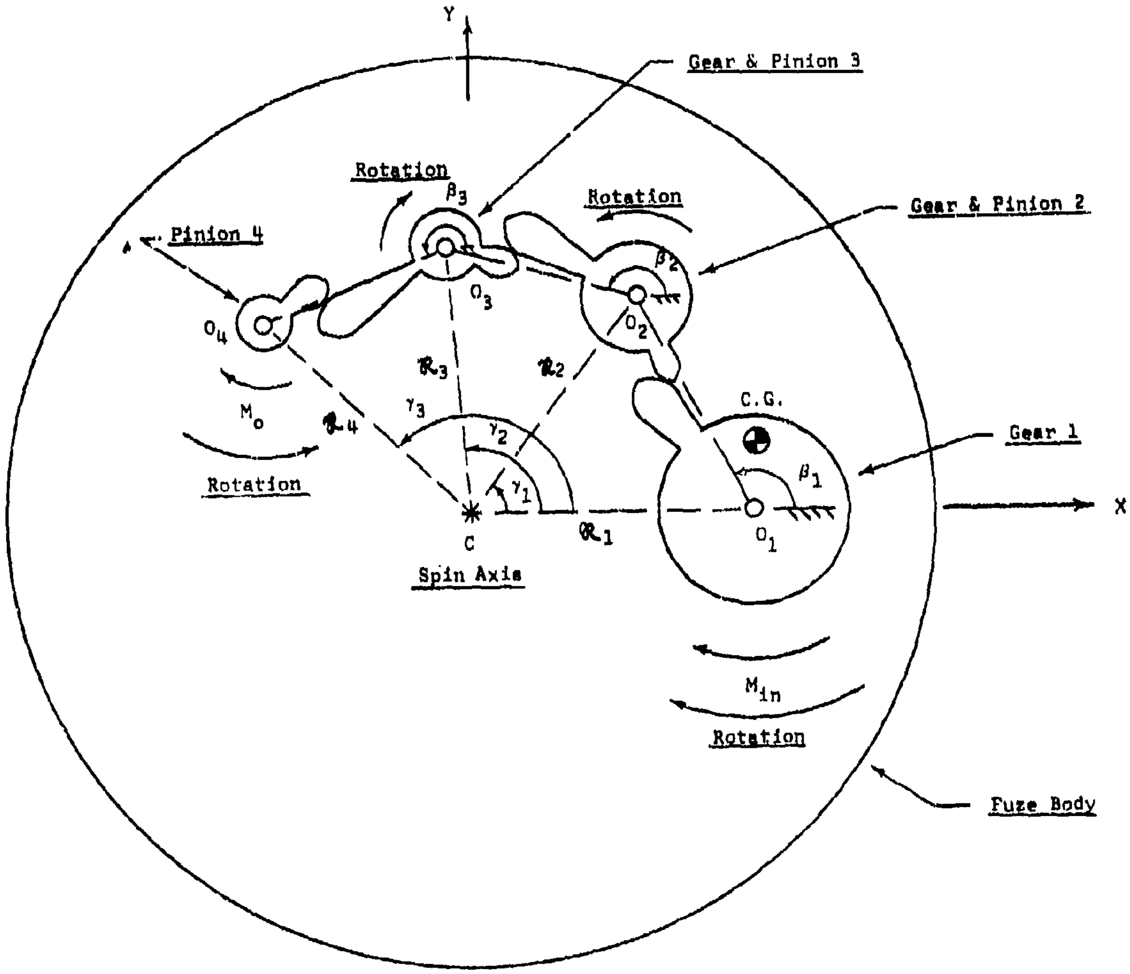

Figure 6. Basic configuration of three pass step-up gear train (shown with clock gear teeth)

Table 9. Step-up gear train comparisons with and without spin*

Number and type	Two step-up mesh efficiency: Initial contact point (ϵ_p)	Maximum point (ϵ_p)	Minimum point (ϵ_p)	Three step-up mesh efficiency: Initial contact point (ϵ_p)	Maximum point (ϵ_p)	Minimum point (ϵ_p)
1. Involute, no spin	0.618	0.787	0.618	0.507	0.708	0.507
2. Involute with spin	0.314	0.440	0.314	0.320	0.481	0.320
3. Clock, no spin	0.611	0.794	0.600	0.499	0.699	0.489
4. Clock with spin	0.319	0.448	0.316	0.320	0.476	0.315

* All have worst possible starting condition.

1. Two Pass Step-up Gear Trains (Fig. 5)

The common parameters of both the involute and the clock type two pass gear trains are listed below. Those parameters and program details which are specific to either one of the trains are discussed separately.

Mesh No. 1 (gear 1 and pinion 2)

P_{d1} = 50, diametral pitch

N_{G1} = 55, number of teeth of gear 1

N_{P2} = 8, number of teeth of pinion 2

R_{p1} = 0.550 in. (1.397 cm), pitch radius of gear 1

r_{p2} = 0.080 in. (0.203 cm), pitch radius of pinion 2

Mesh No. 2 (gear 2 and pinion 3)

P_{d2} = 70, diametral pitch

N_{G2} = 55, number of teeth of gear 2

N_{P3} = 8, number of teeth of pinion 3

R_{p2} = 0.39286 in. (0.9979 cm), pitch radius of gear 2

r_{p3} = 0.05714 in. (0.1451 cm), pitch radius of pinion 3

Further Common Parameters

m_1 = 0.12 x 10^{-3} lb-sec^2/in. (2.101 x 10^{-2} kg), mass of gear 1

m_2 = 0.253 x 10^{-4} lb-sec^2/in. (4.430 x 10^{-3} kg), mass of gear and pinion 2

m_3 = 0.153 x 10^{-5} lb-sec^2/in. (2.679 x 10^{-4} kg), mass of pinion 3

ρ_1 = 0.062 in. (0.157 cm), pivot radius of gear 1

ρ_2 = 0.025 in. (0.064 cm), pivot radius of gear and pinion 2

ρ_3 = 0.018 in. (0.046 cm), pivot radius of pinion 3

$\mathcal{R}_1$ = 0.225 in. (0.572 cm), location of gear 1 from fuze body center

$\mathcal{R}_2$ = 0.497 in. (1.262 cm), location of gear and pinion 2 from fuze body center

R_3 = 0.640 in. (1.626 cm), location of pinion 3 from fuze body center

$md^2 = 0.275 \times 10^{-5}$ lb-sec^2-in. (3.105×10^{-7} kg-m^2), the rotor parameter product of gear 1, responsible for input moment M_{in} in inch pounds when the quantity is multiplied by the square of the spin angular velocity.

Parameters and Computational Details Specific to the Involute Tooth Type Two Pass Step-up Gear Train

The gear and pinion parameters which are specific to the two meshes of the involute two pass gear train are listed in appendix B. They are also shown in appendix B as the output listings of program INVOL1, which computes the dimensions of involute meshes with unequal addenda and unity contact ratio. (See reference 1 for program listing and discussion.)

Point efficiency results of two computer runs for two pass involute trains are shown in table 9. Both runs were made with program INVOL4. Run A-1 simulates zero spin velocity, while run A-2 was made for 1000 rpm. An overall coefficient of friction of $\mu = 0.2$ and a range divisor $K = 25$ were used for both runs. (See appendix B for an explanation concerning the range divisor.) To get the lowest possible starting point efficiency, the initialization parameters J_1 and J_2 were set equal to zero. For these conditions both meshes make initial contact at the beginning of their approach motion. To obtain run A-1, which simulates zero spin and with that the absence of any centrifugal forces on the train components, program INVOL4 was modified by introducing the input moment M_{in}, equal in magnitude to one corresponding to a spin of 1000 rpm.[3] The output of run A-2 is reproduced in appendix B. The output of run A-1 is not given.

Parameters and Computational Details Specific to the Clock Tooth Type Two Pass Step-up Gear Train

The gear and pinion parameters which are specific to the two meshes of the clock tooth type gear train are listed in appendix E. These parameters were obtained with the help of the computer program BRITSTD, which is shown and discussed in appendix C.

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[3]This moment is given by

$$M_{in} = md^2\omega^2 = 0.275 \times 10^{-5} \left(\frac{1000 \times 2\pi}{60}\right)^2$$

$$= 0.30157 \times 10^{-1} \text{ in.-lb } (0.34073 \times 10^{-2} \text{ N.m})$$

Point efficiency results of two computer runs for two pass clock trains are given in table 9. Results for both runs were obtained with the help of the computer program CLOCK4. Run A-3 was made for zero spin, while run A-4 simulates a spin of 1000 rpm. Again, an overall coefficient of friction $\mu = 0.2$ and a range divisor $K = 25$ were used. Since the lowest starting efficiency for this type of gear train is obtained when both meshes make initial contact at the end of recess motion, the initialization parameters J_1 and J_2 were both set equal to 0.9 for these runs. While run A-3 is not shown in this report, the complete output listing of run A-4 is reproduced in appendix E. To obtain run A-3, which simulates zero spin, the input moment was again directly introduced into program CLOCK4 in the manner discussed earlier in connection with the two pass involute train.

2. Three Pass Step-up Gear Trains

As stated before, the basic configuration of both types of three pass step-up gear trains was taken from that of the M125A1 (brass) safing and arming mechanism. The following first enumerates all parameters which are common to both the involute and the clock tooth type gear trains. Subsequently, those parameters and computational details which are specific to either of the two are discussed separately.

Mesh No. 1 (gear 1 and pinion 2)

$P_{d1} = 44$, diametral pitch

$N_{G1} = 42$, number of teeth of gear 1

$N_{P2} = 8$, number of teeth of pinion 2

$R_{p1} = 0.47727$ in. (1.2123 cm), pitch radius of gear 1

$r_{p2} = 0.09091$ in (0.2309 cm), pitch radius of pinion 2

Mesh No. 2 (gear 2 and pinion 3)

$P_{d2} = 65$, diametral pitch

$N_{G2} = 27$, number of teeth of gear 2

$N_{P3} = 9$, number of teeth of pinion 3

$R_{p2} = 0.20769$ in. (0.5275 cm), pitch radius of gear 2

$r_{p3} = 0.06923$ in. (0.1758 cm), pitch radius of pinion 3

Mesh No. 3 (gear 3 and pinion 4)

P_{d3} = 77, diametral pitch

N_{G3} = 27, number of teeth of gear 3

N_{p4} = 9, number of teeth of pinion 4

R_{p3} = 0.17532 in. (0.4453 cm), pitch radius of gear 3

r_{p4} = 0.05844 in. (0.1484 cm), pitch radius of pinion 4

Further Common Parameters

m_1 = 0.12×10^{-3} lb-sec²/in. (2.101×10^{-2} kg), mass of gear 1

m_2 = 0.85×10^{-5} lb-sec²/in. (1.488×10^{-3} kg), mass of gear and pinion 2

m_3 = 0.34×10^{-5} lb-sec²/in. (5.953×10^{-4} kg), mass of gear and pinion 3

m_4 = 0.15×10^{-5} lb-sec²/in. (2.626×10^{-4} kg), mass of pinion 4

ρ_1 = 0.062 in. (0.157 cm), pivot radius of gear 1

ρ_2 = 0.025 in. (0.064 cm), pivot radius of gear and pinion 2

ρ_3 = 0.018 in. (0.046 cm), pivot radius of gear and pinion 3

ρ_4 = 0.016 in. (0.041 cm), pivot radius of pinion 4

$\mathcal{R}_1$ = 0.225 in. (0.572 cm), location radius of gear 1 from fuze body center

$\mathcal{R}_2$ = 0.436 in. (1.107 cm), location radius of gear and pinion 2 from fuze body center

$\mathcal{R}_3$ = 0.504 in. (1.280 cm), location radius of gear and pinion 3 from fuze body center

$\mathcal{R}_4$ = 0.520 in. (1.321 cm), location radius of pinion 4 from fuze body center

md^2 = 0.275×10^{-5} lb-sec²-in. (3.105×10^{-7} kg-m²), rotor parameter of gear 1, responsible for input moment M_{in}. This quantity becomes in.-lb when multiplied by the square of the spin angular velocity.

Parameters and Computational Details Specific to the Involute Tooth Type Three Pass Step-up Gear Train

The gear and pinion parameters specific to the three pass involute step-up gear train are listed in appendix A. They were originally computed with program INVOL1 (appendix C of ref 1).

Point efficiency results of two computer runs for three pass involute trains are shown in table 9. Results for both runs were obtained with the help of the computer program INVOL3. Run B-1 simulates zero spin velocity, while run B-2 was made for a spin velocity of 1000 rpm. An overall coefficient of friction $\mu = 0.2$ and a range divisor $K = 25$ were used for both runs. Since the lowest starting efficiency for this type of gear train occurs when all three meshes make initial contact as early as possible during their approach motion, the initialization parameters J_1, J_2 and J_3 were set equal to zero. To obtain run B-1, which simulates zero spin and with that the absence of centrifugal forces on the gear train components, the computer program INVOL3 was also modified by introducing an input moment M_{in} equal in magnitude to a moment which corresponds to a spin of 1000 rpm.

The output listing of run B-2 is reproduced in appendix A. The output listing of run B-1 is not given.

Parameters and Computational Details Specific to the Clock Tooth Type Three Pass Step-up Gear Train

The gear and pinion parameters of the three meshes of the three pass clock step-up gear train are listed in appendix D. These parameters were computed with the help of computer program BRITSTD (appendix C).

Point efficiency results of two computer runs for three pass clock trains are shown in table 9. Results for both runs were obtained by way of the computer program CLOCK3. Run B-3 was made for zero spin, while run B-4 simulates a spin of 1000 rpm. Again, an overall coefficient of friction $\mu = 0.2$ and a range divisor $K = 25$ are used. Since clock type three pass step-up trains experience the lowest point efficiency at starting when all three meshes make initial contact at the end of their recess motion, the initialization parameters J_1, J_2 and J_3 were set equal to 0.9 for both runs. To obtain run B-3, which simulates zero spin, the input moment M_{in} was again modified in the manner described above for the three pass involute train. The computer output listing of run B-4 is reproduced in appendix D. The output of run B-3 is not given.

3. Conclusions of Efficiency Comparisons and Discussion

Initial contact, maximum and minimum point efficiencies during one tooth cycle of the input gear for two and three pass step-up meshes, with involute and clock type teeth, which operate with or without the presence of spin, are shown in table 9. Graphs of point efficiency versus input gear rotation in a spin environment for the four types of gear trains are shown in figure 7. In each case one tooth cycle of the input gear is shown, using the data in appendixes A, B, D and E (i.e., from computer programs INVOL3, INVOL4, CLOCK3, and

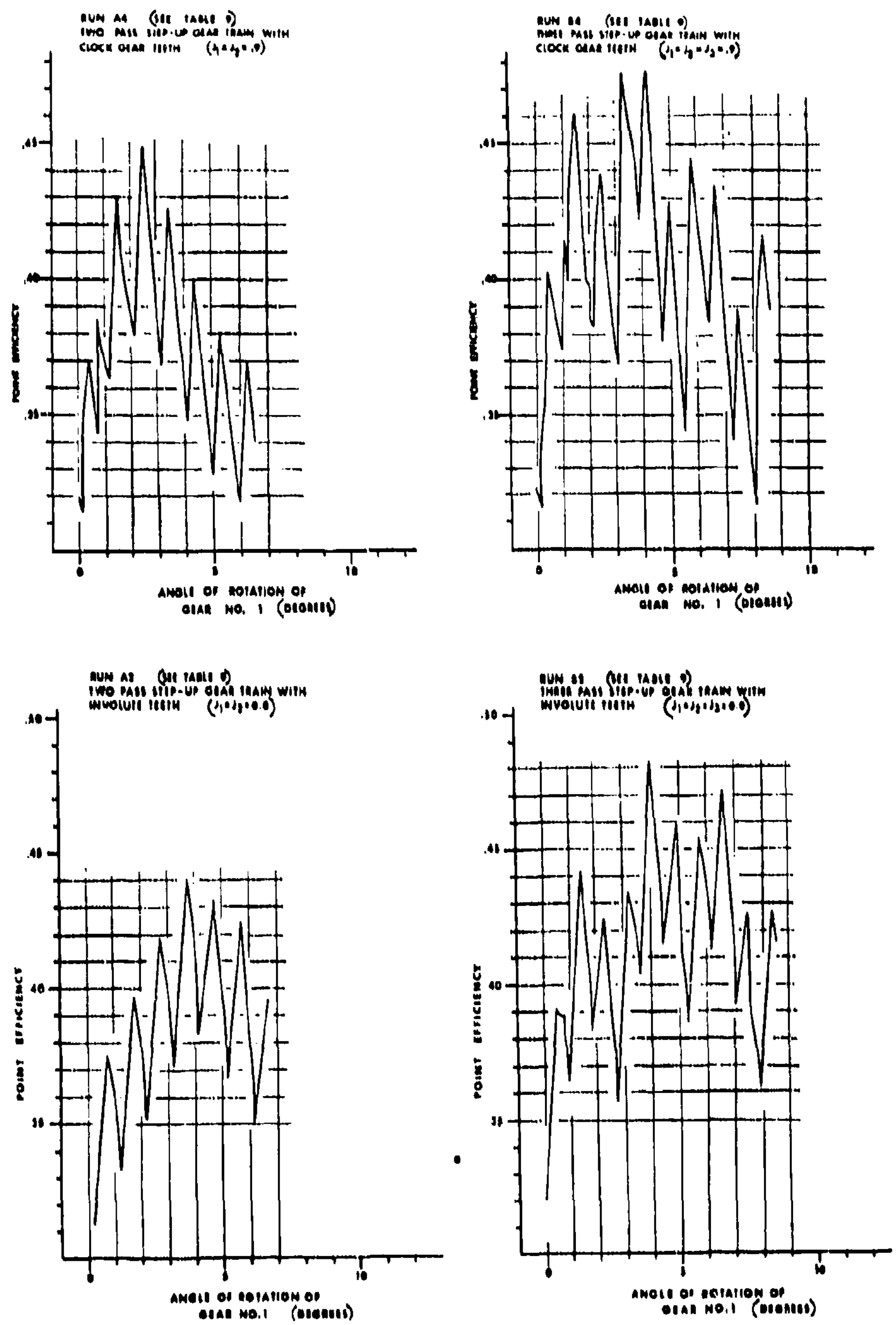

Figure 7. Point efficiencies of two and three pass step-up gear trains in a spin environment for one tooth cycle of the input gear

CLOCK4). All input gear rotation data are adjusted to a zero degree start by subtracting the initial angle in each case.

Subsequently, general factors which influence the point efficiency in multipass step-up gearing are discussed. In addition, an explanation is given for the fact that the mid-cycle efficiencies of the three pass meshes are somewhat higher than those of the two pass meshes when both operate in a spin environment.

The point efficiency comparisons were obtained with the following conditions common to all over-all and component meshes:

a. The worst possible starting conditions were used for all component meshes ($J_1 = 0$, for the involute meshes, and $J_1 = 0.9$, for the clock gear meshes).

b. All meshes have essentially the same step-up ratio (47.265 for the two pass trains and 47.25 for the three pass trains).

c. When spin was simulated, the constant input moment used approximated the one produced by an appropriately sized rotor at a spin rate of 1000 rpm. For the no-spin runs, the identical constant input moment was used.

d. The same coefficient of friction, i.e., $\mu = 0.2$, was used for all meshes and conditions. It applies to pivot as well as to tooth contact friction.

e. All involute meshes have unity contact ratio. This also applies to clock type meshes since in this type of gearing there can never be more than one set of teeth in contact.

Overall Conclusions

The following conclusions were drawn from table 9 and figure 7:

1. For a given mesh and spin condition there is no significant difference in maximum and minimum point efficiencies for the types of involute and clock gearing used. (Compare runs A1 to A3, B1 to B3, A2 to A4, and B2 to B4.)

2. In the absence of spin the two pass step-up meshes show higher maximum and minimum point efficiencies than the three pass meshes. (Compare runs A1 and B1 as well as runs A3 and B3.)

3. While it is somewhat surprising that there is no difference between the initial contact, i.e., minimum, point efficiencies of two and three pass gear trains operating in a spin environment, it is even more surprising that the maximum efficiencies of the three pass trains are somewhat higher than those of the two pass trains. (Compare runs A2 and B2 as well as runs A4 and B4 in table 9.)

The average point efficiency of the three pass gear trains is higher (fig. 7). This fact is reflected by the somewhat higher cycle efficiencies of the three pass trains. (For a definition of the cycle efficiency ε_C see equation 4, [ref 1.]) The following values for the various cycle efficiencies are listed at the end of the computer outputs in the previously mentioned appendixes:

two pass involute: $\varepsilon_C = 0.385$, three pass involute: $\varepsilon_C = 0.414$

two pass clock: $\varepsilon_C = 0.379$, three pass clock: $\varepsilon_C = 0.404$

These lower efficiencies of the two pass trains have their cause in the need for a heavier gear in the second mesh of these trains. This causes a larger centrifugal force and with that a larger referred pinion friction moment than is the case for the three pass trains. (For detail see the discussion in the section entitled Explanation of Higher Efficiencies of Three-Pass Trains.)

The graphs of the two pass trains show the multiple cyclic variations in point efficiency of the second mesh superposed on the single cycle of point efficiency of the first mesh. Similar superpositions of mesh point efficiencies may be observed in the graphs of the three pass trains.

A decrease in the amplitudes of all cyclic variations, based on geometrical rather than frictional modifications, represents a meaningful optimization goal for this type of gear train (fig. 7). This might be facilitated by decreasing the approach action of all involute meshes as much as possible, while maintaining at least a unity contact ratio.

General Factors which Influence the Point Efficiencies of Multipass Step-up Gear Meshes

To understand the factors which determine the point efficiencies of multipass step-up trains, one must consider the general form which the associated expression takes with or without the presence of spin.

Equation 3 of reference 1 defines point efficiency as

$$\varepsilon_p = K_{RATIO} \frac{M_o}{M_{in}} \tag{27}$$

where

K_{RATIO} = instantaneous angular velocity ratio of the output pinion to the input gear

M_o = the instantaneous output equilibrant moment

M_{in} = the instantaneous input moment

The output moment expression for the various meshes and contact conditions was shown in reference 1 to be of the form[4]

$$M_o = K_{in} M_{in} - \sum K_i \omega^2 \tag{28}$$

where

K_{in} = a constant for a given train configuration which depends on various geometric parameters associated with the gears and pinions of the train. In addition it is a function of the tooth geometry, the pivot locations, the pivot radii, and the overall coefficient of the friction.

K_i = constants which are dependent on the same parameters as K_{in}. In addition they are functions of the individual gear or gear and pinion masses m_i. ($i = 1, 2, 3$ for two pass meshes, while for three pass meshes $i = 1, 2, 3, 4$.)

ω = the constant angular velocity of the fuze body.

For a rotor driven mechanism, with constant spin velocity, the input moment M_{in} has the form

$$M_{in} = m_1 \mathcal{R}_1 r_c \ \omega^2 \sin\alpha \tag{29}$$

where

m_1 = mass of the rotor, i.e., of gear 1

$\mathcal{R}_1$ = distance from spin axis to rotor pivot axis

r_c = distance of rotor center of mass from rotor pivot axis

α = rotor angle with respect to fuze body

Substitution of equations 28 and 29 into equation 27, followed by some rearrangement of terms, gives the following expression for the point efficiency of spin rotor driven gear meshes:

$$\varepsilon_p = K_{RATIO} \left(K_{in} - \frac{\sum K_i}{K_{in} m_1 \mathcal{R}_1 r_c \sin\alpha} \right) \tag{30}$$

---

[4] See the following expressions in reference 1: A-125, A-193, H-81, H-118, H-158, H-180, H-216, H-218, H-239, H-241, H-260, H-261, H-277, and H-278.

Equation 30 shows that the point efficiency is independent of spin velocity. It may be maximized for a given configuration by making the constant K_{in} together with the denominator of the second term inside the parenthesis as large as possible, while keeping the summation term as small as possible.

No conclusions concerning the influence of the angular velocity ratio K_{RATIO} on the point efficiency may be drawn since the terms inside the parenthesis are also related to various gear ratios.

In case these types of gear trains operate without spin and the input moment is supplied by a spring, equation 28 becomes

$$M_o = K_{in} M_{in} , \tag{31}$$

and the point efficiency expression (equation 27) reduces to

$$\epsilon_p = K_{RATIO} K_{in} \tag{32}$$

For a given velocity ratio of the train, the point efficiency can again be maximized by maximizing the constant K_{in}. This value is larger for a two pass configuration than for a three pass. (Refer to cases 1 and 3 of table 9.)

Explanation of Higher Efficiencies of Three-Pass Trains

The unexpectedly equal or higher point efficiencies of the three pass meshes, when compared with those of the two pass meshes, may be principally explained by the need for a larger pitch radius, and with that of a larger mass, for gear no. 2.[5] This larger mass, and the associated larger spin axis to pivot axis distance, causes a larger centrifugal force and with that a larger pivot friction moment than is the case for the comparable mesh of the three pass train with its lower step-up ratio. In addition, the increased step-up ratio contributes to the decrease in the available input moment. (See discussion concerning referred friction moments below.)

The above is best illustrated by comparing the sums of the individual pivot friction moments due to centrifugal forces only, as referred to the input gear, for both types of gear trains.

[5]Every effort was made during the design of the two pass train to keep the gear and pinion masses, together with the spin axis to pinion axis distance, as small as possible (table 10).

If the friction moment on an individual gear and, or, pinion is given by M_{fi}, the referred friction moment M_{f1i}, acting on the input gear, may be found by way of the principle of virtual work from

$$M_{f1i} = M_{fi} \dot{\phi}_i/\dot{\phi}_1 \quad (33)$$

where

$\dot{\phi}_i/\dot{\phi}_1$ = angular velocity ratio between the ith gear and, or, pinion and gear no. 1 (Average values must be used for clock type gears.)

i = the gear or pinion number. For the two pass train $i = 1, 2, 3$ and for the three pass train $i = 1, 2, 3, 4$.

The friction moment due to the centrifugal force only on any individual component is given by

$$M_{fi} = m_i \delta\ell_i \rho_i \mu\omega^2 \quad (34)$$

where

m_i = mass of individual component

$\delta\ell_i$ = distance from spin axis to individual pivot axis

ρ_i = individual pivot radius

μ = coefficient of friction

The parameters of equations 33 and 34 together with the referred moments M_{f1i} for both types of gear trains are listed in table 10. The sum of the referred friction moments is higher for the two pass meshes than for the three pass meshes, and thus represents a greater reduction of the identical input moment. For a spin rate of 1000 rpm and a coefficient of friction of $\mu = 0.2$, these friction moments become 1.02×10^{-2} and 0.71×10^{-2} in.-lb, respectively. This shows a considerable increase of friction for the two pass train if one considers that the input moment M_{in} has a magnitude of 3.01×10^{-2} in.-lb. (See data printouts in the various computer programs in the appendixes.)

Table 10. Comparison of referred friction moments

Parameter	Two pass train	Three pass train
$\mathcal{R}_1$	0.225 in. (0.572 cm)	0.225 in. (0.572 cm)
$\mathcal{R}_2$	0.497 (1.262)	0.436 (1.107)
$\mathcal{R}_3$	0.640 (1.626)	0.504 (1.280)
$\mathcal{R}_4$	-	0.520 (1.321)
m_1	0.120×10^{-3} lb-s^2/in. (2.101×10^{-2} kg)	0.120×10^{-3} lb-s^2/in. (2.101×10^{-2} kg)
m_2	0.253×10^{-4} (4.430×10^{-3})	0.850×10^{-5} (1.488×10^{-3})
m_3	0.153×10^{-5} (2.679×10^{-4})	0.340×10^{-5} (5.953×10^{-4})
m_4	-	0.150×10^{-5}) (2.62×10^{-4})
ρ_1	0.062 in. (0.157 cm)	0.062 in. (0.157 cm)
ρ_2	0.025 (0.064)	0.025 (0.064)
ρ_3	0.018 (0.046)	0.018 (0.046)
ρ_4	-	0.016 (0.041)
$\dot{\phi}_2/\dot{\phi}_1$	6.875	5.25
$\dot{\phi}_3/\dot{\phi}_1$	47.265	15.75
$\dot{\phi}_4/\dot{\phi}_1$	-	47.25
M_{f11}	$1.674 \times 10^{-6}\ \mu\omega_2^2$ in.-lb ($0.189 \times 10^{-6}\ \mu\omega^2$ (N.m)	$1.674 \times 10^{-6}\ \mu\omega_2^2$ in.-lb ($0.189 \times 10^{-6}\ \mu\omega^2$ (N.m)
M_{f12}	$21.61 \times 10^{-7}\ \mu\omega_2^2$ ($0.244 \times 10^{-6}\ \mu\omega^2$)	$4.864 \times 10^{-7}\ \mu\omega^2$ ($0.550 \times 10^{-7}\ \mu\omega^2$)
M_{f13}	$8.331 \times 10^{-7}\ \mu\omega^2$ ($0.941 \times 10^{-7}\ \mu\omega^2$)	$4.858 \times 10^{-7}\ \mu\omega^2$ ($0.549 \times 10^{-7}\ \mu\omega^2$)
M_{f14}	-	$5.897 \times 10^{-7}\ \mu\omega^2$ ($0.666 \times 10^{-7}\ \mu\omega^2$)
Sum of referred Friction moments	$46.681 \times 10^{-7}\ \mu\omega^2$ ($5.275 \times 10^{-7}\ \mu\omega^2$)	$32.359 \times 10^{-7}\ \mu\omega^2$ ($3.657 \times 10^{-7}\ \mu\omega^2$)

REFERENCES

1. G.G. Lowen, City College of N.Y., and F.R. Tepper, ARRADCOM, "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

2. British Standard No. 978 for Gears for Instruments and Clockwork Mechanisms, Part 2, Cycloidal Type Gears (1952).

APPENDIX A

COMPUTER PROGRAM INVOL3 (REVISED)

The original program descriptions were given in appendix C of Fuze Gear Train Analysis (ref A-1). The present appendix contains revised descriptions, listings and sample outputs of computer program INVOL3, which computes point and cycle efficiencies for three pass involute gear trains in a spin environment. All meshes have unity contact ratio.

The following changes were made:

1. The diametral pitches of all three meshes are given as data and are printed in the output.

2. The numbers of teeth of all three meshes are given as data and are printed in the output.

3. The initialization parameters J (one for each mesh) are introduced. They are given as part of the data and are printed in the output. This parameter allows the initial point of contact of a given mesh to be chosen at an arbitrary point within the range of possible contact points.

4. The angles β (equations A-200 and A-202, ref A-1) are now printed out by the program in order to be able to judge the effects of various changes in the configuration of the gear train.

The computer program INVOL3 is based on the moment input-output relationship for a three pass step-up gear train operating in a spin environment. All meshes have unity contact ratio. The nomenclature of the program is chosen to coincide as closely as possible with that of the original derivations. The expressions for the contact geometry and other auxiliary geometric terms may be found in appendix A (ref A-1).

Input Parameters

The following parameters represent the input data for the program. Those which involve gear dimensions only must be obtained from the results of INVOL1 (ref A-1) since the moment expressions are derived for unity contact ratio only:

PSUBD1 = P_{d1}

PSUBD2 = P_{d2}

PSUBD3 = P_{d3}

NG1 = N_{G1}

NP2 = N_{P2}

NG2 = N_{G2}

NP3 = N_{P3}

NG3 = N_{G3}

NP4 = N_{P4}

MU = μ, coefficient of friction at all pivots and at all tooth contact points

RPM, revolutions per minute of the fuze body

CAPRP1 = R_{p1}

CAPRP2 = R_{p2}

CAPRP3 = R_{p3}

RP2 = r_{p2}

RP3 = r_{p3}

RP4 = r_{p4}

THETA1 = θ_1

THETA2 = θ_2

THETA3 = θ_3

ISTOP, arbitrary single digit integer for multiple data sets. It must be zero for last set of data.

R1 = $\mathcal{R}_1$

R2 = $\mathcal{R}_2$

R3 = $\mathcal{R}_3$

R4 = $\mathcal{R}_4$

RHO1 = ρ_1

RHO2 = ρ_2

RHO3 = ρ_3

RHO4 = ρ_4

CAPRB1 = R_{b1}

CAPRB2 = R_{b2}

CAPRB3 = R_{b3}

RB2 = r_{b2}

RB3 = r_{b3}

RB4 = r_{b4}

CAPRO1 = R_{o1}

CAPRO2 = R_{o2}

CAPRO3 = R_{o3}

RO2 = r'_{o2}

RO3 = r'_{o3}

RO4 = r'_{o4}

M1 = m_1, mass of input gear 1

M2 = m_2, mass of gear and pinion 2

M3 = m_3, mass of gear and pinion 3

M4 = M_4, mass of pinion 4

MD = md^2, mass-distance product contained in the expression for the input moment M_{in}

K = K_3, the range divisor which is associated with gear 3, the driving gear of the last mesh (eq. A-211, ref A-1)

J1, J2, J3, initialization parameters

Computations

Computation of MIN, GAMMAS and BETAS

To start with, the program computes the input moment

$$MIN = M_{in} = md^2\omega^2 \qquad (A-1)$$

Subsequently, the angles γ_2, γ_3, γ_4 and β_1, β_2, β_3 are established according to the expressions given in appendix A (ref A-1).

Determination of the Gear Train Constants

The determination of the gear train constants consists of the following:

RATIO = K_{RATIO} (eq 2, ref A-1). Since the angular velocity is constant, this parameter may be expressed in terms of the applicable base radii, i.e.,

$$\frac{R_{b1} \times R_{b2} \times R_{b3}}{r_{b2} \times r_{b3} \times r_{b4}}$$

TEST1, TEST2, and TEST3 represent the tangent functions of the mesh pressure angles, which are used in conjunction with the values of the signum functions s.

D1, D2, and D3 are given by equations A-204, A-217, and A-223, reference 1, respectively, and represent the distances between the points of tangency to the base circles along the lines of action of the three meshes.

MTOT = 0 represents the initialization of the sum of the output moments. This is used for the determination of the cycle efficiency.

Determination of Earliest and Latest Possible Values of ALPHAS, Initialization of ALPHAS. Centrifugual Forces

The determination of the earliest and latest possible angles of rotation is accomplished with the help of subroutine ALPHA, at the end of the program, which makes use of equations A-205, A-206, A-218, A-219, A-224, and A-225, reference A-1. The angles of initial contact α_i are determined with the help of the initialization parameters J_i according to:

$$\alpha_i = \alpha_{iIN} + J_i(\alpha_{iFIN} - \alpha_{iIN}) \quad (i=1,2,3) \qquad \text{(A-2)}$$

The additional parameter J_4 serves to distinguish between the two possible contact conditions of mesh no. 1. $J_4 = 0$ when the first set of teeth is in contact. $J_4 = 1$ when the latest possible value of α_1 has been reached and contact is transferred to the second set of teeth. $J_4 = 0$ at all times when $J_1 = 0$, i.e., contact is made in mesh no. 1 at the earliest possible point, and, therefore, contact need never be transferred to the second set of teeth to obtain a complete cycle (cards no. 116 and 131).

The angular increments of gears 3, 2, and 1, i.e., DELAL3, DELAL2, and DELAL1 are determined with the help of equations A-211 through A-213 (ref A-1), respectively.

The centrifugal forces, which act on the pivots of the various gear and/or pinion assemblies, are obtained by way of equations A-33, A-57, A-84, and A-107 (ref A-1).

Point and Cycle Efficiencies

Both point and cycle efficiencies are based on equations A-125 (ref A-1) for the output moment M04 = M_{o4}.

The point efficiency is computed directly in the manner of equation 3, (ref A-1) i.e.,

$$\varepsilon_\rho = K_{RATIO} \frac{M_{o4}}{M_{in}} = \text{POINTEF} \qquad \text{(A-3)}$$

The cycle efficiency is treated in the manner of equations C-8, (ref A-1), i.e.,

$$\varepsilon_p = \frac{K_{RATIO} \Delta\alpha_1 \Sigma M_{o4}}{M_{in} (\alpha_{1FIN} - \alpha_{1IN})} = \text{CYCLEFF} \qquad \text{(A-4)}$$

The program gives the summation as

$$\text{MTOT} = \Sigma M_{o4} \qquad \text{(A-5)}$$

Gear Train Motion Model

The simulation of the gear train motion, which is necessary for the computation of both POINTEF and CYCLEFF, is found in a loop which starts with statement label no. 14 (card no. 129) and ends with card no. 215. As discussed earlier, the motions of the individual driving gears are initialized with the help of the parameters J_1, J_2, and J3. The position of each mesh is subsequently incremented by the appropriate DELAL1, DELAL2, or DELAL3. Whenever the J_i's (i=1,2,3) are not equal to zero, and one of the angles α_{iFIN} has been reached, the particular mesh is reset to its respective angle α_{iIN}. Since mesh 2 and 3 go through numerous cycles while mesh 1 goes through one cycle, this type of resetting occurs many times (cards no. 129 and 130). When $J_1 = 0$, i.e., contact in mesh 1 is made at the earliest possible point, CYCLEFF is determined and the computation is ended once the angle AL1FIN - DELAL1 is reached. When $J_1 \neq 0$, the above occurs when ALPHA1 reaches the magnitude of its initial angle minus DELAL1. (The nature of the numerical integration requires that only K computations be included.)

The values of the signum functions s_1, s_2, and s_3 are determined continuously according to equations A-216, A-222, and A-227 (ref A-1).

The instantaneous distances to the contact points, i.e., A1 = a_1 and A2 = a_2, and A3 = a_3 are determined for each of the meshes by an appropriate adaptations of equation A-203 (ref A-1) (also eqs A-214, A-220, and A-226, ref A-1).

The determination of the instantaneous output moment M04 = M_{o4} requires the continuous computation of the variable quantities A_1 to A_{20}, C_1 to C_6 and D_1 to D_4, which are given originally in conjunction with the various equilibrium conditions in appendix A (ref A-1). The program uses the following nomenclature for these variables:

AA1 to AA20

CC1 to CC6

DD1 to DD4

Output

Again, the output of the program is best explained by means of the sample computation which is shown at the end of the program. This example uses the gear data of the first three sample computations of program INVOL1. The output lists the following:

Input Parameters

Mesh No. 1

CAPRP1 = R_{p1} = 0.47727 in. (1.2123 cm) PSUBD1 = P_{d1} = 44

CAPRB1 = R_{b1} = 0.44849 in. (1.13916 cm) NG1 = N_{G1} = 42

CAPRO1 = R_{o1} = 0.48791 in. (1.2393 cm) NP2 = N_{P2} = 8

RP2 = r_{p2} = 0.09091 in. (0.2309 cm) J1 = 0

RB2 = r_{b2} = 0.08543 in. (0.2170 cm)

RO2 = r'_{o2} = 0.11000 in. (0.2794 cm) (This is a ROFIN as given by INVOL1.)

Also,

THETA1 = θ_1 = 20°

Mesh No. 2

CAPRP2 = R_{p2} = 0.20769 in. (0.5275 cm) PSUBD2 = P_{d2} = 65

CAPRB2 = R_{b2} = 0.19517 in. (0.4957 cm) NG2 = N_{G2} = 27

CAPRO2 = R_{o2} = 0.21579 in. (0.5481 cm)   NP3 = N_{P3} = 9

RP3 = r_{p3} = 0.06923 in. (0.1758 cm)   J2 = 0

RB3 = r_{b3} = 0.06506 in. (0.1652 cm)

RO3 = r'_{o3} = 0.08089 in. (0.2055 cm)

Also

THETA2 = θ_2 = 20°

Mesh No. 3

CAPRP3 = R_{p3} = 0.17532 in. (0.4453 cm)   PSUBD3 = P_{d3} = 77

CAPRB3 = R_{b3} = 0.16475 in. (0.4183 cm)   NG3 = N_{G3} = 27

CAPRO3 = R_{o3} = 0.18216 in. (0.4627 cm)   NP4 = N_{P4} = 9

RP4 = r_{p4} = 0.05844 in. (0.1484 cm)   J3 = 0

RB4 = r_{b4} = 0.05492 in. (0.1395 cm)

RO4 = r'_{o4} = 0.06828 in. (0.1734 cm)

Also,

THETA3 = θ_3 = 20°

In addition,

MU = μ = 0.2

RPM = 1000

M1 = m_1 = 0.12×10^{-3} lb-sec^2/in. (2.101×10^{-2} kg)

M2 = m_2 = 0.85×10^{-5} lb-sec^2/in. (1.488×10^{-3} kg)

M3 = m_3 = 0.34×10^{-5} lb-sec^2/in. (5.952×10^{-4} kg)

M4 = m_4 = 0.15×10^{-5} lb-sec^2/in. (2.626×10^{-4} kg)

R1 = $\mathcal{R}_1$ = 0.225 in. (0.5715 cm)

R2 = $\mathcal{R}_2$ = 0.436 in. (1.1074 cm)

R3 = $\mathcal{R}_3$ = 0.504 in. (1.2802 cm)

R4 = $\mathcal{R}_4$ = 0.520 in. (1.3208 cm)

RHO1	= ρ_1	=	0.062 in. (0.1575 cm)
RHO2	= ρ_2	=	0.025 in. (0.0635 cm)
RHO3	= ρ_3	=	0.018 in. (0.0457 cm)
RHO4	= ρ_4	=	0.016 in. (0.0406 cm)
MD	= md^2	=	0.275×10^{-5} lb-sec^2-in. (3.105×10^{-7} kg-m^2)
K	= 25		

Computed Values

The point efficiency is given as a function of the angle α_1, together with the signum parameters s_1, s_2, and s_3 (given for checking purposes). The cycle efficiency is shown at the end of the output. In addition, the input moment MIN is printed out as well as BETA1D, BETA2D, AND BETA3D.

Computer program INVOL3


```
      PROGRAM INVOL3(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C  POINT AND CYCLE EFFICIENCIES FOR THREE PASS INVOLUTE STEP-UP
C  IN SPIN ENVIRONMENT (ALL MESHES HAVE UNITY CONTACT RATIO)
C
      REAL MIN,MU,M1,M2,M3,M4,MO3,MO4,MTOT,MO,J1,J2,J3,NG1,NG2,NG3,NP2,
     1NP3,NP4
C
C   READ AND WRITE INPUT DATA
C
  100 READ(5,1)PSUBD1,PSUBD2,PSUBD3,NG1,NP2,NG2,NP3,NG3,NP4,MU,RPM,
     1CAPRP1,CAPRP2,CAPRP3,RP2,RP3,RP4,THETA1,THETA2,THETA3,ISTOP
      READ(5,2)R1,R2,R3,R4
      READ(5,3)RHO1,RHO2,RHO3,RHO4
      READ(5,4)CAPRB1,CAPRB2,CAPRB3,RB2,RB3,RB4
      READ(5,5)CAPRO1,CAPRO2,CAPRO3,RO2,RO3,RO4
      READ(5,6)M1,M2,M3,M4
      READ(5,7)MO,K,J1,J2,J3
      PI = 3.14159
      Z = PI/180.
      OMEGA = RPM*2.*PI/60.
      OM2 = OMEGA*OMEGA
    1 FORMAT(3F10.4/6F10.0/F10.3,F10.0/6F10.5/3F10.4/I1)
    2 FORMAT(4F10.4)
    3 FORMAT(4F10.4)
    4 FORMAT(6F10.5)
    5 FORMAT(6F10.5)
    6 FORMAT(4E15.2)
    7 FORMAT(E10.2/I3/3F10.2)
C
C  COMPUTATION OF MIN, GAMMAS AND BETAS
C
      MIN = MO*OM2
      GAMMA2 = ACOS((R1*R1 + R2*R2 - (CAPRP1+RP2)*(CAPRP1+RP2))/
     1(2.*R1*R2))
      GAMA3P = ACOS((R2*R2 + R3*R3 - (CAPRP2+RP3)*(CAPRP2+RP3))/
     1(2.*R2*R3))
      GAMMA3 = GAMMA2 + GAMA3P
      GAMA4P = ACOS((R3*R3 + R4*R4 - (CAPRP3+RP4)*(CAPRP3+RP4))/
     1(2.*R3*R4))
      GAMMA4 = GAMMA3 + GAMA4P
      DELTA2 = ACOS(((CAPRP1+RP2)*(CAPRP1+RP2) + R1*R1 - R2*R2)/
     1(2.*R1*(CAPRP1 + RP2)))
      DELTA3 = ACOS(((CAPRP2+RP3)*(CAPRP2+RP3) + R2*R2 - R3*R3)/
     1(2.*R2*(CAPRP2 + RP3)))
      DELTA4 = ACOS(((CAPRP3+RP4)*(CAPRP3+RP4) + R3*R3 - R4*R4)/
     1(2.*R3*(CAPRP3 + RP4)))
      BETA1 = PI - DELTA2
      BETA2 = GAMMA2 + PI - DELTA3
      BETA3 = GAMMA3 + PI - DELTA4
      BETA1D = BETA1/Z
      BETA2D = BETA2/Z
      BETA3D = BETA3/Z
      WRITE(6,8)PSUBD1,PSUBD2,PSUBD3,NG1,NP2,NG2,NP3,NG3,NP4,MIN,MU,
     1RPM,CAPRP1,CAPRP2,CAPRP3,RP2,RP3,RP4,THETA1,THETA2,THETA3
      WRITE(6,9)R1,R2,R3,R4,M1,M2,M3,M4
      WRITE(6,10)RHO1,RHO2,RHO3,RHO4
```

```
      WRITE(6,11)CAPRB1,CAPRB2,CAPRB3,RB2,RB3,RB4
      WRITE(6,12)CAPRO1,CAPRO2,CAPRO3,RO2,RO3,RO4
      WRITE(6,13)MD,K,J1,J2,J3
      WRITE(6,200)BETA1D,BETA2D,BETA3D
  200 FORMAT(6X,*BETA1D =*,F7.2,3X,*BETA2D =*,F7.2,3X,*BETA3D =*,F7.2/)
    8 FORMAT(*1*,5X,*PSUBD1 =*,F5.0,3X,*PSUBD2 =*,F5.0,3X,*PSUBD3 =*,
     1F5.0//6X,*NG1 =*,F4.0,3X,*NP2 =*,F4.0,3X,*NG2 =*,F4.0,3X,*NP3 =*,
     2F4.0,3X,*NG3 =*,F4.0,3X,*NP4 =*,F4.0//
     3              6X,*MIN =*,E12.5,3X,*MU =*,F6.3,3X,*RPM =*,F6.0//
     46X,*CAPRP1 =*,F8.5,3X,*CAPRP2 =*,F8.5,3X,*CAPRP3 =*,F8.5//6X,
     5*RP2 =*,F8.5,3X,*RP3 =*,F8.5,3X,*RP4 =*,F8.5//6X,
     6*THETA1 =*,F9.5,3X,*THETA2 =*,F9.5,3X,*THETA3 =*,F9.5/)
    9 FORMAT(6X,*R1 =*,F7.5,3X,*R2 =*,F7.5,3X,*R3 =*,F7.5,3X,*R4 =*,F7.5
     1//6X,*M1 =*,E15.5,3X,*M2 =*,E15.5,3X,*M3 =*,E15.5,3X,
     2*M4 =*,E15.5/)
   10 FORMAT(6X,*RHO1 =*,F7.5,3X,*RHO2 =*,F7.5,3X,*RHO3 =*,F7.5,3X,
     1*RHO4 =*,F7.5/)
   11 FORMAT(6X,*CAPRB1 =*,F7.5,3X,*CAPRB2 =*,F7.5,3X,*CAPRB3 =*,F7.5,
     13X,*RB2 =*,F7.5,3X,*RB3 =*,F7.5,3X,*RB4 =*,F7.5/)
   12 FORMAT(6X,*CAPRO1 =*,F7.5,3X,*CAPRO2 =*,F7.5,3X,*CAPRO3 =*,F7.5,3X
     1,*RO2 =*,F7.5,3X,*RO3 =*,F7.5,3X,*RO4 =*,F7.5/)
   13 FORMAT(6X,*MD =*,E10.3//6X,*RANGE DIVISOR =*,I4//6X,*J1 =*,F4.2,
     13X,*J2 =*,F4.2,3X,*J3 =*,F4.2//)
C
C  CONVERSION TO RADIANS
C
      Z = PI/180.
      THETA1 = THETA1*Z
      THETA2 = THETA2*Z
      THETA3 = THETA3*Z
C
C  DETERMINATION OF GEAR TRAIN CONSTANTS
C
      RATIO = CAPRB3*CAPRB2*CAPRB1/(RB2*RB3*RB4)
      TEST1 = TAN(THETA1)
      TEST2 = TAN(THETA2)
      TEST3 = TAN(THETA3)
      D1 = (CAPRB1 + RB2)*TAN(THETA1)
      D2 = (CAPRB2 + RB3)*TAN(THETA2)
      D3 = (CAPRB3 + RB4)*TAN(THETA3)
      MTOT = 0.
C
C  DETERMINATION OF EARLIEST AND LATEST POSSIBLE VALUES OF ALPHAS
C
      CALL ALPHA(CAPRB1,RB2,THETA1,CAPRO1,RO2,AL1IN,AL1FIN)
      CALL ALPHA(CAPRB2,RB3,THETA2,CAPRO2,RO3,AL2IN,AL2FIN)
      CALL ALPHA(CAPRB3,RB4,THETA3,CAPRO3,RO4,AL3IN,AL3FIN)
C
      DELAL3 = (AL3FIN - AL3IN)/K
      DELAL2 = DELAL3*RB3/CAPRB2
      DELAL1 = DELAL2*RB2/CAPRB1
C
C  INITIALIZATION OF ALPHAS
C
      ALPHA1 = AL1IN + (AL1FIN-AL1IN)*J1
      ALPHA2 = AL2IN + (AL2FIN-AL2IN)*J2
      ALPHA3 = AL3IN + (AL3FIN-AL3IN)*J3
```

```
PROGRAM INVOL3      74/74    OPT=1                FTN 4.8+508       04/15/81  10.31.38        PAGE     3

          ALPH1I = ALPHA1
          J4 = 0
C
C  CENTRIFUGAL FORCES
C
          T1 = M1*R1*OM2
          T2 = M2*R2*OM2
          T3 = M3*R3*OM2
          T4 = M4*R4*OM2
C
          DENOM = 1. + MU*MU
C
C  UPDATE VALUES OF ALPHAS
C
   14 IF(ALPHA2 .GT. AL2FIN)ALPHA2 = AL2IN
          IF(ALPHA3 .GT. AL3FIN)ALPHA3 = AL3IN
          IF(ALPHA1.GT.AL1FIN)J4=1
          IF(ALPHA1.GT.AL1FIN)ALPHA1=AL1IN
C
C  TEST TO DETERMINE IF CONTACT POINT IS IN APPROACH OR RECESS
C       IF APPROACH, S = 1.
C       IF RECESS, S = -1.
C       AT PITCH POINT, S = 0.
C
          IF(ALPHA1 .LT. TEST1)S1 = 1.
          IF(ALPHA2 .LT. TEST2)S2 = 1.
          IF(ALPHA3 .LT. TEST3)S3 = 1.
          IF(ALPHA1 .GT. TEST1)S1 = -1.
          IF(ALPHA2 .GT. TEST2)S2 = -1.
          IF(ALPHA3 .GT. TEST3)S3 = -1.
          IF(ALPHA1 .EQ. TEST1)S1 = 0.
          IF(ALPHA2 .EQ. TEST2)S2 = 0.
          IF(ALPHA3 .EQ. TEST3)S3 = 0.
C
C  DETERMINATION OF INPUT FOR MOMENT EXPRESSIONS
C
          A1 = ALPHA1*CAPRB1
          A2 = ALPHA2*CAPRB2
          A3 = ALPHA3*CAPRB3
          AA1 = ABS((SIN(GAMMA4) - MU*COS(GAMMA4))/DENOM)
          AA2 = ABS(((1.+S3*MU*MU)*COS(BETA3+THETA3) + MU*(1.-S3)
         1*SIN(BETA3+THETA3))/DENOM)
          AA3 = ABS((COS(GAMMA4) + MU*SIN(GAMMA4))/DENOM)
          AA4 = ABS(((1.+S3*MU*MU)*SIN(BETA3+THETA3) - MU*(1.-S3)
         1*COS(BETA3+THETA3))/DENOM)
          AA5 = ABS(((1.+MU*MU*S2)*COS(BETA2-THETA2) + MU*(S2-1.)
         1*SIN(BETA2-THETA2))/DENOM)
          AA6 = ABS((SIN(GAMMA3) + MU*COS(GAMMA3))/DENOM)
          AA7 = ABS(((1.-MU*MU*S3)*COS(BETA3+THETA3) - MU*(1.+S3)
         1*SIN(BETA3+THETA3))/DENOM)
          AA8 = ABS(((1.+MU*MU*S2)*SIN(BETA2-THETA2) + MU*(1.-S2)
         1*COS(BETA2-THETA2))/DENOM)
           AA9 = ABS((MU*SIN(GAMMA3) - COS(GAMMA3))/DENOM)
          AA10 = ABS(((1.-MU*MU*S3)*SIN(BETA3+THETA3) + MU*(1.+S3)
         1*COS(BETA3+THETA3))/DENOM)
          AA11 = ABS((MU*(1.-S1)*SIN(BETA1+THETA1) + (1.+S1*MU*MU)
         1*COS(BETA1+THETA1))/DENOM)
```

Computer program INVOL3 (cont)


```
      AA12 = ABS((SIN(GAMMA2) - MU*COS(GAMMA2))/DENOM)
      AA13 = ABS((MU*(1.+S2)*SIN(BETA2-THETA2) + (1.-MU*MU*S2)
     1*COS(BETA2-THETA2))/DENOM)
      AA14 = ABS((MU*(1.-S1)*COS(BETA1+THETA1) - (1.+MU*MU*S1)
     1*SIN(BETA1+THETA1))/DENOM)
      AA15 = ABS((MU*SIN(GAMMA2) + COS(GAMMA2))/DENOM)
      AA16 = ABS(((1.-MU*MU*S2)*SIN(BETA2-THETA2) - MU*(1.+S2)
     1*COS(BETA2-THETA2))/DENOM)
      AA17 = ABS(((1.-MU*MU*S1)*SIN(BETA1+THETA1) + MU*(1.+S1)
     1*COS(BETA1+THETA1))/DENOM)
      AA18 = ABS(1./DENOM)
      AA19 = ABS((MU*(1.+S1)*SIN(BETA1+THETA1) - (1.-MU*MU*S1)
     1*COS(BETA1+THETA1))/DENOM)
      AA20 = ABS(MU/DENOM)
      DD1 = RB4 - MU*(S3*(D3-A3) + RHO4*(AA2+AA4))
      DD2 = -MU*(RHO3*(AA5+AA8) + S2*(D2-A2)) + RB3
      DD3 = RB2 - MU*(S1*(D1-A1) + RHO2*(AA11+AA14))
      DD4 = CAPRB1 - MU*(S1*A1 - RHO1*(AA17+AA19))
      CC1 = MU*RHO4*(AA1+AA3)
      CC2 = CAPRB3 - MU*(S3*A3 - RHO3*(AA7+AA10))
      CC3 = MU*RHO3*(AA6+AA9)
      CC4 = CAPRB2 - MU*(S2*A2 - RHO2*(AA13+AA16))
      CC5 = MU*RHO2*(AA12+AA15)
      CC6 = MU*RHO1*(AA18+AA20)
C
C  OUTPUT MOMENT
C
      ALPH1D = ALPHA1*180./PI
      MO4 = DD1*DD2*DD3/(CC2*CC4*DD4)*(MIN-T1*CC6) - T2*CC5*DD1*DD2
     1/(CC2*CC4) - T3*CC3*DD1/CC2 - T4*CC1
      POINTEF = RATIO*MO4/MIN
      WRITE(6,15)ALPH1D,S1,S2,S3,POINTEF
   15 FORMAT(6X,*ALPHA1 =*,F6.2,* (DEG)*,3X,*S1 =*,F5.1,3X,*S2 =*,F5.1,
     13X,*S3 =*,F5.1,3X,*POINT EFFICIENCY =*,F7.5)
      MTOT = MTOT + MO4
C
C  ADVANCE GEAR TRAIN TO NEXT POSITION
C
      ALPHA1 = ALPHA1 + DELAL1
      IF((J4.EQ.1 .AND. ALPHA1.GT.ALPH1I-DELAL1) .OR. (J1.EQ.0. .AND.
     1ALPHA1.GT.AL1FIN-DELAL1))GO TO 16
      ALPHA2 = ALPHA2 + DELAL2
      ALPHA3 = ALPHA3 + DELAL3
      GO TO 14
   16 CYCLEFF = RATIO*DELAL1*MTOT/(MIN*(AL1FIN-AL1IN))
      WRITE(6,17)CYCLEFF
   17 FORMAT(*0*,5X,*CYCLE EFFICIENCY =*,F5.3)
      IF(ISTOP .NE. 0)GO TO 100
      STOP
      END
```

Computer program INVOL3 (cont)

```
SUBROUTINE ALPHA       74/74    OPT=1                    FTN 4.8+508        04/15/81  10.31.38        PAGE     1

                SUBROUTINE ALPHA(CAPRB,RB,THETA,CAPRO,RO,ALIN,ALFIN)
          C
          C   THIS SUBROUTINE COMPUTES THE INITIAL AND FINAL VALUES OF ALPHAS
          C
                ALIN = ((CAPRB + RB)*TAN(THETA) - SQRT(RO*RO - RB*RB))/CAPRB
                ALFIN = SQRT(CAPRO*CAPRO - CAPRB*CAPRB)/CAPRB
                RETURN
                END
```

Computer program INVOL3 (cont)

```
PSUBD1 =  44.   PSUBD2 =  65.   PSUBD3 =  77.

NG1 = 42.   NP2 =  8.   NG2 = 27.   NP3 =  9.   NG3 = 27.   NP4 =  9.

MIN =  .30157E-01   MU =  .200   RPM = 1000.

CAPRP1 =  .47727   CAPRP2 =  .20769   CAPRP3 =  .17532

RP2 =  .09091   RP3 =  .06923   RP4 =  .05844

THETA1 = 20.00000   THETA2 = 20.00000   THETA3 = 20.00000

R1 = .22500   R2 = .43600   R3 = .50400   R4 = .52000

M1 =       .12000E-03   M2 =       .85000E-05   M3 =       .34000E-05   M4 =       .15000E-05

RHO1 = .06200   RHO2 = .02500   RHO3 = .01800   RHO4 = .01600

CAPRB1 = .44949   CAPRB2 = .19517   CAPRB3 = .16475   RB2 = .08543   RB3 = .06506   RB4 = .05492

CAPRO1 = .48791   CAPRO2 = .21579   CAPRO3 = .18216   RO2 = .11000   RO3 = .08089   RO4 = .06828

MD =  .275E-05

RANGE DIVISOR =  25

J1 =0.00   J2 =0.00   J3 =0.00


BETA1D = 135.82   BETA2D = 207.77   BETA3D = 247.36

ALPHA1 = 15.97 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .32011
ALPHA1 = 16.01 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .32510
ALPHA1 = 16.04 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .330:4
ALPHA1 = 16.08 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .33522
ALPHA1 = 16.11 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .34035
ALPHA1 = 16.14 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .34552
ALPHA1 = 16.18 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .35075
ALPHA1 = 16.21 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .35602
ALPHA1 = 16.24 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .36134
ALPHA1 = 16.28 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .36671
ALPHA1 = 16.31 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .37213
ALPHA1 = 16.35 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .37760
ALPHA1 = 16.38 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38311
ALPHA1 = 16.41 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38868
ALPHA1 = 16.45 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .39097
ALPHA1 = 16.48 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38960
ALPHA1 = 16.52 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38823
ALPHA1 = 16.55 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38684
ALPHA1 = 16.58 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38544
ALPHA1 = 16.62 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38403
ALPHA1 = 16.65 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38260
ALPHA1 = 16.68 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38117
ALPHA1 = 16.72 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .37972
ALPHA1 = 16.75 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .37826
ALPHA1 = 16.79 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .37678
ALPHA1 = 16.82 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .37530
ALPHA1 = 16.85 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .36388
ALPHA1 = 16.89 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .36937
ALPHA1 = 16.92 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .37491
ALPHA1 = 16.96 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38050
```

Computer program INVOL3 (cont)

```
ALPHA1 = 16.99 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38614
ALPHA1 = 17.02 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .39184
ALPHA1 = 17.06 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .39758
ALPHA1 = 17.09 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40338
ALPHA1 = 17.12 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40923
ALPHA1 = 17.16 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41513
ALPHA1 = 17.19 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42109
ALPHA1 = 17.23 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42710
ALPHA1 = 17.26 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43316
ALPHA1 = 17.29 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43928
ALPHA1 = 17.33 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .44174
ALPHA1 = 17.36 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43973
ALPHA1 = 17.40 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43535
ALPHA1 = 17.43 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43098
ALPHA1 = 17.46 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .42664
ALPHA1 = 17.50 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .42232
ALPHA1 = 17.53 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .41802
ALPHA1 = 17.57 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .41375
ALPHA1 = 17.60 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .40950
ALPHA1 = 17.63 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .40527
ALPHA1 = 17.67 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .40106
ALPHA1 = 17.70 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .39687
ALPHA1 = 17.73 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .38234
ALPHA1 = 17.77 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .38552
ALPHA1 = 17.80 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .38871
ALPHA1 = 17.84 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .39190
ALPHA1 = 17.87 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .39509
ALPHA1 = 17.90 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .39828
ALPHA1 = 17.94 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .40147
ALPHA1 = 17.97 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .40466
ALPHA1 = 18.01 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .40786
ALPHA1 = 18.04 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41105
ALPHA1 = 18.07 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41425
ALPHA1 = 18.11 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41744
ALPHA1 = 18.14 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .42064
ALPHA1 = 18.17 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .42384
ALPHA1 = 18.21 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .42346
ALPHA1 = 18.24 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .41918
ALPHA1 = 18.28 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .41492
ALPHA1 = 18.31 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .41068
ALPHA1 = 18.34 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .40647
ALPHA1 = 18.38 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .40228
ALPHA1 = 18.41 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .39811
ALPHA1 = 18.45 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .39396
ALPHA1 = 18.48 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .38983
ALPHA1 = 18.51 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .37024
ALPHA1 = 18.55 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .36884
ALPHA1 = 18.58 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .36742
ALPHA1 = 18.61 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .35624
ALPHA1 = 18.65 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .36167
ALPHA1 = 18.68 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .36714
ALPHA1 = 18.72 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .37267
ALPHA1 = 18.75 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .37825
ALPHA1 = 18.78 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38387
ALPHA1 = 18.82 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38955
ALPHA1 = 18.85 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .39529
ALPHA1 = 18.89 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40107
ALPHA1 = 18.92 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40690
ALPHA1 = 18.95 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41279
ALPHA1 = 18.99 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41873
ALPHA1 = 19.02 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42473
```

Computer program INV013 (cont)

```
ALPHA1 = 19.05 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43078
ALPHA1 = 19.09 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .43323
ALPHA1 = 19.12 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .43169
ALPHA1 = 19.16 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .43013
ALPHA1 = 19.19 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42856
ALPHA1 = 19.22 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42698
ALPHA1 = 19.26 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42538
ALPHA1 = 19.29 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42377
ALPHA1 = 19.33 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42215
ALPHA1 = 19.36 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42052
ALPHA1 = 19.39 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .41887
ALPHA1 = 19.43 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .41721
ALPHA1 = 19.46 (DEG)   S1 =  1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .41554
ALPHA1 = 19.50 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40300
ALPHA1 = 19.53 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40896
ALPHA1 = 19.56 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41498
ALPHA1 = 19.60 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42105
ALPHA1 = 19.63 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42777
ALPHA1 = 19.66 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43335
ALPHA1 = 19.70 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43958
ALPHA1 = 19.73 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .44587
ALPHA1 = 19.77 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .45222
ALPHA1 = 19.80 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .45862
ALPHA1 = 19.83 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .46508
ALPHA1 = 19.87 (DEG)   S1 =  1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .47160
ALPHA1 = 19.90 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .47775
ALPHA1 = 19.94 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .48137
ALPHA1 = 19.97 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .49098
ALPHA1 = 20.00 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .47621
ALPHA1 = 20.04 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .47147
ALPHA1 = 20.07 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .46675
ALPHA1 = 20.10 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .46206
ALPHA1 = 20.14 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .45739
ALPHA1 = 20.17 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .45275
ALPHA1 = 20.21 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .44813
ALPHA1 = 20.24 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .44353
ALPHA1 = 20.27 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43896
ALPHA1 = 20.31 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43442
ALPHA1 = 20.34 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .42990
ALPHA1 = 20.38 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41427
ALPHA1 = 20.41 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41766
ALPHA1 = 20.44 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .42106
ALPHA1 = 20.48 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .42445
ALPHA1 = 20.51 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .42785
ALPHA1 = 20.54 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .43124
ALPHA1 = 20.58 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .43464
ALPHA1 = 20.61 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .43804
ALPHA1 = 20.65 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .44144
ALPHA1 = 20.68 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .44484
ALPHA1 = 20.71 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .44824
ALPHA1 = 20.75 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .45164
ALPHA1 = 20.78 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .45504
ALPHA1 = 20.82 (DEG)   S1 =  1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .45845
ALPHA1 = 20.85 (DEG)   S1 =  1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .45801
ALPHA1 = 20.88 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .45464
ALPHA1 = 20.92 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .44912
ALPHA1 = 20.95 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .44365
ALPHA1 = 20.98 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43821
ALPHA1 = 21.02 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43282
ALPHA1 = 21.05 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .41061
ALPHA1 = 21.09 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .40824
```

Computer program INVOL3 (cont)

```
ALPHA1 = 21.12 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .40586
ALPHA1 = 21.15 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .40348
ALPHA1 = 21.19 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .40110
ALPHA1 = 21.22 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .39870
ALPHA1 = 21.26 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38586
ALPHA1 = 21.29 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .39083
ALPHA1 = 21.32 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .39584
ALPHA1 = 21.36 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40088
ALPHA1 = 21.39 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40595
ALPHA1 = 21.43 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41106
ALPHA1 = 21.46 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41621
ALPHA1 = 21.49 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42138
ALPHA1 = 21.53 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42659
ALPHA1 = 21.56 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43184
ALPHA1 = 21.59 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43712
ALPHA1 = 21.63 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .44243
ALPHA1 = 21.66 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .44778
ALPHA1 = 21.70 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .45317
ALPHA1 = 21.73 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .45478
ALPHA1 = 21.76 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .45221
ALPHA1 = 21.80 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .44964
ALPHA1 = 21.83 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .44706
ALPHA1 = 21.87 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .44448
ALPHA1 = 21.90 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .44189
ALPHA1 = 21.93 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .43930
ALPHA1 = 21.97 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .43671
ALPHA1 = 22.00 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .43411
ALPHA1 = 22.03 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .43151
ALPHA1 = 22.07 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42890
ALPHA1 = 22.10 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42629
ALPHA1 = 22.14 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41258
ALPHA1 = 22.17 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41779
ALPHA1 = 22.20 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42303
ALPHA1 = 22.24 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42830
ALPHA1 = 22.27 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43361
ALPHA1 = 22.31 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .43895
ALPHA1 = 22.34 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .44433
ALPHA1 = 22.37 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .44974
ALPHA1 = 22.41 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .45519
ALPHA1 = 22.44 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .46025
ALPHA1 = 22.47 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .46287
ALPHA1 = 22.51 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .46547
ALPHA1 = 22.54 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .46805
ALPHA1 = 22.58 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .47063
ALPHA1 = 22.61 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .46927
ALPHA1 = 22.64 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .46365
ALPHA1 = 22.68 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .45807
ALPHA1 = 22.71 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .45253
ALPHA1 = 22.75 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .44703
ALPHA1 = 22.78 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .44157
ALPHA1 = 22.81 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43616
ALPHA1 = 22.85 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .43079
ALPHA1 = 22.88 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .42546
ALPHA1 = 22.92 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .42017
ALPHA1 = 22.95 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .41493
ALPHA1 = 22.98 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .40972
ALPHA1 = 23.02 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .39391
ALPHA1 = 23.05 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .39631
ALPHA1 = 23.08 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .39871
ALPHA1 = 23.12 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .40109
ALPHA1 = 23.15 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .40347
```

Computer program INVOL3 (cont)

```
ALPHA1 = 23.19 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .40583
ALPHA1 = 23.22 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .40818
ALPHA1 = 23.25 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41053
ALPHA1 = 23.29 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41286
ALPHA1 = 23.32 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41519
ALPHA1 = 23.36 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41750
ALPHA1 = 23.39 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .41981
ALPHA1 = 23.42 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .42210
ALPHA1 = 23.46 (DEG)   S1 = -1.0   S2 = -1.0   S3 =  1.0   POINT EFFICIENCY = .42439
ALPHA1 = 23.49 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .42309
ALPHA1 = 23.52 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .41790
ALPHA1 = 23.56 (DEG)   S1 = -1.0   S2 = -1.0   S3 = -1.0   POINT EFFICIENCY = .41275
ALPHA1 = 23.59 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .39138
ALPHA1 = 23.62 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38914
ALPHA1 = 23.66 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38689
ALPHA1 = 23.69 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38464
ALPHA1 = 23.73 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38239
ALPHA1 = 23.76 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .38012
ALPHA1 = 23.80 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .37786
ALPHA1 = 23.83 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .37559
ALPHA1 = 23.86 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .37331
ALPHA1 = 23.90 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .36117
ALPHA1 = 23.93 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .36584
ALPHA1 = 23.96 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .37055
ALPHA1 = 24.00 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .37529
ALPHA1 = 24.03 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38006
ALPHA1 = 24.07 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38485
ALPHA1 = 24.10 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .38969
ALPHA1 = 24.13 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .39455
ALPHA1 = 24.17 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .39944
ALPHA1 = 24.20 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40437
ALPHA1 = 24.24 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .40933
ALPHA1 = 24.27 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41432
ALPHA1 = 24.30 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .41935
ALPHA1 = 24.34 (DEG)   S1 = -1.0   S2 =  1.0   S3 =  1.0   POINT EFFICIENCY = .42441
ALPHA1 = 24.37 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42590
ALPHA1 = 24.40 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42346
ALPHA1 = 24.44 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .42101
ALPHA1 = 24.47 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .41856
ALPHA1 = 24.51 (DEG)   S1 = -1.0   S2 =  1.0   S3 = -1.0   POINT EFFICIENCY = .41611

CYCLE EFFICIENCY = .414
```

REFERENCE

A-1 G.G. Lowen, City College of N.Y., and F.R. Tepper, ARRADCOM, "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

APPENDIX B

COMPUTER PROGRAM INVOL4 (REVISED)

The original program descriptions were given in appendix C of Fuze Gear Train Analysis (ref B-1). The following appendix contains revised descriptions, listings and sample outputs of computer program INVOL4, which computes point and cycle efficiencies for two pass involute gear trains in a spin environment. All meshes have unity contact ratio.

The following changes were made:

1. The diametral pitches of both meshes are given as data and are printed in the output.

2. The numbers of teeth of both meshes are given as data and are printed in the output.

3. The initialization parameters J (one for each of the two meshes) are introduced. They are given as part of the data and are printed in the output. Again, these parameters allow the arbitrary choice of the initial point of contact of a given mesh anywhere within the range of possible contact points.

In addition to these changes, it contains gear computations (according to program INVOL1) which are necessary to give the two pass step-up gear train the same overall gear ratio as that of the three pass step-up gear train.

The program INVOL4 is based on appendix A (ref B-1) which derives the moment input-output relationship for a two pass step-up gear train, operating in a spin environment. Here again, all meshes have unity contact ratio. INVOL4 is very similar to INVOL3 in its construction. Again, the expressions for the contact geometry and other auxiliary geometric terms may be found in appendix A (ref B-1).

Input Parameters

The following parameters represent the input data for the program. Those which involve gear dimensions only must be obtained from the results of INVOL1 (ref B-1) since the moment expressions are again derived for unity contact ratio only.

PSUBD1 = P_{d1}

PSUBD2 = P_{d2}

NG1 = N_{G1}

NP2 = N_{P2}

NG2 = N_{G2}

NP3 = N_{P3}

MU = μ, coefficient of friction at all pivots and at all tooth contact points

RPM, revolutions per minute of the fuze body

CAPRP1 = R_{p1}

CAPRP2 = R_{p2}

RP2 = r_{p2}

RP3 = r_{p3}

THETA1 = θ_1

THETA2 = θ_2

ISTOP arbitrary single digit integer for multiple data sets. It must be zero for last set of data.

R1 = $\mathcal{R}_1$

R2 = $\mathcal{R}_2$

R3 = $\mathcal{R}_3$

RHO1 = ρ_1

RHO2 = ρ_2

RHO3 = ρ_3

CAPRB1 = R_{b1}

CAPRB2 = R_{b2}

RB2 = r_{b2}

RB3 = r_{b3}

CAPRO1 = R_{o1}

CAPRO2 = R_{o2}

RO2 = r'_{o2}

RO3 = r'_{o3}

M1 = m_1, mass of input gear 1

M2 = m_2, mass of gear and pinion 2

M3 = m_3, mass of pinion 3

MD = md^2, mass-distance product contained in the expression for the input moment M_{in}

K = K_2, the range divisor which is associated with gear 2, the driving gear of the last mesh for this case (eq A-207, ref B-1)

J1, J2, initialization parameters

Computations

Computation of MIN, Gammas and Betas

To start with, the program computes the input moment

$$MIN = M_{in} = md^2\omega^2 \qquad (B-1)$$

The program computes the angles γ_2, γ_3 and β_1, β_2 according to the expression given in appendix A (ref B-1).

Determination of the Gear Train Constants

The determination of the gear train constants consists of the following:

RATIO = K_{RATIO}, (eq 2, ref B-1). Since the angular velocity is constant, this parameter may be expressed in terms of the applicable base radii, i.e.,

$$\frac{R_{b1} \times R_{b2}}{r_{b2} \times r_{b3}}$$

TEST1 and TEST2 represent the tangent functions of the mesh pressure angles, which are used in conjunction with the values of the signum functions s.

D1 and D2 are given by equations A-204 and A-217 (ref B-1), respectively, and represent the distances between the points of tangency to the base circles along the lines of action of the two meshes.

MTOT = 0 represents the initialization of the sum of the output moments. This is used for the determination of the cycle efficiency.

Determination of Earliest and Latest Possible Values of ALPHAS, Initialization of ALPHAS. Centrifugal Forces

The determination of the earliest and latest possible angles of rotation is accomplished with the help of subroutine ALPHA, at the end of the program, which makes use of equations A-205, A-206, A-218, and A-219 (ref B-1). The angles of initial contact α_1 are determined with the help of the initialization parameters J_1 according to:

$$\alpha_i = \alpha_{iIN} + J_i(\alpha_{iFIN} - \alpha_{iIN}) \quad (i=1,2) \qquad \text{(B-2)}$$

The additional parameter J_3 serves to distinguish between the two possible contact conditions of mesh no. 1. $J_3 = 0$ while the first set of teeth is in contact. $J_3 = 1$ when the latest possible value of α_1 has been reached and contact is transferred to the second set of teeth. $J_3 = 0$ at all times when $J_1 = 0$, i.e., contact is made in mesh no. 1 at the earliest possible time, and therefore, contact need never be transferred to the second set of teeth to obtain a complete contact cycle (cards no. 93 and 106).

The angular increments of gears 2 and 1, i.e., DELAL2 and DELAL1, are determined with the help of equations A-207 and A-208 (ref B-1), respectively.

The centrifugal forces, which act on the pivots of the various gear and/or pinion assemblies, are obtained by way of equations A-131, A-154, and A-178 (ref B-1).

Point and Cycle Efficiencies

Both point and cycle efficiencies are based on equations A-193 (ref B-1) for the output moment MO3 = M_{o3}.

The point efficiency is computed directly in the manner of equation 3 (ref B-1) i.e.,

$$\varepsilon_p = K_{RATIO} \frac{M_{o3}}{M_{in}} = \text{POINTEF} \qquad \text{(B-3)}$$

The cycle efficiency is treated in the manner of equation A-3 of appendix A, i.e.,

$$\varepsilon_C = \frac{K_{RATIO} \quad \Delta\alpha_1 \ \Sigma M_{o3}}{M_{in} \ (\alpha_{1FIN} - \alpha_{1IN})} = \text{CYCLEFF} \qquad \text{(B-4)}$$

The program gives the summation as

$$MTOT = \Sigma M_{o3} \qquad (B-5)$$

Gear Train Motion Model

The simulation of the gear train motion, which is necessary for the computation of both POINTEF and CYCLEFF, is found in a loop which begins with statement label no. 14 (card no. 105) and ends with card no. 171.

The motions of the individual driving gears are initialized with the help of the parameters J_1 and J_2. The position of each mesh is subsequently incremented by the appropriate DELAL1 and DELAL2. Whenever the J_i's (i=1,2) are not equal to zero, and one of the angles α_{iFIN} has been reached, the particular mesh is reset to its respective angle α_{iIN}. Since mesh 2 goes through a number of cycles while mesh 1 goes through one cycle, mesh 2 has to be reset to its starting position AL2IN once the angle AL2FIN has been reached. This is accomplished by the conditional statement on card no. 105. When $J_1 = 0$, i.e., contact in mesh 1 is made at the earliest possible point, CYCLEFF is determined and the computation is ended once the angle AL1FIN - DELAL1 is reached. When $J_1 \neq 0$, the above occurs when ALPHA1 reaches the magnitude of its initial angle minus DELAL1. (The nature of the numerical integration requires that only K computations be included.)

The values of the signum functions s_1 and s_2 are determined continuously according to equations A-216 and A-222 (ref B-1).

The instantaneous distances to the contact points, i.e., A1 = a_1 and A2 = a_2, are determined for each of the meshes by appropriate adaptations of equation A-203 (ref B-1) (also equations A-214 and A-220 (ref B-1)).

The determination of the instantaneous output moment MO3 = M_{o3} requires the continuous computation of the variable quantities A_1 to A_{14}, C_1 to C_4 and D_1 to D_3, which are given originally in conjunction with the various equilibrium conditions in appendix A (ref B-1). The program uses the following nomenclature for these variables:

AA1 to AA14

CC1 to CC4

DD1 to DD3

Output

The output of the program is again best explained with the help of the sample computation shown at the end of the program. This example uses the gear data with the help of computer program INVOL1. The output lists the following:

Input Parameters

Mesh No. 1

CAPRP1 = R_{p1} = 0.55000 in. (1.3970 cm)	PSUBD1 = P_{d1} = 50
CAPRB1 = R_{b1} = 0.51683 in. (1.3127 cm)	NG1 = N_{G1} = 55
CAPRO1 = R_{o1} = 0.55936 in. (1.4208 cm)	NP2 = N_{P2} = 8
RP2 = r_{p2} = 0.08000 in. (0.2032 cm)	J1 = 0
RB2 = r_{b2} = 0.07518 in. (0.1910 cm)	
RO2 = r'_{o2} = 0.09655 in. (0.2452 cm) (This is a ROFIN as given by INVOL1.)	

Also,

THETA1 = θ_1 = 20°

Mesh No. 2

CAPRP2 = R_{p2} = 0.39286 in. (0.9979 cm)	PSUBD2 = P_{d2} = 70
CAPRB2 = R_{b2} = 0.36916 in. (0.9377 cm)	NG2 = N_{G2} = 55
CAPRO2 = R_{o2} = 0.39954 in. (1.0148 cm)	NP3 = N_{P3} = 8
RP3 = r_{p3} = 0.05714 in. (0.1451 cm)	J2 = 0
RB3 = r_{b3} = 0.05370 in. (0.1364 cm)	
RO3 = r'_{o3} = 0.06898 in. (0.1752 cm)	

Also,

THETA2 = θ_2 = 20°

In addition,

MU = μ = 0.2

RPM = 1000

M1 = m_1 = 0.12×10^{-3} lb-sec^2/in. (2.101×10^{-2} kg)

M2 = m_2 = 0.253×10^{-4} lb-sec^2/in. (4.430×10^{-3} kg)

M3 = m_3 = 0.153×10^{-5} lb-sec^2/in. (2.679×10^{-4} kg)

R1	=	$\mathcal{R}_1$	=	0.225 in. (0.5715 cm)
R2	=	$\mathcal{R}_2$	=	0.497 in. (1.2624 cm)
R3	=	$\mathcal{R}_3$	=	0.640 in. (1.6256 cm)
RHO1	=	ρ_1	=	0.062 in. (0.1575 cm)
RHO2	=	ρ_2	=	0.025 in. (0.0635 cm)
RHO3	=	ρ_3	=	0.018 in. (0.0457 cm)
MD	=	md^2	=	0.275×10^{-5} lb-sec^2-in. (3.105×10^{-7} kg-m^2)
K	=	25		

Computed Values

The point efficiency is given as a function of the angle α_1, together with the signum parameters s_1 and s_2 (given for checking purposes). The cycle efficiency is shown at the end of the output. In addition, the input moment MIN is printed out.

Use of Computer Program INVOL1 to Obtain Unity Contact Ratio Parameters for Both Meshes

The following gives the outputs of computer program INVOL1 (app A, ref B-1) for the present two pass step-up gear mesh with a total step-up ratio of (55/8) x (55/8) = 47.265. The above is essentially the same as the gear ratio of the three pass gear train of appendix A.

Output of computer program INVOLI

```
DIAMETRAL PITCH (PSUBD) = 50.00
GEAR NUMBER OF TEETH (NG) = 55
PINION NUMBER OF TEETH (NP) = 8
PRESSURE ANGLE (THETA) = 20.00
GEAR PITCH RADIUS (CAPRP) = .55000   PINION PITCH RADIUS (RP) = .08000
GEAR BASE RADIUS (CAPRB) = .51683   PINION BASE RADIUS (RB) = .07518
STANDARD TOOTH THICKNESS AT PITCH RADII (TSTAND) = .03142
HOB WITHDRAWAL DISTANCE (C) = .01064
GEAR BLANK RADIUS (CAPRO) = .55936   ORIGINAL PINION BLANK RADIUS (RO) = .11064
ORIGINAL CONTACT RATIO (CRATIO) = 1.349
PINION OUTSIDE RADIUS FOR UNITY CONTACT RATIO (ROFIN) = .09655
FINAL CONTACT RATIO (CRFIN) = 1.000
GEAR TOOTH THICKNESS AT PITCH CIRCLE (CAPTC) = .02367   PINION TOOTH THICKNESS AT PITCH CIRCLE (TC) = .03916
GEAR PRESSURE ANGLE AT OUTSIDE RADIUS (THEOGD) = 22.48626   PINION PRESSURE ANGLE AT FINAL OUTSIDE RADIUS (THEOPD) = 38.86456
GEAR TOOTH THICKNESS AT OUTSIDE RADIUS (CAPTO) = .01572   PINION TOOTH THICKNESS AT FINAL OUTSIDE RADIUS (TO) = .02551
GEAR TOOTH THICKNESS AT BASE CIRCLE (CAPTB) = .03765   THEORETICAL PINION TOOTH THICKNESS AT BASE CIRCLE (TB) = .03984
RADIUS OF ROOT CIRCLE OF GEAR (CAPROOT) = .51622   MINIMUM ALLOWABLE RADIUS OF ROOT CIRCLE OF GEAR (CAPRMIN) = .48360
THE GEAR IS NOT UNDERCUT
RADIUS OF ROOT CIRCLE OF PINION (ROOT) = .06750
```

Output of computer program INVOL1 (cont)

```
DIAMETRAL PITCH (PSUBD) = 70.00
GEAR NUMBER OF TEETH (NG) = 55
PINION NUMBER OF TEETH (NP) =  8
PRESSURE ANGLE (THETA) = 20.00
GEAR PITCH RADIUS (CAPRP) =   .39286   PINION PITCH RADIUS (RP) =   .05714
GEAR BASE RADIUS (CAPRB) =   .36916   PINION BASE RADIUS (RB) =   .05370
STANDARD TOOTH THICKNESS AT PITCH RADII (TSTAND) =  .02244
HOB WITHDRAWAL DISTANCE (C) =  .00760
GEAR BLANK RADIUS (CAPRO) =   .39954   ORIGINAL PINION BLANK RADIUS (RO) =   .07903
ORIGINAL CONTACT RATIO (CRATIO) = 1.349
PINION OUTSIDE RADIUS FOR UNITY CONTACT RATIO (ROFIN) =   .06896
FINAL CONTACT RATIO (CRFIN) = 1.000
GEAR TOOTH THICKNESS AT PITCH CIRCLE (CAPTC) =   .01691   PINION TOOTH THICKNESS AT PITCH CIRCLE (TC) =  .02797
GEAR PRESSURE ANGLE AT OUTSIDE RADIUS (THEOGD) = 22.48626   PINION PRESSURE ANGLE AT FINAL OUTSIDE RADIUS (THEOPD) = 38.86456
GEAR TOOTH THICKNESS AT OUTSIDE RADIUS (CAPTO) =  .01195   PINION TOOTH THICKNESS AT FINAL OUTSIDE RADIUS (TO) =  .01822
GEAR TOOTH THICKNESS AT BASE CIRCLE (CAPTB) =  .02689   THEORETICAL PINION TOOTH THICKNESS AT BASE CIRCLE (TB) =  .02789
RADIUS OF ROOT CIRCLE OF GEAR (CAPROOT) =  .36873   MINIMUM ALLOWABLE RADIUS OF ROOT CIRCLE OF GEAR (CAPRMIN) =  .34543
THE GEAR IS NOT UNDERCUT
RADIUS OF ROOT CIRCLE OF PINION (ROOT) =  .04822
```

Computer program INVOL4

```
PROGRAM INVOL4     74/74   OPT=1                   FTN 4.8+508      04/15/81  10.35.05      PAGE    1

      PROGRAM INVOL4(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C  POINT AND CYCLE EFFICIENCIES FOR TWO PASS INVOLUTE STEP-UP GEAR TRAIN
C  IN SPIN ENVIRONMENT (ALL MESHES HAVE UNITY CONTACT RATIO)
C
      REAL MIN,MU,M1,M2,M3,MO3,MTOT,MD,J1,J2,NG1,NP2,NG2,NP3
C
C   READ AND WRITE INPUT DATA
C
  100 READ(5,1)PSUBD1,PSUBD2,NG1,NP2,NG2,NP3,MU,RPM,CAPRP1,CAPRP2,RP2,
     1RP3,THETA1,THETA2,ISTOP
      READ(5,2)R1,R2,R3
      READ(5,3)RHO1,RHO2,RHO3
      READ(5,4)CAPRB1,CAPRB2,RB2,RB3
      READ(5,5)CAPRO1,CAPRO2,RO2,RO3
      READ(5,6)M1,M2,M3
      READ(5,7)MD,K,J1,J2
    1 FORMAT(2F10.4/4F10.0/F10.3,F10.0/4F10.5/2F10.4/I1)
    2 FORMAT(3F10.5)
    3 FORMAT(3F10.5)
    4 FORMAT(4F10.5)
    5 FORMAT(4F10.5)
    6 FORMAT(3E10.4)
    7 FORMAT(E10.4/I3/2F10.2)
      PI = 3.14159
      OMEGA = RPM*2.*PI/60.
      OM2 = OMEGA*OMEGA
C
C  COMPUTATION OF MIN, GAMMAS AND BETAS
C
      MIN = MD*OM2
      GAMMA2 = ACOS((R1*R1 + R2*R2 - (CAPRP1+RP2)*(CAPRP1+RP2))/
     1(2.*R1*R2))
      GAMA3P = ACOS((R2*R2 + R3*R3 - (CAPRP2+RP3)*(CAPRP2+RP3))/
     1(2.*R2*R3))
      GAMMA3 = GAMMA2 + GAMA3P
      DELTA2 = ACOS(((CAPRP1+RP2)*(CAPRP1+RP2) + R1*R1 - R2*R2)/
     1(2.*R1*(CAPRP1 + RP2)))
      DELTA3 = ACOS(((CAPRP2+RP3)*(CAPRP2+RP3) + R2*R2 - R3*R3)/
     1(2.*R2*(CAPRP2 + RP3)))
      BETA1 = PI - DELTA2
      BETA2 = GAMMA2 + PI - DELTA3
      WRITE(6,8)PSUBD1,PSUBD2,NG1,NP2,NG2,NP3,MIN,MU,RPM,CAPRP1,CAPRP2,
     1RP2,RP3,THETA1,THETA2
      WRITE(6,9)R1,R2,R3,M1,M2,M3
      WRITE(6,10)RHO1,RHO2,RHO3
      WRITE(6,11)CAPRB1,CAPRB2,RB2,RB3
      WRITE(6,12)CAPRO1,CAPRO2,RO2,RO3
      WRITE(6,13)MD,K,J1,J2
    8 FORMAT(*1*,5X,*PSUBD1 =*,F5.0,3X,*PSUBD2 =*,F5.0//6X,
     1*NG1 =*,F4.0,3X,*NP2 =*,F4.0,3X,*NG2 =*,F4.0,3X,*NP3 =*,F4.0//
     2            6X,*MIN =*,E12.5,3X,*MU =*,F6.3,3X,*RPM =*,F6.0//6X,
     3*CAPRP1 =*,F8.5,3X,*CAPRP2 =*,F8.5//6X,*RP2 =*,F8.5,3X,*RP3 =*,
     4F8.5//6X,*THETA1 =*,F8.3,3X,*THETA2 =*,F8.3/)
    9 FORMAT(6X,*R1 =*,F7.5,3X,*R2 =*,F7.5,3X,*R3 =*,F7.5//6X,*M1 =*,
     1E12.5,3X,*M2 =*,E12.5,3X,*M3 =*,E12.5/)
   10 FORMAT(6X,*RHO1 =*,F7.5,3X,*RHO2 =*,F7.5,3X,*RHO3 =*,F7.5/)
```

Computer program INVOL4 (cont)

```
PROGRAM INVOL4      74/74    OPT=1                        FTN 4.8+508        04/15/81  10.35.05        PAGE      2

         11 FORMAT(6X,*CAPRB1 =*,F7.5,3X,*CAPRB2 =*,F7.5,3X,*RB2 =*,F7.5,3X,
           1*RB3 =*,F7.5/)
         12 FORMAT(6X,*CAPRO1 =*,F7.5,3X,*CAPRO2 =*,F7.5,3X,*RO2 =*,F7.5,3X,
           1* RO3 =*,F7.5/)
         13 FORMAT(6X,*MU =*,E10.3//6X,*RANGE DIVISOR =*,I4//6X,*J1 =*,F4.2,3X
           2,*J2 =*,F4.2//)
      C
      C  CONVERSION TO RADIANS
      C
            Z = PI/180.
            THETA1 = THETA1*Z
            THETA2 = THETA2*Z
      C
      C  DETERMINATION OF GEAR TRAIN CONSTANTS
      C
            RATIO = (CAPRB2*CAPRB1)/(RB2*RB3)
            TEST1 = TAN(THETA1)
            TEST2 = TAN(THETA2)
            D1 = (CAPRB1 + RB2)*TAN(THETA1)
            D2 = (CAPRB2 + RB3)*TAN(THETA2)
            MTOT = 0.
      C
      C  DETERMINATION OF EARLIEST AND LATEST POSSIBLE VALUES OF ALPHAS
      C
            CALL ALPHA(CAPRB1,RB2,THETA1,CAPRO1,RO2,AL1IN,AL1FIN)
            CALL ALPHA(CAPRB2,RB3,THETA2,CAPRO2,RO3,AL2IN,AL2FIN)
      C
            DELAL2 = (AL2FIN - AL2IN)/K
            DELAL1 = DELAL2-RB2/CAPRB1
      C
      C  INITIALIZATION OF ALPHAS
      C
            ALPHA1 = AL1IN + (AL1FIN-AL1IN)*J1
            ALPHA2 = AL2IN + (AL2FIN-AL2IN)*J2
            ALPHI1 = ALPHA1
            J3 = 0
      C
      C  CENTRIFUGAL FORCES
      C
            T1 = M1*R1*OM2
            T2 = M2*R2*OM2
            T3 = M3*R3*OM2
      C
            DENOM = 1. + MU*MU
      C
      C  UPDATE VALUES OF ALPHAS
      C
         14 IF(ALPHA2 .GT. AL2FIN)ALPHA2 = AL2IN
            IF(ALPHA1.GT.AL1FIN)J3=1
            IF(ALPHA1.GT.AL1FIN)ALPHA1=AL1IN
      C
      C  TEST TO DETERMINE IF CONTACT POINT IS IN APPROACH OR RECESS
      C       IF APPROACH, S = 1.
      C       IF RECESS, S = -1.
      C       AT PITCH POINT, S = 0.
      C
            IF(ALPHA1 .LT. TEST1)S1 = 1.
```

```
PROGRAM INVOL4      74/74    OPT=1                    FTN 4.8+508         04/15/81  10.35.05          PAGE      3

      IF(ALPHA2 .LT. TEST2)S2 = 1.
      IF(ALPHA1 .GT. TEST1)S1 = -1.
      IF(ALPHA2 .GT. TEST2)S2 = -1.
      IF(ALPHA1 .EQ. TEST1)S1 = 0.
      IF(ALPHA2 .EQ. TEST2)S2 = 0.
C
C  DETERMINATION OF INPUT FOR MOMENT EXPRESSIONS
C
      A1 = ALPHA1*CAPRB1
      A2 = ALPHA2*CAPRB2
      AA1 = ABS(((1.+MU*MU*S2)*COS(BETA2-THETA2) + MU*(S2-1.)*
     1SIN(BETA2-THETA2))/DENOM)
      AA2 = ABS((SIN(GAMMA3) + MU*COS(GAMMA3))/DENOM)
      AA3 = ABS(((1.+MU*MU*S2)*SIN(BETA2-THETA2) + MU*(1.-S2)*COS(BETA2
     1-THETA2))/DENOM)
      AA4 = ABS((MU*SIN(GAMMA3) - COS(GAMMA3))/DENOM)
      AA5 = ABS((MU*(1.-S1)*SIN(BETA1+THETA1) + (1.+S1*MU*MU)*
     1COS(BETA1+THETA1))/DENOM)
      AA6 = ABS((SIN(GAMMA2) - MU*COS(GAMMA2))/DENOM)
      AA7 = ABS((MU*(1.+S2)*SIN(BETA2-THETA2) + (1.-MU*MU*S2)*
     1COS(BETA2-THETA2))/DENOM)
      AA8 = ABS((MU*(1.-S1)*COS(BETA1+THETA1) - (1.+MU*MU*S1)*
     1SIN(BETA1+THETA1))/DENOM)
      AA9 = ABS((MU*SIN(GAMMA2) + COS(GAMMA2))/DENOM)
      AA10 = ABS(((1.-MU*MU*S2)*SIN(BETA2-THETA2) - MU*(1.+S2)*
     1COS(BETA2-THETA2))/DENOM)
      AA11 = ABS(((1.-MU*MU*S1)*SIN(BETA1+THETA1) + MU*(1.+S1)*
     1COS(BETA1+THETA1))/DENOM)
      AA12 = 1./DENOM
      AA13 = ABS((MU*(1.+S1)*SIN(BETA1+THETA1) - (1.-MU*MU*S1)*
     1COS(BETA1+THETA1))/DENOM)
      AA14 = MU/DENOM
      CC1 = MU*RHO3*(AA2+AA4)
      CC2 = CAPRB2 - MU*(S2*A2-RHO2*(AA7+AA10))
      CC3 = MU*RHO2*(AA6+AA9)
      CC4 = MU*RHO1*(AA12+AA14)
      DD1 = RB3 - MU*(S2*(D2-A2)+RHO3*(AA1+AA3))
      DD2 = RB2 - MU*(S1*(D1-A1)+RHO2*(AA5+AA8))
      DD3 = CAPRB1 - MU*(S1*A1-RHO1*(AA11+AA13))
      ALPH1D = ALPHA1/Z
C
C  OUTPUT MOMENT
C
      MO3 = (DD1*DD2)/(CC2*DD3)*(MIN-T1*CC4) - T2*CC3*DD1/CC2 - T3*CC1
      POINTEF = RATIO*MO3/MIN
      WRITE(6,15)ALPH1D,S1,S2,POINTEF
   15 FORMAT(6X,*ALPHA1 =*,F6.2,3X,*S1 =*,F5.1,3X,*S2 =*,F5.1,3X,
     1*POINT EFFICIENCY =*,F7.5)
      MTOT = MTOT + MO3
C
C  ADVANCE GEAR TRAIN TO NEXT POSITION
C
      ALPHA1 = ALPHA1 + DELAL1
      IF((J3.EQ.1 .AND. ALPHA1.GT.ALPH1I-DELAL1) .OR. (J1.EQ.0. .AND.
     1ALPHA1.GT.AL1FIN-DELAL1))GO TO 16
      ALPHA2 = ALPHA2 + DELAL1*CAPRB1/RB2
      GO TO 14
```

Computer program INVOL4 (cont)


```
16 CYCLEFF = (RATIO-DELAL1*MTOT)/(MIN*(AL1FIN-AL1IN))
   WRITE(6,17)CYCLEFF
17 FORMAT(*0*,5X,*CYCLE EFFICIENCY =*,F5.3)
   IF(ISTOP.NE.0)GO TO 100
   STOP
   END
```

Computer program INVOL4 (cont)

```
SUBROUTINE ALPHA       74/74    OPT=1                         FTN 4.8+508        04/15/81  10.35.05        PAGE      1

              SUBROUTINE ALPHA(CAPRB,RB,THETA,CAPRO,RO,ALIN,ALFIN)
          C
          C   THIS SUBROUTINE COMPUTES THE INITIAL AND FINAL VALUES OF ALPHAS
          C
              ALIN = ((CAPRB + RB)*TAN(THETA) - SQRT(RO*RO - RB*RB))/CAPRB
              ALFIN = SQRT(CAPRO*CAPRO - CAPRB*CAPRB)/CAPRB
              RETURN
              END
```

Computer program INVOL4 (cont)

```
PSUBD1 =  50.   PSUBD2 =  70.

NG1 = 55.   NP2 =  8.   NG2 = 55.   NP3 =  8.

MIN =  .30157E-01   MU =  .200   RPM = 1000.

CAPRP1 =  .55000   CAPRP2 =  .39286

RP2 =  .08000   RP3 =  .05714

THETA1 =  20.000   THETA2 =  20.000

R1 = .22500   R2 = .49700   R3 = .64000

M1 =  .12000E-03   M2 =  .25300E-04   M3 =  .15300E-05

RHO1 = .06200   RHO2 = .02500   RHO3 = .01800

CAPRB1 = .51683   CAPRB2 = .36916   RB2 = .07518   RB3 = .05370

CAPRO1 = .55936   CAPRO2 = .39954   RO2 = .09655   RO3 = .06898

MD =  .275E-05

RANGE DIVISOR =  25

J1 =0.00   J2 =0.00

ALPHA1 = 17.17   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .31414
ALPHA1 = 17.21   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .31839
ALPHA1 = 17.25   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .32266
ALPHA1 = 17.29   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .32695
ALPHA1 = 17.32   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .33126
ALPHA1 = 17.36   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .33560
ALPHA1 = 17.40   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .33995
ALPHA1 = 17.44   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .34432
ALPHA1 = 17.48   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .34871
ALPHA1 = 17.51   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .35313
ALPHA1 = 17.55   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .35756
ALPHA1 = 17.59   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .36202
ALPHA1 = 17.63   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .36649
ALPHA1 = 17.67   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37099
ALPHA1 = 17.71   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37551
ALPHA1 = 17.74   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .37385
ALPHA1 = 17.78   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .37143
ALPHA1 = 17.82   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .36901
ALPHA1 = 17.86   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .36660
ALPHA1 = 17.90   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .36417
ALPHA1 = 17.93   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .36174
ALPHA1 = 17.97   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .35931
ALPHA1 = 18.01   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .35686
ALPHA1 = 18.05   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .35441
ALPHA1 = 18.09   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .35196
ALPHA1 = 18.12   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .34950
ALPHA1 = 18.16   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .33295
ALPHA1 = 18.20   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .33738
ALPHA1 = 18.24   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .34183
ALPHA1 = 18.28   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .34630
ALPHA1 = 18.32   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .35079
ALPHA1 = 18.35   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .35530
```

Computer program INVOL4 (cont)

```
ALPHA1 = 18.39   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .35983
ALPHA1 = 18.43   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .36439
ALPHA1 = 18.47   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .36896
ALPHA1 = 18.51   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37356
ALPHA1 = 18.54   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37818
ALPHA1 = 18.58   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .38281
ALPHA1 = 18.62   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .38748
ALPHA1 = 18.66   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .39216
ALPHA1 = 18.70   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .39686
ALPHA1 = 18.73   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .39507
ALPHA1 = 18.77   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .39251
ALPHA1 = 18.81   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .38995
ALPHA1 = 18.85   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .38739
ALPHA1 = 18.89   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .38481
ALPHA1 = 18.92   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .38223
ALPHA1 = 18.96   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .37965
ALPHA1 = 19.00   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .37706
ALPHA1 = 19.04   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .37446
ALPHA1 = 19.08   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .37186
ALPHA1 = 19.12   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .36925
ALPHA1 = 19.15   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .35189
ALPHA1 = 19.19   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .35650
ALPHA1 = 19.23   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .36113
ALPHA1 = 19.27   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .36578
ALPHA1 = 19.31   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37045
ALPHA1 = 19.34   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37514
ALPHA1 = 19.38   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37986
ALPHA1 = 19.42   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .38460
ALPHA1 = 19.46   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .38936
ALPHA1 = 19.50   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .39414
ALPHA1 = 19.53   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .39894
ALPHA1 = 19.57   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .40376
ALPHA1 = 19.61   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .40861
ALPHA1 = 19.65   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .41347
ALPHA1 = 19.69   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .41836
ALPHA1 = 19.73   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .41646
ALPHA1 = 19.76   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .41375
ALPHA1 = 19.80   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .41104
ALPHA1 = 19.84   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .40832
ALPHA1 = 19.88   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .40560
ALPHA1 = 19.92   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .40287
ALPHA1 = 19.85   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .40014
ALPHA1 = 19.93   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .39740
ALPHA1 = 20.03   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .39466
ALPHA1 = 20.07   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .39190
ALPHA1 = 20.11   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .38915
ALPHA1 = 20.14   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37096
ALPHA1 = 20.18   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .37575
ALPHA1 = 20.22   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .38057
ALPHA1 = 20.26   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .38540
ALPHA1 = 20.30   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .39026
ALPHA1 = 20.34   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .39513
ALPHA1 = 20.37   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .40003
ALPHA1 = 20.41   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .40495
ALPHA1 = 20.45   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .40990
ALPHA1 = 20.49   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .41486
ALPHA1 = 20.53   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .41985
ALPHA1 = 20.56   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .42486
ALPHA1 = 20.60   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .42989
ALPHA1 = 20.64   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .43495
ALPHA1 = 20.68   S1 =  1.0   S2 =  1.0   POINT EFFICIENCY = .44002
```

Computer program INVOL4 (cont)

```
ALPHA1 = 20.72   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .43800
ALPHA1 = 20.75   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .43514
ALPHA1 = 20.79   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .43228
ALPHA1 = 20.83   S1 =  1.0   S2 = -1.0   POINT EFFICIENCY = .42942
ALPHA1 = 20.87   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .42978
ALPHA1 = 20.91   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .42538
ALPHA1 = 20.94   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .42100
ALPHA1 = 20.98   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .41664
ALPHA1 = 21.02   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .41229
ALPHA1 = 21.06   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .40796
ALPHA1 = 21.10   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .40365
ALPHA1 = 21.14   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .38349
ALPHA1 = 21.17   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .38701
ALPHA1 = 21.21   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .39052
ALPHA1 = 21.25   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .39404
ALPHA1 = 21.29   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .39755
ALPHA1 = 21.33   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .40105
ALPHA1 = 21.36   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .40455
ALPHA1 = 21.40   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .40805
ALPHA1 = 21.44   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .41155
ALPHA1 = 21.48   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .41504
ALPHA1 = 21.52   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .41852
ALPHA1 = 21.55   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .42201
ALPHA1 = 21.59   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .42549
ALPHA1 = 21.63   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .42896
ALPHA1 = 21.67   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .43243
ALPHA1 = 21.71   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .42891
ALPHA1 = 21.75   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .42458
ALPHA1 = 21.78   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .42027
ALPHA1 = 21.82   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .41598
ALPHA1 = 21.86   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .41171
ALPHA1 = 21.90   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .40745
ALPHA1 = 21.94   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .40321
ALPHA1 = 21.97   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .39899
ALPHA1 = 22.01   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .39478
ALPHA1 = 22.05   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .39059
ALPHA1 = 22.09   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .38641
ALPHA1 = 22.13   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .36697
ALPHA1 = 22.16   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .37034
ALPHA1 = 22.20   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .37371
ALPHA1 = 22.24   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .37707
ALPHA1 = 22.28   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .38043
ALPHA1 = 22.32   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .38379
ALPHA1 = 22.36   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .38714
ALPHA1 = 22.39   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .39049
ALPHA1 = 22.43   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .39383
ALPHA1 = 22.47   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .39717
ALPHA1 = 22.51   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .40051
ALPHA1 = 22.55   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .40384
ALPHA1 = 22.58   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .40717
ALPHA1 = 22.62   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .41049
ALPHA1 = 22.66   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .41381
ALPHA1 = 22.70   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .41040
ALPHA1 = 22.74   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .40621
ALPHA1 = 22.77   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .40204
ALPHA1 = 22.81   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .39789
ALPHA1 = 22.85   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .39376
ALPHA1 = 22.89   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .38954
ALPHA1 = 22.93   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .38553
ALPHA1 = 22.96   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .38145
ALPHA1 = 23.00   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .37737
```

Computer program INVOL4 (cont)

```
ALPHA1 = 23.04   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .37332
ALPHA1 = 23.08   S1 = -1.0   S2 = -1.0   POINT EFFICIENCY = .36928
ALPHA1 = 23.12   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .35055
ALPHA1 = 23.16   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .35378
ALPHA1 = 23.19   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .35700
ALPHA1 = 23.23   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .36021
ALPHA1 = 23.27   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .36342
ALPHA1 = 23.31   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .36663
ALPHA1 = 23.35   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .36983
ALPHA1 = 23.38   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .37303
ALPHA1 = 23.42   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .37623
ALPHA1 = 23.46   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .37942
ALPHA1 = 23.50   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .38261
ALPHA1 = 23.54   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .38579
ALPHA1 = 23.57   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .38897
ALPHA1 = 23.61   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .39214
ALPHA1 = 23.65   S1 = -1.0   S2 =  1.0   POINT EFFICIENCY = .39531

CYCLE EFFICIENCY = .385
```

REFERENCE

B-1 G.G. Lowen, City College of N.Y., and F.R. Tepper, ARRADCOM, "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

APPENDIX C

DESIGN OF CLOCK TOOTH GEAR AND PINION SET ACCORDING TO BRITISH STANDARD NO. 978

The present appendix deals with the design of clock teeth according to British Standard No. 978 (ref C-1): Gears for Instruments and Clockwork Mechanisms; Part 2, Cycloidal Type Gears.*

Computer program BRITSTD, shows the design of gear and pinion meshes with clock teeth in such a manner that its output data may serve as the input data for the computer programs CLOCK1, CLOCK2, CLOCK3, and CLOCK4 of Fuze Gear Train Analysis (ref C-2).

British Standard No. 978

The British Standard No. 978 (ref C-1) is used to determine the important dimensions for clock type gears and pinions. It originally employs the module (m) as a basic parameter. It is presently more practical to operate in terms of diametral pitch (P_d), so that

$$P_d = \frac{1}{m} \qquad \text{(C-1)}$$

With the above, the module may become an irrational fraction.

Gear Design Parameters

The important design parameters for the gears of step-up meshes are shown in tables 2 and 3 of reference C-1. These parameters are: the tooth thickness along the pitch circle, the addendum, and the radius of curvature of the addendum. The addendum factor f as well as the addendum radius factor f_r of table 3 of reference C-1 are functions of the gear ratio and the number of teeth in the mating pinion. Similar information is given by charts 1 and 2 of reference C-1.

Pinion Design Parameters

Pinions are designed according to clause 5, and figures 3 and 4, as well as table 4 of reference C-1.

*This standard was used since it was the only complete standard available to the authors at the time this work was undertaken.

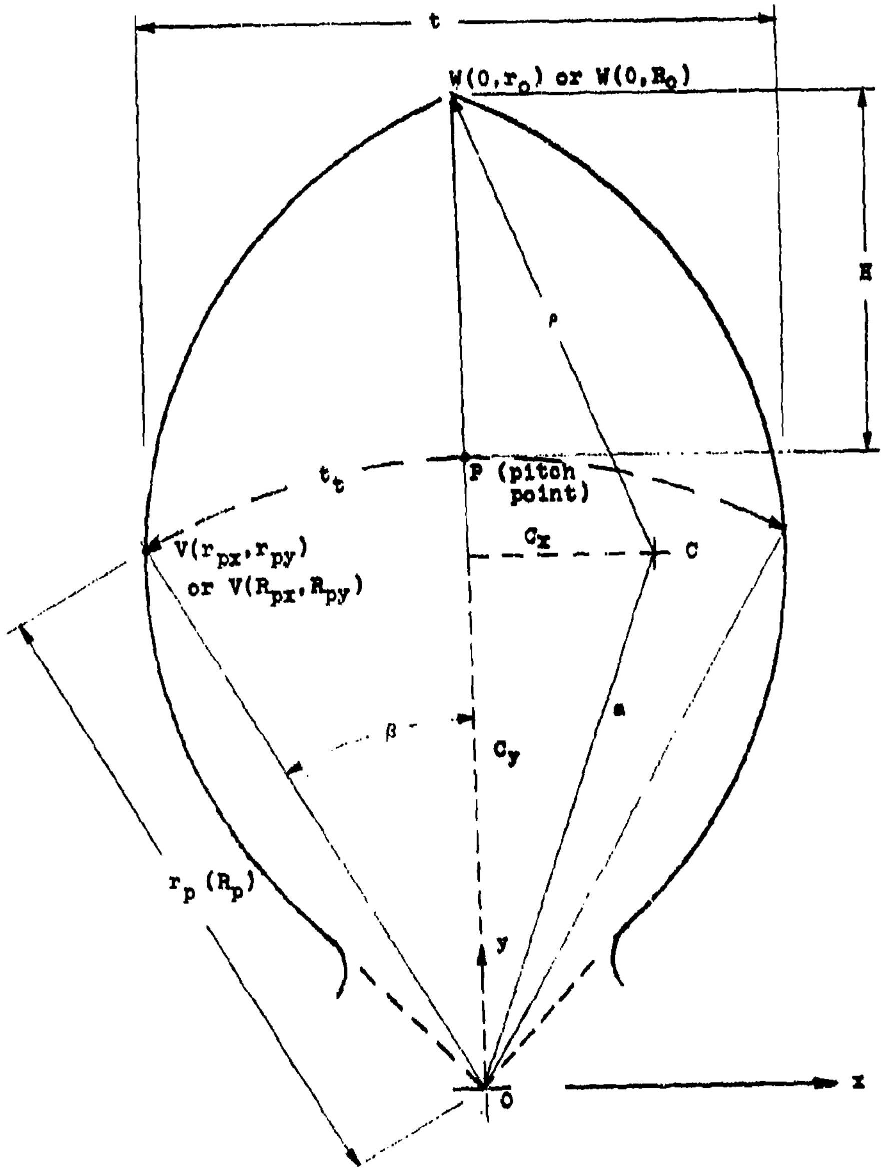

Figure C-1. Geometry of clock tooth for determination of center of curvature C

Clock Tooth Design With British Standard

1. Determination of Center of Curvature of Addendum Radius

Before the clock gear design program proper can be shown, it is necessary to derive a procedure by which the location of the center of curvature C of the addendum radius of curvature may be determined whenever the center of curvature is not located on the intersection of the center line of the tooth and the pitch circle, i.e., the addendum height equals the radius of curvature of the addendum.

The British Standard (ref C-1) provides information concerning the tooth thickness t_t along the pitch circle, the addendum height H, as well as the radius of curvature ρ of the addendum. (Note change of nomenclature when compared to reference C-1.)

A schematic representation of a clock tooth which is used in the determination of the coordinates C_x and C_y of the center of curvature C is shown in figure C-1. The following derivation is based on the idea that the location of the center of curvature of a circle of radius ρ may be determined if the coordinates of the two points W and V on this circle are known. The equation of this circle is given by

$$(x - C_x)^2 + (y - C_y)^2 = \rho^2 \qquad \text{(C-2)}$$

For point V with the known coordinates $x = r_{px}$ and $y = r_{py}$, the above becomes

$$(r_{px} - C_x)^2 + (r_{py} - C_y)^2 = \rho^2 \qquad \text{(C-3)}$$

For point W with the known coordinates x = 0 and $y = r_o$, one obtains

$$C^2_x + (r_o - C_y)^2 = \rho^2 \qquad \text{(C-4)}$$

where

r_p = pitch radius

$$r_o = r_p + H \qquad \text{(C-5)}$$

$$\beta = \tan^{-1}(t_t/2r_p) \qquad \text{(C-6)}$$

$$r_{px} = -r_p \sin\beta \qquad \text{(C-7)}$$

$$r_{py} = r_p \cos\beta \qquad \text{(C-8)}$$

Simultaneous solution of equations C-3 and C-4 leads to

$$C_y = \frac{-(CD - r_o E^2) \pm \sqrt{(CD - r_o E^2)^2 - (D^2 + E^2)(C^2 - AE^2)}}{D^2 + E^2} \qquad \text{(C-9)}$$

and

$$C_x = \frac{C + DC_y}{E} \qquad \text{(C-10)}$$

where, in the above

$$A = \rho^2 - r_o^2 \qquad \text{(C-11)}$$

$$B = \rho^2 - r_p^2 \qquad \text{(C-12)}$$

$$C = A - B \qquad \text{(C-13)}$$

$$D = 2(r_o - r_{py}) \qquad \text{(C-14)}$$

$$E = 2r_{px} \qquad \text{(C-15)}$$

It is to be noted that the smaller of the two possible solutions in equation C-9 must govern.

2. Computer Program BRITSTD

The computer program BRITSTD is designed to furnish the input parameters necessary for computer programs CLOCK1, CLOCK2, CLOCK3, and CLOCK4 of reference C-2.

Input Parameters. The following parameters represent the input data for the computer program:

PSUBD = P_d, the diametral pitch.

NG = N_G, number of teeth of the gear

NP = N_P, number of teeth of the pinion

F = f, constant for addendum computation (tables 2 and 3 or chart 1 of reference C-1). Obtained by linear interpolation if not directly available from standard.

FR = f_r, constant for determination of radius of curvature ρ (see tables 2 and 3 or chart 2, ref C-1). Also obtained by linear interpolation if not directly available from tables.

PROFILE = 1, corresponds to Profile A of figure 4 and table 4 (ref C-1)

PROFILE = 2, corresponds to Profile B of figure 4 and table 4 (ref C-1)

PROFILE = 3, corresponds to Profile C of figure 4 and table 4 (ref C-1)

ISTOP = arbitrary single digit integer for multiple data sets. Must be zero for last data set.

Computations.

Design of Gear. To start with, the program determines the module with the help of equation C-1. It further determines (for nomenclature, see figure C-1):

TTG = t_{tG}, according to table 2 of reference C-1. Note that the subscript G stands for gear.

ADDG = H_G, according to table 2 of reference C-1

RHOG = ρ_G, according to table 2 of reference C-1

CAPRP = $R_p = \frac{N_G m}{2}$

ROG = $R_{oG} = R_p + H_G$

BETAG = $\beta_G = \frac{t_{tG}}{(2R_p)}$

CAPRPX = R_{px}, the x coordinate of point V (fig. C-1)

CAPRPY = R_{py}, the y coordinate of point V (fig. C-1)

The subroutine CENTER computes the x and y coordinates C_x and C_y of the center of curvature according to equations C-10 and C-9, respectively, together with the distance a = OC, as well as the maximum tooth thickness according to

$$t = 2(\rho - C_x) \qquad \text{(C-16)}$$

For programming purposes the maximum tooth thickness of the gear becomes

$$TG = t_G$$

while for the pinion it is expressed by

$$TP = t_P$$

Pinion Design. The computation of the pinion parameters starts with the determination of the pinion radius

$$RP = r_P$$

It is to be noted that the designations of all pinion variables are similar to those of the gear variables with the letter P substituted for the letter G.

Statement numbers 29 through 34 represent profile selection tests according to figure 4 and table 4 of reference C-1. The resulting computations depend upon the pinion profile chosen as well as the number of pinion teeth involved. The specific pinion parameters are computed according to the formulae in the table 4 (ref C-1). Whenever the addendum radius center of curvature does not coincide with the pitch point, subroutine CENTER is called for the determination of the desired dimensions.

Mesh Starting Test. The mesh starting test is based upon equation E-49 (ref C-2), which, when satisified, assures that initial contact is made in the round on round phase of contact. To perform this test, the parameters b (the center distance between gear and pinion), the angle γ_G, according to equation D-5 (ref C-2), and the length of flat f_G, according to equation D-7, (ref C-2), must first be determined. If the mesh starts in the normal manner, the program will print out MESH BEGINS IN NORMAL MANNER. In case the mesh causes an abnormal situation, the program will print MESH BEGINS WITH FLAT ON ROUND.

Output. The output of the program is best explained with the help of the first of the five sets of results shown at the end of the program. The underlined values represent the needed inputs to all computer programs dealing with clock teeth. The relevant values of the first three sets of results will serve as input to the revised computer program CLOCK3, as given in appendix D. Similarly, the relevant values of the fourth and fifth sets of results represent input for the revised computer program CLOCK4, given in appendix E.

Input Parameters.

PSUBD	=	P_d =	44
F	=	f =	1.450
FR	=	f_r =	2.137
PROFILE	=	2.0	
NG	=	n_G =	42
NP	=	n_P =	8

Computed Values.

For the gear			For the pinion		
CAPRP	= R_p	= 0.47727 in. (1.2122 cm)	RP	= r_p	= 0.09091 in. (0.2309 cm)
AG	= a_G	= 0.47343 in. (1.2025 cm)	AP	= a_P	= 0.09083 in. (0.2307 cm)
RHOG	= ρ_G	= 0.04857 in. (0.1234 cm)	RHOP	= ρ_P	= 0.01591 in. (0.0404 cm)
TG	= t_G	= 0.03609 in. (0.0917 cm)	TP	= t_P	= 0.02382 in. (0.0605 cm)
TTG	= t_{tG}	= 0.03568 in. (0.0906 cm)	TTP	= t_{tP}	= 0.02386 in. (0.0606 cm)
CXG	= C_{xG}	= 0.03052 in. (0.0775 cm)	CXP	= C_{xP}	= 0.00400 in. (0.0102 cm)
CYG	= C_{yG}	= 0.47245 in. (1.2000 cm)	CYP	= C_{yP}	= 0.09074 in. (0.2305 cm)

Also, MESH BEGINS IN NORMAL MANNER

Computer program BRITSTD

```
PROGRAM BRITSTD    74/74   OPT=1                    FTN 4.6+420      01/12/79  15.58.47      PAGE   1

      PROGRAM BRITSTD(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      REAL NG,NP,MOD
 1000 READ(5,1)PSUBD,NG,NC,F,FR,PROFILE,ISTOP
    1 FORMAT(6F10.5,9X,I1)
      WRITE(6,2)PSUBD,F,FR,PROFILE
    2 FORMAT(*1*/6X,*PSUBD =*,F4.0/6X,*F =*,F6.3,/6X,*FR =*,F6.3/
     16X,*PROFILE =*,F3.0/)
      MOD = 1./PSUBD
C
C  DESIGN OF GEAR
C
      TTG = 1.57*MOD
      ADDG = F*MOD
      RHOG = FR*MOD
      CAPRP = NG*MOD/2.
      ROG = CAPRP + ADDG
      BETAG = TTG/(2.*CAPRP)
      CAPRPX = -CAPRP*SIN(BETAG)
      CAPRPY = CAPRP*COS(BETAG)
      CALL CENTER(RHOG,ROG,CAPRPX,CAPRPY,AG,TG,CXG,CYG)
      WRITE(6,3)CAPRP,AG,RHOG,TG,NG,TTG,CXG,CYG
    3 FORMAT(    6X,*CAPRP =*,F8.5/6X,*AG =*,F8.5/6X,*RHOG =*,F8.5/6X,
     1*TG =*,F8.5/6X,*NG =*,F4.0/6X,*TTG =*,F8.5/6X,*CXG =*,F8.5/6X,
     2*CYG =*,F8.5/)
C
C  PINION DESIGN
C
      RP = NP*MOD/2.
      IF(NP .LE. 10. .AND. PROFILE .EQ. 1.)GO TO 4
      IF(NP .LE. 10. .AND. PROFILE .EQ. 2.)GO TO 6
      IF(NP .LE. 10. .AND. PROFILE .EQ. 3.)GO TO 7
      IF(NP .GE. 11. .AND. PROFILE .EQ. 1.)GO TO 8
      IF(NP .GE. 11. .AND. PROFILE .EQ. 2.)GO TO 9
      IF(NP .GE. 11. .AND. PROFILE .EQ. 3.)GO TO 10
    4 RHOP = .525*MOD
      AP = RP
      TP = 2.*RHOP
      WRITE(6,5)RP,AP,RHOP,TP,NP
    5 FORMAT(6X,*RP =*,F8.5/6X,*AP =*,F8.5/6X,*RHOP =*,F8.5/6X,*TP =*,
     1F8.5/6X,*NP =*,F4.0/)
      GO TO 102
    6 TTP = 1.05*MOD
      ADDP = .67*MOD
      RHOP = .70*MOD
      ROP = RP + ADDP
      BETAP = TTP/(2.*RP)
      RPX = -RP*SIN(BETAP)
      RPY = RP*COS(BETAP)
      CALL CENTER(RHOP,ROP,RPX,RPY,AP,TP,CXP,CYP)
      GO TO 100
    7 TTP = 1.05*MOD
      ADDP = .855*MOD
      RHOP = 1.05*MOD
```

Computer program BRITSTD (cont)

```
      PROGRAM BRITSTD    74/74    OPT=1                    FTN 4.6+420        01/12/79  15.58.47         PAGE    2

            ROP = RP + ADDP
            BETAP = TTP/(2.*RP)
            RPX = -RP*SIN(BETAP)
            RPY = RP*COS(BETAP)
            CALL CENTER(RHOP,ROP,RPX,RPY,AP,TP,CXP,CYP)
            GO TO 100
          8 RHOP = .625*MOD
            AP = RP
            TP = 2.*RHOP
            WRITE(6,5)RP,AP,RHOP,TP,MF
            GO TO 102
          9 TTP = 1.25*MOD
            ADDP = .885*MOD
            RHOP = .84*MOD
            ROP = RP + ADDP
            BETAP = TTP/(2.*RP)
            RPX = -RP*SIN(BETAP)
            RPY = RP*COS(BETAP)
            CALL CENTER(RHOP,ROP,RPX,RPY,AP,TP,CXP,CYP)
            GO TO 100
         10 TTP = 1.25*MOD
            ADDP = 1.85*MOD
            RHOP = 1.25*MOD
            ROP = RP + ADDP
            BETAP = TTP/(2.*RP)
            RPX = -RP*SIN(BETAP)
            RPY = RP*COS(BETAP)
            CALL CENTER(RHOP,ROP,RPX,RPY,AP,TP,CXP,CYP)
        100 WRITE(6,101)RP,AP,RHOP,TP,MP,TTP,CXP,CYP
        101 FORMAT(6X,*RP =*,F8.5/6X,*AP =*,F8.5/6X,*RHOP =*,F8.5/6X,*TP =*,
           1F8.5/6X,*MP =*,F4.0/6X,*TTP =*,F8.5/6X,*CXP =*,F8.5/6X,*CYP =*,
           2F8.5/)
      C
      C  MESH STARTING TEST
      C
        102 B = CAPRP - RP
            GAMMAG = ASIN(RHOG/AG)
            FG = AG*SIN(GAMMAG)
            TEST = AP + SQRT(FG*FG + RHOP*RHOP)
            IF(B .LT. TEST)GO TO 105
        103 WRITE(6,104)
        104 FORMAT(6X,*MESH BEGINS IN NORMAL MANNER*)
            IF(ISTOP .NE. 0)GO TO 1000
            GO TO 9999
        105 WRITE(6,106)
        106 FORMAT(6X,*MESH BEGINS WITH FLAT ON ROUND*)
            IF(ISTOP .NE. 0)GO TO 1000
       9999 STOP
            END
```

Computer program BRITSTD (cont)

```
SUBROUTINE CENTER      74/74    OPT=1                    FTN 4.6+420       01/12/79  15.50.47       PAGE    1

      SUBROUTINE CENTER(RHO,RO,RX,RY,AA,T,CX,CY)
      A = RHO*RHO - RO*RO
      B = RHO*RHO - RX*RX - RY*RY
      C = A - B
      D = 2.*(RO - RY)
      E = 2.*RX
      ROOT = SQRT((C*D-   RO*E*E)**2 - (D*D+E*E)*(C*C-A*E*E))
      CY1 = (-(C*D-RO*E*E) + ROOT)/(D*D+E*E)
      CY2 = (-(C*D-RO*E*E) - ROOT)/(D*D+E*E)
      IF(CY1 .LT. CY2)GO TO 1
      CY = CY2
      GO TO 2
    1 CY = CY1
    2 CX = (C+CY*D)/E
      AA = SQRT(CX*CX+CY*CY)
      T = 2.*(RHO-CX)
      RETURN
      END
```

Computer program BRITSTD (cont)

```
PSURD = 44.
F = 1.450
FR = 2.137
PROFILE = 2.

CAPRP =  .47727
AG =  .47343
RHOG =  .04857
TG =  .03609
NG = 42.
TTG =  .03568
CXG =  .03052
CYG =  .47245

RP =  .09091
AP =  .09083
RHOP =  .01591
TP =  .02382
NP =  8.
TTP =  .02386
CXP =  .00406
CYP =  .09074

MFSH BEGINS IN NORMAL MANNER
```

Computer program BRITSTD (cont)

```
PSURD = 65.
F = 1.465
FR = 2.160
PROFILE = 2.

CAPRP =  .20769
AG =  .20559
RHOG =  .03323
TG =  .02438
NG = 27.
TTG =  .02415
CXG =  .02104
CYG =  .20451

RP =  .06923
AP =  .06917
RHOP =  .01077
TP =  .01613
NP =  9.
TTP =  .01615
CXP =  .00270
CYP =  .06911

MESH BEGINS IN NORMAL MANNER
```

Computer program BRITSTD (cont)

```
PSURD = 77.
F = 1.465
FR = 2.140
PROFILE = 2.

CAPRP =  .17532
AG =  .17355
RHOG =  .02805
TG =  .02058
NG = 27.
TTG =  .02039
CXG =  .01776
CYG =  .17264

RP =  .05844
AP =  .05839
RHOP =  .00909
TP =  .01362
NP =  9.
TTP =  .01364
CXP =  .00228
CYP =  .05834

MFSH BEGINS IN NORMAL MANNER
```

Computer program BRITSTD (cont)

```
PSUBD = 50.
F = 1.467
FR = 2.161
PROFILE = 2.

CAPRP = .55000
AG = .54656
RHOG = .04322
TG = .03175
NG = 55.
TTG = .03140
CXG = .02735
CYG = .54587

RP = .08000
AP = .07993
RHOP = .01400
TP = .02096
NP = 8.
TTP = .02100
CXP = .00352
CYP = .07985

MESH BEGINS IN NORMAL MANNER
```

Computer program BRITSTD (cont)

```
PSUBD = 70.
F = 1.467
FR = 2.161
PROFILE = 2.

CAPRP =  .39285
AG =  .39040
RHOG =  .03087
TG =  .02268
NG = 55.
TTG =  .02243
CXG =  .01953
CYG =  .38991

RP =  .05714
AP =  .05709
RHOP =  .01000
TP =  .01497
NP =  8.
TTP =  .01500
CXP =  .00251
CYP =  .05704

MESH BEGINS IN NORMAL MANNER
```

REFERENCE

C-1 British Standard No. 978 for Gears for Instruments and Clockwork Mechanisms, Part 2, Cycloidal Type Gears (1952).

C-2 G.G. Lowen, City College of N.Y., and F.R. Tepper, ARRADCOM, "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

APPENDIX D

COMPUTER PROGRAM CLOCK3 (REVISED)

The original program descriptions were given in appendix I of Fuze Gear Train Analysis (ref D-1). The following appendix contains revised descriptions, listings and sample outputs of computer program CLOCK3, which computes point and cycle efficiencies for three pass clock gear trains in a spin environment.

The following changes were made:

1. The diametral pitches of all three meshes are given as data and are printed in the output.

2. The initialization parameters J are introduced. They are given as part of the data and are listed in the output. These parameters allow the initial points of contact of the three meshes to be chosen at arbitrary points within the ranges of possible contact points.

The kinematics of computer program CLOCK3 is based on the work in appendix G (ref D-1), while the moment input-output relationships are derived in appendix H (ref D-1). Even though the fuze related geometry produces different expressions for the various meshes, the kinematic computations of the individual meshes are very similar to those shown in computer program CLOCK1 in appendix F (ref D-1) for the single mesh in the standard position. It is also assumed that all three meshes will have been tested by computer program CLOCK1 (ref D-1) for their geometric suitability, i.e., whether there is enough room for tip radii.

Input Parameters

The following parameters represent the input data for the program (for explanations and nomenclature, see appendixes C and F, reference D-1):

PSUBD1, PSUBD2, PSUBD3 = P_{d1}, P_{d2}, P_{d3}

MU, coefficient of friction

RPM, spin velocity

CAPRP1, CAPRP2, CAPRP3, RP2, RP3, RP4, pitch radii of gears and pinions with nomenclature of figure G-1 (ref D-1)

RHOG1, RHOG2, RHOG3, RHOP1, RHOP2, RHOP3, radii of curvature of circular arc portion of gear and pinion teeth

ACG1, ACG2, ACG3[D-1] = a_{CGi}, distance from the center of rotation of the gear of the i^{th} mesh to the center of curvature of the circular arc portion of the gear tooth. (Unless otherwise noted, this and all following numbering schemes refer to those associated with the mesh mechanics as given in the text of appendixes G and H of reference D-1).

ACP1, ACP2, ACP3 = a_{CPi}, distance from the center of rotation of the pinion of the i^{th} mesh to the center of curvature of the circular arc portion of the pinion tooth

R1, R2, R3, R4 = δ_i (nomenclature of fig. G-1, ref D-1)

TG1, TG2, TG3, TP1, TP2, TP3, maximum thicknesses of gear and pinion teeth (mesh nomenclature)

NG1, NG2, NG3, NP2, NP3, NP4, numbers of teeth in various gears and pinions (nomenclature of fig. G-1, ref D-1)

RHO1, RHO2, RHO3, RHO4, gear and/or pinion pivot radii (nomenclature of fig. G-1, ref D-1)

M1, M2, M3, M4, masses of gear and/or pinion combinations

MD = md^2, see appendix A of this report

K, range divisor

J1, J2, J3, initialization parameters

The angular velocity of the input gear is incorporated into the program as PHDOT1 = 1. All velocity computations are based on this model. The input motion in the fuze gearing model is negative (fig. G-1, ref D-1).

Computations

Computation of Gear Tooth Parameters

The tooth parameters of the gears and pinions of all three meshes are first computed. These computations are essentially the same as those shown in computer program CLOCK1 (ref D-1) for a single mesh. Certain parameters are omitted because they have been checked separately by using computer program CLOCK1 (ref D-1) and are not required for the kinematics of computer program CLOCK3 (ref D-1).

[D-1] Since many parts of the computer program were written before the nomenclature for these distances was changed in the report from a_{CGi} and a_{CPi} to a_{Gi} and a_{Pi}, there is a certain discrepancy between the program and the report.

In addition, the pivot to pivot distances B1, B2 and B3 are obtained.

Computation of MIN, GAMMAS and BETAS

To begin with, the program computes the input moment

$$MIN = M_{in} = md^2 \omega^2 \quad \text{(D-1)}$$

Subsequently, the angles γ_2, γ_3, γ_4 and β_1, β_2, β_3 are established according to the expressions of appendix A (ref D-1).

Computation of Other Parameters

The angles $\Delta\phi_i$ and $\Delta\psi_i$ between the centerlines of adjacent gear and pinion teeth, respectively, are determined in this section of the computations. In addition, the lengths L_i are found (equations G-7, G-53 and G-88, ref D-1). Finally, the centrifugal forces Q_1, Q_2, Q_3 and Q_4 are computed according to equations H-65, H-46, H-25 and H-6 (ref D-1), respectively.

Preliminary Computations for Mesh 1

Determination of Transition Angle. The primary consideration for determining the transition angles in the fuze related clock gear meshes is identical with that used in appendix F (ref D-1). The transition angle ψ_T is established as that angle for which, depending upon whether the input angle ϕ has counterclockwise or clockwise motion, a small increase or decrease in ϕ, respectively, will cause the associated value of g to become smaller than its transition value f_p. Since the gear mesh 1 turns in a clockwise direction, the above increment of ϕ will be negative.

The program uses this criterion in the following manner:

1. Transition angles ψ_{1T1} and ψ_{1T2} are computed according to equation G-39 (ref D-1).

2. The subroutine TRANS1 (which is valid for meshes in which the input gear has clockwise rotation, as is the case also for mesh 3) is called, and the angle ϕ_{1T1} (PHIT), which is associated with ψ_{1T1}, is computed with the help of equations G-40 and G-41 (ref. D-1).

3. The angle ϕ is made slightly smaller than ϕ_{1T1} to produce the angle PHINEXT, and equation G-29 (ref D-1) is used to find the associated angle PSINEX. Since there are two such angles, the subroutine selects the one which is

closest in value to the transition angle ψ_{1T1}. Subsequently, the associated value of g_{11} is computed according to equation G-27 (ref D-1).

4. Steps 1 and 2 are then repeated identically for the second transition angle ψ_{1T2}. This results in the determination of g_{12}.

5. Control returns to the main program, and that value of ψ_{1T} is chosen for which the associated value of g_1 is smaller than f_{p1}.

For checking, a subsidiary test, which is similar to the one shown in appendix F (ref D-1), is added to the program. It is based on the idea that, for the correct transition angle ψ_{1T}, the line representing the flat portion of the pinion will make a smaller angle with the centerline O_1O_2 than will be the case for the incorrect one. TEST11 and TEST12 find these angles with the help of the expressions shown below. These expressions hold for all values of β_1 and make use of a new variable ψ_{test}, which had to be introduced since the tests require that the transition angles be expressed in a range between -180° and +180°. Thus,

For $0° < \psi_{test} < 180°$

$$TEST11 = \left| \pi - \beta_1 + \psi_{test} - \alpha_{P1} \right|. \tag{D-2}$$

For $-180° < \psi_{test} < 0°$

$$TEST12 = \left| \pi + \beta_1 - (\psi_{test} + 2\pi - \alpha_{P1}) \right| \tag{D-3}$$

To determine the angle ψ_{test}, let

$$\psi_{test} = \psi_{1T} \text{ if } -180^0 < \psi_{1T} < 180^0 \tag{D-4}$$

$$\psi_{test} = \psi_{1T} + 2\pi \text{ if } \psi_{1T} < -180^0 \tag{D-5}$$

$$\psi_{test} = \psi_{1T} - 2\pi \text{ if } \psi_{1T} > 180^0 \tag{D-6}$$

Determination of Correct Sign for Round on Flat Regime. The sign preceding the square root in equation G-29 (ref D-1), for the round on flat regime, is determined with the help of ϕ_{1T}. The condition yielding that angle ψ_{1F} which is closest to the angle ψ_{1T} governs. The variable SIGN1F is used for the sign in question.

Computation of Latest and Earliest Possible Values of ϕ_1 and ψ_1. The latest and earliest possible values of the gear and pinion angles ϕ_1 and ψ_1, respectively, are found by continuously evaluating the round on flat regime equation G-29 (ref D-1), using the previously determined value of SIGN1F, and simultaneously checking the contact condition for the subsequent set of teeth as given by equation G-46 (ref D-1).[D-2] This loop is initiated at the transition angle ϕ_{1T}, and it is terminated when the condition of equation G-46 (ref D-1) is met. This allows the determination of the angles PHI1F and PSI1FF, at which the first set of teeth loses contact, as well as of the angles PHI1I and PSI1I at which the second set of teeth simultaneously comes into engagement. The earliest possible engagement angles PHI1I and PSI1I are obtained by adding $\Delta\phi_1$ to the loss of contact angle PHI1F and by subtracting $\Delta\psi_1$ from the loss of contact angle PSI1FF. (PHI1F and PSI1FF represent the latest possible values of ϕ_1 and ψ_1.)

Determination of Correct Sign for Round on Round Regime. Equation G-12 (ref D-1) is used to determine the angle ψ_1, while the gear and pinion are in the round on round regime. The correct sign for this expression is obtained by comparing the value ψ_1, as computed with PHI1I, with the value for PSI1I. SIGN1R is the variable used for the desired sign.

Preliminary Computations for Mesh 2

Determination of Transition Angle. The primary criterion for determining the transition angle is again similar to that used in appendix F (ref D-1) and described earlier for mesh 1.

1. Transition angles ψ_{2T1} and ψ_{2T2} are computed according to equation G-79 (ref D-1).

2. The subroutine TRANS2, which is valid for meshes in which the input gear has counterclockwise rotation, is called, and the angle ϕ_{2T1}, which is associated with ψ_{2T1} is computed with the help of equations G-80 and G-81 (ref D-1).

3. The angle ϕ_2 is made slightly larger than ϕ_{2T1} to produce the angle PHINEXT, and equation G-71 (ref D-1) is used to find the associated output angle PSINEX. Since there are two such angles, the subroutine selects the one which is closest to the transition value ψ_{2T1}. Subsequently, the associated value of g_{21} is computed according to equation G-69 (ref D-1).

[D-2] As in appendixes A and B, the actual initial contact does not necessarily coincide with the earliest possible one. Again, use is made of the initialization parameters J_i ($i = 1, 2, 3$).

4. Steps 2 and 3 are then repeated identically for the second transition angle ψ_{2T2}. This results in the determination of g_{22}.

5. Control returns to the main program, and that value of ψ_{2T} is chosen for which the associated value of g_2 is smaller than f_{p2}.

The procedure for the associated subsidiary test for the transition angle is similar to that for mesh 1 and is given by:

For $0° < \psi_{test} < 180°$

$$TEST21 = \left| \pi - \beta_2 + \psi_{test} + \alpha_{p2} \right| \quad \text{(D-7)}$$

For $-180° < \psi_{test} < 0°$

$$TEST22 = \left| \beta_2 + \pi - (\psi_{test} + 2\pi + \alpha_{p2}) \right| \quad \text{(D-8)}$$

To determine the angle ψ_{test}, let

$$\psi_{test} = \psi_{2T} \text{ if } -180^0 < \psi_{2T} < 180^0 \quad \text{(D-9)}$$

$$\psi_{test} = \psi_{2T} + 2\pi \text{ if } \psi_{2T} < -180^0 \quad \text{(D-10)}$$

$$\psi_{test} = \psi_{2T} - 2\pi \text{ if } \psi_{2T} > 180^0 \quad \text{(D-11)}$$

Determination of Correct Sign for Round on Flat Regime. The sign preceding the square root in equation G-71 (ref D-1), for the round on flat regime, is determined with the help of ϕ_{2T}. The condition yielding that angle ψ_{2F} which is closest to the angle ψ_{2T} governs. The variable SIGN2F is used for the sign in question.

Computation of Latest and Earliest Possible Values of ϕ_2 and ψ_2. The latest and earliest possible values of the gear and pinion angles ϕ_2 and ψ_2, respectively, are found by continuously evaluating the round on flat equation G-71 (ref D-1), using the previously determined value of SIGN2F, and simultaneously checking the contact condition for the subsequent set of teeth, as given by equation G-86 (ref D-1). This loop is initiated at the transition angle ϕ_{2T} and is terminated when the condition of equation G-86 (ref D-1) is met. (Recall that in meshes 1 and 3 the driving gear turns clockwise, while in mesh 2 it turns in a counterclockwise direction.) This allows the determination of the two angles PHI2F and PSI2FF at which the first set of teeth loses contact as well as of the angles PHI2I and PSI2I at which the second set of teeth simultaneously comes into contact. The earliest possible engagement angles PHI2I and PSI2I are obtained by subtracting $\Delta\phi_2$ from the loss of contact angle PSI2F and by adding $\Delta\psi_2$ to the loss of contact angle PSI2FF. (PHI2F and PSI2FF represent the latest possible values of ϕ_2 and ψ_2.)

Determination of Correct Sign for Round on Round Regime. Equation G-58 (ref D-1) is used to determine the angle ψ_2 while the gear and pinion are in the round on round phase of motion. The correct sign for this expression is obtained by comparing the value of ψ_2, as computed with PHI2I, with the previously obtained value for PSI2I. SIGN2R is the variable used for the desired sign.

Preliminary Computations for Mesh 3

Determination of Transition Angle. The determination of the transition angle for mesh 3 runs along parallel lines to the one shown for mesh 1 since the driving gear also rotates in a clockwise direction. In all cases, the parameters of appendix G (ref D-1) are used.

1. Transition angles ψ_{3T1} and ψ_{3T2} are computed with the help of equation G-99 (ref D-1).

2. The subroutine TRANS1 determines the angle ϕ_{3T1}, associated with ψ_{3T1}, to equations G-100 and G-101 (ref D-1).

3. PHINEXT, which is now obtained by a decrease of the angle ϕ_3 from ϕ_{3T1}, serves as the input variable of equation G-94 (ref D-1), and is used to determine PSINEX. Appropriate controls, as described before, determine the angle ψ_{3T1}. In addition, the associated value of g_{31} is computed with the help of equation G-95 (ref D-1).

4. Steps 2 and 3 are again repeated for the second transition angle ψ_{3T2} and g_{22} is determined.

5. After control is returned to the main program, that value of ψ_{3T} is chosen for which the associated value of g_3 is smaller than f_{p3}.

The subsidiary test for the transition angles runs parallel to that described for mesh 1, i.e.,

For $0° < \psi_{test} < 180°$

$$\text{TEST31} = \left| \pi - \beta_3 + \psi_{test} - \alpha_{P3} \right| \tag{D-12}$$

For $-180° < \psi_{test} < 0^0$

$$TEST32 = \left| \pi + \beta_3 - (\psi_{test} + 2\pi - \alpha_{P3}) \right| \qquad (D-13)$$

To determine the angle ψ_{test}, let

$$\psi_{test} = \psi_{3T} \text{ if } -180^0 < \psi_{3T} < 180^0 \qquad (D-14)$$

$$\psi_{test} = \psi_{3T} + 2\pi \text{ if } \psi_{3T} < -180^0 \qquad (D-15)$$

$$\psi_{test} = \psi_{3T} - 2\pi \text{ if } \psi_{3T} > 180^0 \qquad (D-16)$$

Determination of Correct Sign for Round on Flat Regime. The sign preceding the square root in equation G-94 (ref D-1), for the round on flat regime, is determined with the help of the angle ϕ_{3T}. The condition yielding that angle ψ_{3F} which is closest to the angle ψ_{3T} will govern. The variable SIGN3F is used for the sign in question.

Computation of Latest and Earliest Possible Values of ϕ_3 and ψ_3. The latest and earliest possible values of the gear and pinion angles ϕ_3 and ψ_3, respectively, are found by continuously evaluating the round on flat regime equation G-94 (ref D-1), using the previously determined value of SIGN3F, and simultaneously checking the contact condition for the subsequent set of teeth, as given by equation G-102 (ref D-1). This loop is initiated at the transition angle ϕ_{3T} and it is terminated when the condition of equation G-102 (ref D-1) is met. This allows the determination of the two angles PHI3F and PSI3FF at which the first set of teeth loses contact as well as the angles PHI3I and PSI3I at which the second set of teeth simultaneously comes into contact. The earliest possible engagement angles PHI3I and PSI3I are obtained by adding $\Delta\phi_3$ to the loss of contact angle PHI3F and by subtracting $\Delta\psi_3$ from the loss of contact angle PSI3FF. (PHI3F and PSI3FF represent the latest possible values of ϕ_3 and ψ_3.)

Determination of Correct Sign for Round on Round Regime. Equation G-87 (ref D-1) is used to determine the angle ψ_3 while the gear and pinion are in the round on round phase of motion. The correct sign for this expression is obtained by comparing the value of ψ_3, as computed with PHI3I, with the previously obtained value for PSI3I. SIGN3R is the variable used for the desired sign.

Gear Train Motion Model: Initial Contact Angles, Point and Cycle Efficiency. The simulation of the gear train model, which is necessary for the computation of both POINTEF and CYCLEFF, is found in a loop, starting with statement label no. 29 (card no. 459) and ending with card no. 824. The motions of the individual driving gears are initialized at the angles PHI1, PHI2 and PHI3, respectively, with the help of the initialization parameters J_i according to

$$\phi_i = \phi_{iI} + J_i \, (\phi_{iF} - \phi_{iI}) \quad (i=1,2,3) \qquad (D-17)$$

The additional parameter J_4 is set equal to zero to mark the first cycle of computations (see statement no. 456). J_4 becomes equal to unity for all subsequent computations (see statement no. 823).

The parameter J_5 is used to distinguish between the two possible contact conditions of mesh no. 1. $J_5 = 0$ whenever the first set of teeth is in contact. $J_5 = 1$ once the latest possible value of ϕ_1 has been reached, and contact must be transferred to the second set of teeth in order to obtain a complete cycle of motion for this mesh. $J_5 = 0$ at all times if $J_1 = 0$, i.e., contact is made in mesh no. 1 at the earliest possible point.

The meshes will be in round on round contact until they reach their respective transition angles PHI1T, PHI2T and PHI3T. Once the transition angles are passed, the meshes will be in round on flat contact. These regimes continue until the latest possible angles PHI1F, PHI2F and PHI3F are reached.

The increment DDPHI1 of the angle PHI1 of the input gear 1 is obtained from an adaptation of equations A-211 and A-213 (ref D-1), in which tooth numbers, rather than base circle radii, are used. The increment DDPHI2 of gear 2 is related to the increment of the pinion angle PSI1. Similarly, the increment DDPH13 is obtained with the help of the pinion angle PSI2.

While the motion of gear 1 is terminated when the angle PHI1 reaches one increment before its starting angle, both gears 2 and 3 must be reset to their respective earliest angles whenever they have reached PHI2F and PHI3F, respectively.[D-3]

The appropriate choice of moment equation depends upon which of the eight possible combinations of contact conditions, as indicated by table H-1 (ref D-1), is applicable.

The following discusses the kinematics of the individual meshes as well as the determination of the point and cycle efficiencies in greater detail.

Kinematics.

1. Mesh 1

Depending on whether PHI1 is larger or smaller than PHI1T, the parameters of the round on round or the round on flat regime are computed. (Recall that gear 1 turns in a clockwise direction.)

[D-3] If $J_1 = 0$, the computation is terminated for PHI1 < PHI1F + DDPHI1. If $J_1 > 0$, and, therefore, $J_5 = 1$, computation is terminated when PHI1 < PHI1A + DDPHI1. In the above, PHI1A represents the starting angle of mesh 1 in the manner of equation D-17. (See statement no. 454.)

For the round on round phase, the following calculations are made:

ψ_1, according to equation G-11 (ref D-1), and with the help of the previously determined SIGN1R

λ_1, according to equation G-13 and G-14 (ref D-1)

$\dot{\psi}_1$, according to equation G-15 (ref D-1)

$V_{S1/T1_R}$, according to equation G-20 (ref D-1)

s_{1R}, according to equation H-1 (ref D-1) as adapted to mesh 1

For the round on flat phase, the following calculations are made:

ψ_1, according to equation G-29 (ref D-1) and with the help of the previously determined SIGN1F

g_1, according to equation G-27 (ref D-1)

$\dot{\psi}_1$, according to equation G-30 (ref D-1)

$V_{S1/T1_F}$, according to equation G-33 (ref D-1)

s_{1F}, according to equation H-2 (ref D-1) as adapted to mesh 1

2. Mesh 2

The increment DDPHI2, for each round of computations, is obtained with the help of the change in the angle ψ_1 between the present and the previous computation, i.e., as shown at statement label no. 31:

$$\text{DDPHI2} = \text{PSI1} - \text{PSI1P} \quad \text{(D-18)}$$

For the first round of computations, the previous ψ_1, i.e., PSI1P, is equal to that PSI1 which corresponds to PHI1A.

It must be recalled that gear 2 rotates in a positive direction, and therefore, the angle ϕ_2 increases with continued motion. The angle PHI2 is re-indexed to PHI2I once it becomes larger than PHI2F.

As for mesh 1, comparison with the transition angle decides whether the mesh is in the round on round or in the round on flat regime.

The following round on round parameters are calculated:

ψ_2, according to equation G-58 (ref D-1), and with the help of the previously determined SIGN2R

λ_2, according to equations G-59 and G-60 (ref D-1)

Note that the input anglular velocity for mesh 2, i.e., $\dot{\phi}_2$, equals the momentary value of $\dot{\psi}_1$.

$\dot{\psi}_2$, according to equation G-61 (ref D-1)

$V_{S2/T2_R}$, according to equation G-63 (ref D-1)

s_{2R}, according to equation H-1 (ref D-1), as adapted to mesh 2

For the round on flat phase, the following calculations are made:

ψ_2, according to equation G-71 (ref D-1), and with the help of the previously determined SIGN2F

s_2, according to equation G-69 (ref D-1)

Again, $\dot{\phi}_2$ equals the momentary value of $\dot{\psi}_1$

$\dot{\psi}_2$, according to equation G-72 (ref D-1)

$V_{S2/T2_F}$, according to equation G-74 (ref D-1)

s_{2F}, according to equation H-2 (ref D-1), as adapted to mesh 2

3. Mesh 3

The increment DDPHI3, for each round of computations, is obtained with the help of the change in the angle ψ_2 between the present and the previous computation, i.e., as shown at statement label no. 33:

$$\text{DDPHI3} = \text{PSI2} - \text{PSI2P} \qquad \text{(D-19)}$$

For the first round of computations, the previous ψ_2, i.e., PSI2P, is equal to that PSI2 which corresponds to the initial value of PHI2, as obtained with the help of J_2.

Gear 3 rotates in a negative (clockwise) direction, and therefore, the angle ϕ_3 decreases with continued rotation. The angle PHI3, which represents this angle, is re-indexed to PHI3I once it becomes smaller than PHI3F.

As for meshes 1 and 2, comparison with the applicable transition angle decides whether the mesh is in the round on round or in the round on flat regime.

The following round on round parameters are calculated:

ψ_3, according to equation G-87 (ref D-1), and with the help of the previously determined SIGN3R

λ_3, according to equation G-89 and G-90 (ref D-1)

Note that the input angular velocity for mesh 3, i.e., $\dot{\phi}_3$, equals the momentary value of $\dot{\psi}_2$.

$\dot{\psi}_3$, according to equation G-91 (ref D-1)

$V_{S3/T3_R}$, according to equation G-92 (ref D-1)

s_{3R}, according to equation H-1 (ref D-1) as adapted to mesh 3

For the round on flat phase, the following calculations are made:

ψ_3, according to equation G-94 (ref D-1), and with the help of the previously determined SIGN3F

g_3, according to equation G-95 (ref D-1)

Again, $\dot{\phi}_3$ is equal to the momentary value of $\dot{\psi}_2$.

$\dot{\psi}_3$, according to equation G-96 (ref D-1)

$V_{S3/T3_F}$, according to equation G-97 (ref D-1)

s_{3F}, according to equation H-2 (ref D-1) as adapted to mesh 3

Moment Computations, Point and Cycle Efficiencies. Regardless of the combination of contact conditions, the point efficiency is computed according to equation 3 (ref D-1), i.e.,

$$\varepsilon_p = \text{POINTEF} = K_{RATIO} \frac{M_{o4i}}{M_{in}} \qquad \text{(D-20)}$$

where, with $\dot{\phi}_1 = -1$,

$$K_{RATIO} = \left| \dot{\psi}_3 \right| \qquad \text{(D-21)}$$

The cycle efficiency determination is based on equation C-10 (ref D-1), which represents an adaptation of equation 4 (ref D-1):

$$\varepsilon_C = \frac{\Delta\phi_1 \Sigma\varepsilon_P}{\phi_{1FIN} - \phi_{1IN}} \quad \text{(D-22)}$$

The associated expression in the program, at statement label no. 45, becomes

CYCLEFF = -MTOT*DDPHI1/(PHI1F-PHI1I) (D-23)

where

MTOT = MTOT + POINTEF (D-24)

The moment computations begin with the statement label no. 35, and initially consist of the determination of the variables A1 to A64 and C1 to C32, appendix H (ref D-1). The governing contact combination (table H-1, ref D-1) is determined with the help of the 8 moment control statements, which start with card no. 748. Once the appropriate combination is established, the program is directed to one of the 8 associated moment expressions. These expressions for M_{o4i} coincide in nomenclature with those given by equations H-81, H-118, H-158, H-180, H-216, H-218, H-239 and H-241 (ref D-1). They are listed in the above order, beginning with statement label no. 36 and ending with statement label no. 43.

In devising the control statements, the manner of rotation of the individual mesh input gears had to be taken into account. Thus:

For mesh 3:

Round on round (R) corresponds to PHI3I > PHI3 > PHI3T

Round on flat (F) corresponds to PHI3T > PHI3 > PHI3F

For mesh 2:

Round on round (R) corresponds to PHI2I < PHI2 < PHI2T

Round on flat (F) corresponds to PHI2T < PHI2 < PHI2F

For mesh 1:

Round on round (R) corresponds to PHI1I > PHI1 > PHI1T

Round on flat (F) corresponds to PHI1T > PHI1 > PHI1F

Output

The output of the program is best explained with the help of the sample problem at the end of the program.

Input Parameters (first sets of gear data, appendix C)

Mesh 1

CAPRP1	= R_{p1}	= 0.47727 in. (1.2122 cm)	PSUBD1	=	P_{d1} = 44
RP2	= r_{p2}	= 0.09091 in. (0.2309 cm)	J1	=	0.90
ACG1	= a_{G1}	= 0.47343 in. (1.2025 cm)			
ACP1	= a_{p1}	= 0.09083 in. (0.2307 cm)			
RHOG1	= ρ_{G1}	= 0.04857 in. (0.1234 cm)			
RHOP1	= ρ_{p1}	= 0.01591 in. (0.0404 cm)			
TG1	= t_{G1}	= 0.03609 in. (0.0917 cm)			
TP1	= t_{p1}	= 0.02382 in. (0.0605 cm)			
NG1	= n_{G1}	= 42			
NP2	= n_{p2}	= 8			

Mesh 2

CAPRP2	= R_{p2}	= 0.20769 in. (0.5275 cm)	PSUBD2	=	P_{d2} = 65
RP3	= r_{p3}	= 0.06923 in. (0.1758 cm)	J2	=	0.90
ACG2	= a_{G2}	= 0.20559 in. (0.5222 cm)			
ACP2	= a_{p2}	= 0.06917 in. (0.1757 cm)			

RHOG2 = ρ_{G2} = 0.03323 in. (0.0844 cm)

RHOP2 = ρ_{P2} = 0.01077 in. (0.274 cm)

TG2 = t_{G2} = 0.02438 in. (0.0619 cm)

TP2 = t_{P2} = 0.01613 in. (0.0410 cm)

NG2 = n_{G2} = 27

NP3 = n_{P3} = 9

Mesh 3

CAPRP3 = R_{p3} = 0.17532 in. (0.4453 cm)

RP4 = r_{p4} = 0.05844 in. (0.1484 cm)

ACG3 = a_{G3} = 0.17355 in. (0.4408 cm)

ACP3 = a_{P3} = 0.05839 in. (0.1483 cm)

RHOG3 = ρ_{G3} = 0.02805 in. (0.0712 cm)

RHOP3 = ρ_{P3} = 0.00909 in. (0.0231 cm)

TG3 = t_{G3} = 0.02058 in. (0.0523 cm)

TP3 = t_{P3} = 0.01362 in. (0.0346 cm)

NG3 = n_{G3} = 27

NP4 = n_{P4} = 9

PSUBD3 = P_{d3} = 77

J3 = 0.90

In addition

MU = μ = 0.2

RPM = 1000

M1 = m_1 = 0.12×10^{-3} lb-sec^2/in. (2.101×10^{-2} kg)

M2 = m_2 = 0.85×10^{-5} lb-sec^2/in. (1.488×10^{-3} kg)

M3 = m_3 = 0.34×10^{-5} lb-sec^2/in. (5.953×10^{-4} kg)

M4 = m_4 = 0.15×10^{-5} lb-sec^2/in. (2.626×10^{-4} kg)

R1 = $\mathcal{R}_1$ = 0.225 in. (0.572 cm)

R2 = $\mathcal{R}_2$ = 0.436 in. (1.107 cm)

R3 = $\mathcal{R}_3$ = 0.504 in. (1.280 cm)

R4 = $\mathcal{R}_4$ = 0.520 in. (1.321 cm)

RHO1 = ρ_1 = 0.062 in. (0.157 cm)

RHO2 = ρ_2 = 0.025 in. (0.064 cm)

RHO3 = ρ_3 = 0.018 in. (0.046 cm)

RHO4 = ρ_4 = 0.016 in. (0.041 cm)

MD = md^2 = 0.275×10^{-5} lb-sec^2-in. (3.105×10^{-7} kg-m^2)

K = 25

Computed Values

At the beginning of the output, one finds MIN = M_{in}. Subsequently, the following are listed for each mesh:

- f_{pi}, the length of the pinion flats
- β_i, the fuze body pivot to pivot line angles
- ψ_{Ti} and ϕ_{Ti}, the transition angles
- ϕ_{Ii} and ψ_{Ii}, the earliest angles
- ϕ_{Fi} and ψ_{Fi}, the latest angles

Finally, for the full range of the input angle ϕ_1, the point efficiency POINTEF is listed, in addition to other parameters which are useful for checking purposes. Note that DPSI1, DPSI2 and DPSI3 represent $\dot{\psi}_1$, $\dot{\psi}_2$, $\dot{\psi}_3$, respectively. The cycle efficiency CYCLEFF is found at the end of the output.

Computer program *CLOCK3*


```
      PROGRAM CLOCK3(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C     POINT AND CYCLE EFFICIENCIES FOR THREE PASS CLOCK (OGIVAL) STEP UP
C     GEAR TRAIN IN SPIN ENVIRONMENT
C
      REAL MU,LAMDA1,LAMDA2,LAMDA3,MO4,MO41,MO42,MO43,MO44,MO45,MO46,MO4
     17,MO48,LX1,LY1,L1,LX2,LY2,L2,LX3,LY3,L3,NP2,NP3,NP4,NG1,NG2,NG3,MI
     2N,M1,M2,M3,M4,MTOT,MD,LL1,LL2,LL3,K,J1,J2,J3,J4,J5
    1 READ (5,61) PSUBD1,PSUBD2,PSUBD3,NG1,NP2,NG2,NP3,NG3,NP4
      READ (5,64) MU,RPM,CAPRP1,CAPRP2,CAPRP3,RP2,RP3,RP4,ACG1,ACG2,ACG3
     1,ACP1,ACP2,ACP3,ISTOP
      READ (5,82) R1,R2,R3,R4
      READ (5,62) RHOG1,RHOG2,RHOG3,RHOP1,RHOP2,RHOP3
      READ (5,63) TG1,TG2,TG3,TP1,TP2,TP3
      READ (5,85) M1,M2,M3,M4
      READ (5,65) RHO1,RHO2,RHO3,RHO4,MD,K,J1,J2,J3
      PI=3.14159
      Z=PI/180.
      OMEGA=RPM*2.*PI/60.
      OM2=OMEGA*OMEGA
      PHDOT1=-1.
C
C     COMPUTATION OF GEAR TOOTH PARAMETERS
C
      CXG1=RHOG1-TG1/2.
      DELG1=ASIN(CXG1/CAPRP1)
      CXP1=RHOP1-TP1/2.
      DELP1=ASIN(CXP1/RP2)
      GAMMP1=ASIN(RHOP1/RP2)
      ALPHP1=GAMMP1-DELP1
      FP1=ACP1*COS(GAMMP1)
      B1=CAPRP1+RP2
      CXG2=RHOG2-TG2/2.
      DELG2=ASIN(CXG2/CAPRP2)
      CXP2=RHOP2-TP2/2.
      DELP2=ASIN(CXP2/RP3)
      GAMMP2=ASIN(RHOP2/RP3)
      ALPHP2=GAMMP2-DELP2
      FP2=ACP2*COS(GAMMP2)
      B2=CAPRP2+RP3
      CXG3=RHOG3-TG3/2.
      DELG3=ASIN(CXG3/CAPRP3)
      CXP3=RHOP3-TP3/2.
      DELP3=ASIN(CXP3/RP4)
      GAMMP3=ASIN(RHOP3/RP4)
      ALPHP3=GAMMP3-DELP3
      FP3=ACP3*COS(GAMMP3)
      B3=CAPRP3+RP4
C
C     COMPUTATION OF MIN, GAMMAS AND BETAS
C
      MIN=MD*OM2
      DELTA2=ACOS(((CAPRP1+RP2)*(CAPRP1+RP2)+R1*R1-R2*R2)/(2.*R1*(CAPRP1
```

Computer program CLOCK3 (cont)

PROGRAM CLOCK3 74/74 OPT=1 FTN 4.6+420 07/31/79 08.15.34 PAGE 2

```
     1+RP2)))
      DELTA3=ACOS(((CAPRP2+RP3)*(CAPRP2+RP3)+R2*R2-R3*R3)/(2.*R2*(CAPRP2
     1+RP3)))
      DELTA4=ACOS(((CAPRP3+RP4)*(CAPRP3+RP4)+R3*R3-R4*R4)/(2.*R3*(CAPRP3
     1+RP4)))
      GAMMA2=ACOS((R1*R1+R2*R2-(CAPRP1+RP2)*(CAPRP1+RP2))/(2.*R1*R2))
      GAMM3P=ACOS((R2*R2+R3*R3-(CAPRP2+RP3)*(CAPRP2+RP3))/(2.*R2*R3))
      GAMMA3=GAMMA2+GAMM3P
      GAMM4P=ACOS((R3*R3+R4*R4-(CAPRP3+RP4)*(CAPRP3+RP4))/(2.*R3*R4))
      GAMMA4=GAMMA3+GAMM4P
      BETA1=PI-DELTA2
      BETA2=GAMMA2+PI-DELTA3
      BETA3=GAMMA3+PI-DELTA4
      BETA1D=BETA1/Z
      BETA2D=BETA2/Z
      BETA3D=BETA3/Z
      WRITE (6,66) PSUBD1,PSUBD2,PSUBD3,MIN,MU,RPM,CAPRP1,CAPRP2,CAPRP3,
     1RP2,RP3,RP4,ACG1,ACG2,ACG3,ACP1,ACP2,ACP3
      WRITE (6,69) NG1,NG2,NG3,NP2,NP3,NP4
      WRITE (6,83) R1,R2,R3,R4
      WRITE (6,67) RHOG1,RHOG2,RHOG3,RHOP1,RHOP2,RHOP3
      WRITE (6,68) TG1,TG2,TG3,TP1,TP2,TP3
      WRITE (6,86) M1,M2,M3,M4
      WRITE (6,70) RHO1,RHO2,RHO3,RHO4,MD,K,PHDOT1,J1,J2,J3
      WRITE (6,84) FP1,FP2,FP3
      WRITE (6,71) BETA1D,BETA2D,BETA3D
C
C     COMPUTATION OF OTHER PARAMETERS
C
      DPHI1=360./NG1*Z
      DPSI1=360./NP2*Z
      DPHI2=360./NG2*Z
      DPSI2=360./NP3*Z
      DPHI3=360./NG3*Z
      DPSI3=360./NP4*Z
      L1=RHOG1+RHOP1
      L2=RHOG2+RHOP2
      L3=RHOG3+RHOP3
      Q1=M1*R1*OM2
      Q2=M2*R2*OM2
      Q3=M3*R3*OM2
      Q4=M4*R4*OM2
C
C     PRELIMINARY COMPUTATIONS FOR MESH 1
C
C     DETERMINATION OF TRANSITION ANGLE OF MESH 1
C
      A1T=RHOG1*COS(BETA1+ALPHP1)+FP1*SIN(BETA1+ALPHP1)
      B1T=-RHOG1*SIN(BETA1+ALPHP1)+FP1*COS(BETA1+ALPHP1)
      C1T=(ACG1*ACG1-RHOG1*RHOG1-B1*B1-FP1*FP1)/(2.*B1)
      ROOT1T=A1T*A1T+B1T*B1T-C1T*C1T
      Y1T1=A1T+SQRT(ROOT1T)
      Y1T2=A1T-SQRT(ROOT1T)
```

Computer program CLOCK3 (cont)

```
PROGRAM CLOCK3      74/74    OPT=1                    FTN 4.6+420       07/31/79  08.15.34        PAGE     3

      X1T=B1T+C1T
      PSI1T1=2.*ATAN2(Y1T1,X1T)
      PSI1T2=2.*ATAN2(Y1T2,X1T)
      PSITE11=PSI1T1
      PSITE12=PSI1T2
      IF (PSI1T1.GT.PI) PSITE11=PSI1T1-2.*PI
      IF (PSI1T1.LT.PI) PSITE11=PSI1T1+2.*PI
      IF (PSI1T2.GT.PI) PSITE12=PSI1T2-2.*PI
      IF (PSI1T2.LT.PI) PSITE12=PSI1T2+2.*PI
      IF (PSITE11.GE.0.) TEST11=ABS(PI-BETA1+PSITE11-ALPHP1)/Z
      IF (PSITE12.GE.0.) TEST12=ABS(PI-BETA1+PSITE12-ALPHP1)/Z
      IF (PSITE11.LT.0.) TEST11=ABS(PI+BETA1-(PSITE11+2.*PI-ALPHP1))/Z
      IF (PSITE12.LT.0.) TEST12=ABS(PI+BETA1-(PSITE12+2.*PI-ALPHP1))/Z
      IF (PSI1T1.LT.0.) PSI1T1=PSI1T1+2.*PI
      IF (PSI1T2.LT.0.) PSI1T2=PSI1T2+2.*PI
      PSI1T1D=PSI1T1/Z
      PSI1T2D=PSI1T2/Z
      WRITE (6,46) PSI1T1D,TEST11
      WRITE (6,47) PSI1T2D,TEST12
      CALL TRANS1 (RHOG1,ALPHP1,BETA1,FP1,ACG1,B1,DELG1,Z,PSI1T1,PHI1T1,
     1G11)
      IF (G11.GT.FP1) GO TO 2
      PHI1T=PHI1T1
      PSI1T=PSI1T1
      GO TO 4
    2 CALL TRANS1 (RHOG1,ALPHP1,BETA1,FP1,ACG1,B1,DELG1,Z,PSI1T2,PHI1T2,
     1G12)
      IF (G12.LT.FP1) GO TO 3
      WRITE (6,72)
      STOP
    3 PHI1T=PHI1T2
      PSI1T=PSI1T2
    4 IF (PHI1T.LT.0.) PHI1T=PHI1T+2.*PI
      IF (PSI1T.LT.0.) PSI1T=PSI1T+2.*PI
      PHI1TD=PHI1T/Z
      PSI1TD=PSI1T/Z
      WRITE (6,73) PHI1TD,PSI1TD
C
C     DETERMINATION OF CORRECT SIGN FOR ROUND ON FLAT REGIME OF MESH 1
C
      A1F=ACG1*COS(PHI1T+DELG1+ALPHP1)-B1*COS(BETA1+ALPHP1)
      B1F=-ACG1*SIN(PHI1T+DELG1+ALPHP1)+B1*SIN(BETA1+ALPHP1)
      C1F=RHOG1
      ROOT1F=A1F*A1F+B1F*B1F-C1F*C1F
      Y1F1=A1F+SQRT(ROOT1F)
      Y1F2=A1F-SQRT(ROOT1F)
      X1F=B1F+C1F
      PSI1F1=2.*ATAN2(Y1F1,X1F)
      PSI1F2=2.*ATAN2(Y1F2,X1F)
      IF (PSI1F1.LT.0.) PSI1F1=PSI1F1+2.*PI
      IF (PSI1F2.LT.0.) PSI1F2=PSI1F2+2.*PI
      IF (ABS(PSI1F1-PSI1T).LT.ABS(PSI1F2-PSI1T)) GO TO 5
      SIGN1F=-1.
```

Computer program CLOCK3 (cont)


```
      GO TO 6
    5 SIGN1F=1.
C
C     LATEST AND EARLIEST POSSIBLE VALUES OF PHI AND PSI FOR MESH 1
C
    6 DO 7 I=1,2000
      PHID1=PHI1TD-(I-1.)/100.
      PHI1=PHID1*Z
      A1F=ACG1*COS(PHI1+DELG1+ALPHP1)-B1*COS(BETA1+ALPHP1)
      B1F=-ACG1*SIN(PHI1+DELG1+ALPHP1)+B1*SIN(BETA1+ALPHP1)
      C1F=RHOG1
      ROOT1F=A1F*A1F+B1F*B1F-C1F*C1F
      Y1F=A1F+SIGN1F*SQRT(ROOT1F)
      X1F=B1F+C1F
      PSI1F=2.*ATAN2(Y1F,X1F)
      IF (PSI1F.LT.0.) PSI1F=PSI1F+2.*PI
      LX1=B1*COS(BETA1)+ACP1*COS(PSI1F-DPSI1+DELP1)-ACG1*COS(PHI1+DPHI1+
     1DELG1)
      LY1=B1*SIN(BETA1)+ACP1*SIN(PSI1F-DPSI1+DELP1)-ACG1*SIN(PHI1+DPHI1+
     1DELG1)
      LL1=SQRT(LX1*LX1+LY1*LY1)
      DELEL1=LL1-L1
      IF (DELEL1.LE.0.) GO TO 8
    7 CONTINUE
    8 PHI1F=PHI1
      PSI1FF=PSI1F
      PHI1I=PHI1F+DPHI1
      PSI1I=PSI1FF-DPSI1
      IF (PSI1I.LT.0.) PSI1I=PSI1I+2.*PI
      PHI1ID=PHI1I/Z
      PSI1ID=PSI1I/Z
      PHI1FD=PHI1F/Z
      PSI1FD=PSI1FF/Z
      WRITE (6,74) PHI1ID,PSI1ID,PHI1FD,PSI1FD
C
C     DETERMINATION OF CORRECT SIGN FOR ROUND ON ROUND REGIME OF MESH 1
C
      A1R=ACG1*SIN(PHI1I+DELG1-DELP1)-B1*SIN(BETA1-DELP1)
      B1R=ACG1*COS(PHI1I+DELG1-DELP1)-B1*COS(BETA1-DELP1)
      C1R=(ACP1*ACP1+ACG1*ACG1+B1*B1-L1*L1-2.*ACG1*B1*COS(PHI1I+DELG1-BE
     1TA1))/(2.*ACP1)
      ROOT1R=A1R*A1R+B1R*B1R-C1R*C1R
      Y1R1=A1R+SQRT(ROOT1R)
      Y1R2=A1R-SQRT(ROOT1R)
      X1R=B1R+C1R
      PSI1R1=2.*ATAN2(Y1R1,X1R)
      PSI1R2=2.*ATAN2(Y1R2,X1R)
      IF (PSI1R1.LT.0.) PSI1R1=PSI1R1+2.*PI
      IF (PSI1R2.LT.0.) PSI1R2=PSI1R2+2.*PI
      IF (ABS(PSI1I-PSI1R1).LT.ABS(PSI1I-PSI1R2)) GO TO 9
      SIGN1R=-1.
      GO TO 10
    9 SIGN1R=1.
```

Computer program CLOCK3 (cont)

```
PROGRAM CLOCK3      74/74    OPT=1                        FTN 4.6+420         07/31/79  08.15.34         PAGE      5

      C
      C     PRELIMINARY COMPUTATIONS FOR MESH 2
      C
      C     DETERMINATION OF TRANSITION ANGLE OF MESH 2
      C
         10 A2T=-RHOG2*COS(BETA2-ALPHP2)+FP2*SIN(BETA2-ALPHP2)
            B2T=RHOG2*SIN(BETA2-ALPHP2)+FP2*COS(BETA2-ALPHP2)
            C2T=(ACG2*ACG2-RHOG2*RHOG2-B2*B2-FP2*FP2)/(2.*B2)
            ROOT2T=A2T*A2T+B2T*B2T-C2T*C2T
            Y2T1=A2T+SQRT(ROOT2T)
            Y2T2=A2T-SQRT(ROOT2T)
            X2T=B2T+C2T
            PSI2T1=2.*ATAN2(Y2T1,X2T)
            PSI2T2=2.*ATAN2(Y2T2,X2T)
            PSITE21=PSI2T1
            PSITE22=PSI2T2
            IF (PSI2T1.GT.PI) PSITE21=PSI2T1-2.*PI
            IF (PSI2T1.LT.PI) PSITE21=PSI2T1+2.*PI
            IF (PSI2T2.GT.PI) PSITE22=PSI2T2-2.*PI
            IF (PSI2T2.LT.PI) PSITE22=PSI2T2+2.*PI
            IF (PSITE21.GE.0.) TEST21=ABS(PI-BETA2+PSITE21+ALPHP2)/Z
            IF (PSITE21.LT.0.) TEST21=ABS(BETA2+PI-(PSITE21+2.*PI+ALPHP2))/Z
            IF (PSITE22.GE.0.) TEST22=ABS(PI-BETA2+PSITE22+ALPHP2)/Z
            IF (PSITE22.LT.0.) TEST22=ABS(BETA2+PI-(PSITE22+2.*PI+ALPHP2))/Z
            IF (PSI2T1.LT.0.) PSI2T1=PSI2T1+2.*PI
            IF (PSI2T2.LT.0.) PSI2T2=PSI2T2+2.*PI
            PSI2T1D=PSI2T1/Z
            PSI2T2D=PSI2T2/Z
            WRITE (6,48) PSI2T1D,TEST21
            WRITE (6,49) PSI2T2D,TEST22
            CALL TRANS2 (RHOG2,ALPHP2,BETA2,FP2,ACG2,B2,DELG2,Z,PSI2T1,PHI2T1,
           1G21)
            IF (G21.GT.FP2) GO TO 11
            PHI2T=PHI2T1
            PSI2T=PSI2T1
            GO TO 13
         11 CALL TRANS2 (RHOG2,ALPHP2,BETA2,FP2,ACG2,B2,DELG2,Z,PSI2T2,PHI2T2,
           1G22)
            IF (G22.LT.FP2) GO TO 12
            WRITE (6,75)
            STOP
         12 PHI2T=PHI2T2
            PSI2T=PSI2T2
         13 IF (PHI2T.LT.0.) PHI2T=PHI2T+2.*PI
            IF (PSI2T.LT.0.) PSI2T=PSI2T+2.*PI
            PHI2TD=PHI2T/Z
            PSI2TD=PSI2T/Z
            WRITE (6,76) PHI2TD,PSI2TD
      C
      C     DETERMINATION OF CORRECT SIGN FOR ROUND ON FLAT REGIME OF MESH 2
      C
            A2F=ACG2*COS(PHI2T-DELG2-ALPHP2)-B2*COS(BETA2-ALPHP2)
            B2F=-ACG2*SIN(PHI2T-DELG2-ALPHP2)+B2*SIN(BETA2-ALPHP2)
```

Computer program CLOCK3 (cont)

```
PROGRAM CLOCK3      74/74    OPT=1                         FTN 4.6+420        07/31/79  08.15.34        PAGE     6

            C2F=-RHOG2                                                                A 266
            ROOT2F=A2F*A2F+B2F*B2F-C2F*C2F                                            A 267
            Y2F1=A2F+SQRT(ROOT2F)                                                     A 268
            Y2F2=A2F-SQRT(ROOT2F)                                                     A 269
            X2F=B2F+C2F                                                               A 270
            PSI2F1=2.*ATAN2(Y2F1,X2F)                                                 A 271
            PSI2F2=2.*ATAN2(Y2F2,X2F)                                                 A 272
            IF (PSI2F1.LT.0.) PSI2F1=PSI2F1+2.*PI                                     A 273
            IF (PSI2F2.LT.0.) PSI2F2=PSI2F2+2.*PI                                     A 274
            IF (ABS(PSI2F1-PSI2T).LT.ABS(PSI2F2-PSI2T)) GO TO 14                      A 275
            PSI2F1D=PSI2F1/Z                                                          A 276
            PSI2F2D=PSI2F2/Z                                                          A 277
            SIGN2F=-1.                                                                A 278
            GO TO 15                                                                  A 279
         14 SIGN2F=1.                                                                 A 280
      C                                                                               A 281
      C     LATEST AND EARLIEST POSSIBLE VALUES OF PHI AND PSI FOR MESH 2             A 282
      C                                                                               A 283
         15 DO 16 I=1,1000                                                            A 284
            PHID2=PHI2TD+(I-1.)/100.                                                  A 285
            PHI2=PHID2*Z                                                              A 286
            A2F=ACG2*COS(PHI2-DELG2-ALPHP2)-B2*COS(BETA2-ALPHP2)                      A 287
            B2F=-ACG2*SIN(PHI2-DELG2-ALPHP2)+B2*SIN(BETA2-ALPHP2)                     A 288
            C2F=-RHOG2                                                                A 289
            ROOT2F=A2F*A2F+B2F*B2F-C2F*C2F                                            A 290
            Y2F=A2F+SIGN2F*SQRT(ROOT2F)                                               A 291
            X2F=B2F+C2F                                                               A 292
            PSI2F=2.*ATAN2(Y2F,X2F)                                                   A 293
            IF (PSI2F.LT.0.) PSI2F=PSI2F+2.*PI                                        A 294
            LX2=B2*COS(BETA2)+ACP2*COS(PSI2F+DPSI2-DELP2)-ACG2*COS(PHI2-DPHI2-        A 295
           1DELG2)                                                                    A 296
            LY2=B2*SIN(BETA2)+ACP2*SIN(PSI2F+DPSI2-DELP2)-ACG2*SIN(PHI2-DPHI2-        A 297
           1DELG2)                                                                    A 298
            LL2=SQRT(LX2*LX2+LY2*LY2)                                                 A 299
            DELEL2=LL2-L2                                                             A 300
            IF (DELEL2.LE.0.) GO TO 17                                                A 301
         16 CONTINUE                                                                  A 302
         17 PHI2F=PHI2                                                                A 303
            PSI2FF=PSI2F                                                              A 304
            PHI2I=PHI2F-DPHI2                                                         A 305
            PSI2I=PSI2FF+DPSI2                                                        A 306
            IF (PSI2I.GT.2.*PI) PSI2I=PSI2I-2.*PI                                     A 307
            PHI2ID=PHI2I/Z                                                            A 308
            PSI2ID=PSI2I/Z                                                            A 309
            PHI2FD=PHI2F/Z                                                            A 310
            PSI2FD=PSI2FF/Z                                                           A 311
            WRITE (6,77) PHI2ID,PSI2ID,PHI2FD,PSI2FD                                  A 312
      C                                                                               A 313
      C     DETERMINATION OF CORRECT SIGN FOR ROUND ON ROUND REGIME OF MESH 2         A 314
      C                                                                               A 315
            A2R=B2*SIN(BETA2+DELP2)-ACG2*SIN(PHI2I-DELG2+DELP2)                       A 316
            B2R=B2*COS(BETA2+DELP2)-ACG2*COS(PHI2I-DELG2+DELP2)                       A 317
            C2R=(L2*L2-B2*B2-ACG2*ACG2-ACP2*ACP2+2.*ACG2*B2*COS(PHI2I-DELG2-BE        A 318
```

Computer program CLOCK3 (cont)

```
      PROGRAM CLOCK3     74/74   OPT=1                    FTN 4.6+420      07/31/79  08.15.34      PAGE    7

     1TA2))/(2.*ACP2)                                                   A 319
      ROOT2R=A2R*A2R+B2R*B2R-C2R*C2R                                    A 320
      Y2R1=A2R+SQRT(ROOT2R)                                             A 321
      Y2R2=A2R-SQRT(ROOT2R)                                             A 322
      X2R=B2R+C2R                                                       A 323
      PSI2R1=2.*ATAN2(Y2R1,X2R)                                         A 324
      PSI2R2=2.*ATAN2(Y2R2,X2R)                                         A 325
      IF (PSI2R1.LT.0.) PSI2R1=PSI2R1+2.*PI                             A 326
      IF (PSI2R2.LT.0.) PSI2R2=PSI2R2+2.*PI                             A 327
      IF (ABS(PSI2I-PSI2R1).LT.ABS(PSI2I-PSI2R2)) GO TO 18              A 328
      SIGN2R=-1.                                                        A 329
      GO TO 19                                                          A 330
   18 SIGN2R=1.                                                         A 331
C                                                                       A 332
C     PRELIMINARY COMPUTATIONS FOR MESH 3                               A 333
C                                                                       A 334
C     DETERMINATION OF TRANSITION ANGLE OF MESH 3                       A 335
C                                                                       A 336
   19 A3T=RHOG3*COS(BETA3+ALPHP3)+FP3*SIN(BETA3+ALPHP3)                 A 337
      B3T=-RHOG3*SIN(BETA3+ALPHP3)+FP3*COS(BETA3+ALPHP3)                A 338
      C3T=(ACG3*ACG3-RHOG3*RHOG3-B3*B3-FP3*FP3)/(2.*B3)                 A 339
      ROOT3T=A3T*A3T+B3T*B3T-C3T*C3T                                    A 340
      Y3T1=A3T+SQRT(ROOT3T)                                             A 341
      Y3T2=A3T-SQRT(ROOT3T)                                             A 342
      X3T=B3T+C3T                                                       A 343
      PSI3T1=2.*ATAN2(Y3T1,X3T)                                         A 344
      PSI3T2=2.*ATAN2(Y3T2,X3T)                                         A 345
      PSITE31=PSI3T1                                                    A 346
      PSITE32=PSI3T2                                                    A 347
      IF (PSI3T1.GT.PI) PSITE31=PSI3T1-2.*PI                            A 348
      IF (PSI3T1.LT.PI) PSITE31=PSI3T1+2.*PI                            A 349
      IF (PSI3T2.GT.PI) PSITE32=PSI3T2-2.*PI                            A 350
      IF (PSI3T2.LT.PI) PSITE32=PSI3T2+2.*PI                            A 351
      IF (PSITE31.GE.0.) TEST31=ABS(PI-BETA3+PSITE31-ALPHP3)/Z          A 352
      IF (PSITE31.LT.0.) TEST31=ABS(PI+BETA3-(PSITE31+2.*PI-ALPHP3))/Z  A 353
      IF (PSITE32.GE.0.) TEST32=ABS(PI-BETA3+PSITE32-ALPHP3)/Z          A 354
      IF (PSITE32.LT.0.) TEST32=ABS(PI+BETA3-(PSITE32+2.*PI-ALPHP3))/Z  A 355
      IF (PSI3T1.LT.0.) PSI3T1=PSI3T1+2.*PI                             A 356
      IF (PSI3T2.LT.0.) PSI3T2=PSI3T2+2.*PI                             A 357
      PSI3T1D=PSI3T1/Z                                                  A 358
      PSI3T2D=PSI3T2/Z                                                  A 359
      WRITE (6,50) PSI3T1D,TEST31                                       A 350
      WRITE (6,51) PSI3T2D,TEST32                                       A 361
      CALL TRANS1 (RHOG3,ALPHP3,BETA3,FP3,ACG3,B3,DELG3,Z,PSI3T1,PHI3T1,  A 362
     1G31)                                                              A 363
      IF (G31.GT.FP3) GO TO 20                                          A 364
      PHI3T=PHI3T1                                                      A 365
      PSI3T=PSI3T1                                                      A 366
      GO TO 22                                                          A 367
   20 CALL TRANS1 (RHOG3,ALPHP3,BETA3,FP3,ACG3,B3,DELG3,Z,PSI3T2,PHI3T2,  A 368
     1G32)                                                              A 369
      IF (G32.LT.FP3) GO TO 21                                          A 370
      WRITE (6,78)                                                      A 371
```

```
      STOP
   21 PHI3T=PHI3T2
      PSI3T=PSI3T2
   22 IF (PHI3T.LT.0.) PHI3T=PHI3T+2.*PI
      IF (PSI3T.LT.0.) PSI3T=PSI3T+2.*PI
      PHI3TD=PHI3T/Z
      PSI3TD=PSI3T/Z
      WRITE (6,79) PHI3TD,PSI3TD
C
C     DETERMINATION OF CORRECT SIGN FOR ROUND ON FLAT REGIME OF MESH 3
C
      A3F=ACG3*COS(PHI3T+DELG3+ALPHP3)-B3*COS(BETA3+ALPHP3)
      B3F=-ACG3*SIN(PHI3T+DELG3+ALPHP3)+B3*SIN(BETA3+ALPHP3)
      C3F=RHOG3
      ROOT3F=A3F*A3F+B3F*B3F-C3F*C3F
      Y3F1=A3F+SQRT(ROOT3F)
      Y3F2=A3F-SQRT(ROOT3F)
      X3F=B3F+C3F
      PSI3F1=2.*ATAN2(Y3F1,X3F)
      PSI3F2=2.*ATAN2(Y3F2,X3F)
      IF (PSI3F1.LT.0.) PSI3F1=PSI3F1+2.*PI
      IF (PSI3F2.LT.0.) PSI3F2=PSI3F2+2.*PI
      IF (ABS(PSI3F1-PSI3T).LT.ABS(PSI3F2-PSI3T)) GO TO 23
      SIGN3F=-1.
      GO TO 24
   23 SIGN3F=1.
C
C     LATEST AND EARLIEST POSSIBLE VALUES OF PHI AND PSI FOR MESH 3
C
   24 DO 25 I=1,2000
      PHID3=PHI3TD-(I-1.)/100.
      PHI3=PHID3*Z
      A3F=ACG3*COS(PHI3+DELG3+ALPHP3)-B3*COS(BETA3+ALPHP3)
      B3F=-ACG3*SIN(PHI3+DELG3+ALPHP3)+B3*SIN(BETA3+ALPHP3)
      C3F=RHOG3
      ROOT3F=A3F*A3F+B3F*B3F-C3F*C3F
      Y3F=A3F+SIGN3F*SQRT(ROOT3F)
      X3F=B3F+C3F
      PSI3F=2.*ATAN2(Y3F,X3F)
      IF (PSI3F.LT.0.) PSI3F=PSI3F+2.*PI
      LX3=B3*COS(BETA3)+ACP3*COS(PSI3F-DPSI3+DELP3)-ACG3*COS(PHI3+DPHI3+
     1DELG3)
      LY3=B3*SIN(BETA3)+ACP3*SIN(PSI3F-DPSI3+DELP3)-ACG3*SIN(PHI3+DPHI3+
     1DELG3)
      LL3=SQRT(LX3*LX3+LY3*LY3)
      DELEL3=LL3-L3
      IF (DELEL3.LE.0.) GO TO 26
   25 CONTINUE
   26 PHI3F=PHI3
      PSI3FF=PSI3F
      PHI3I=PHI3F+DPHI3
      PSI3I=PSI3FF-DPSI3
      IF (PSI3I.LT.0.) PSI3I=PSI3I+2.*PI
```

```
          IF (PSI3I.LT.0.) PSI3I=PSI3I+2.*PI                          A 425
          PHI3ID=PHI3I/Z                                              A 426
          PSI3ID=PSI3I/Z                                              A 427
          PHI3FD=PHI3F/Z                                              A 428
          PSI3FD=PSI3FF/Z                                             A 429
          WRITE (6,85) PHI3ID,PSI3ID,PHI3FD,PSI3FD                    A 430
C                                                                     A 431
C         DETEPMINATION OF CORRECT SIGN OF ROUND ON ROUND REGIME FOR MESH 3  A 432
C                                                                     A 433
          A3R=ACG3*SIN(PHI3I+DELG3-DELP3)-B3*SIN(BETA3-DELP3)         A 434
          B3R=ACG3*COS(PHI3I+DELG3-DELP3)-B3*COS(BETA3-DELP3)         A 435
          C3R=(ACP3*ACP3+ACG3*ACG3+B3*B3-L3*L3-2.*ACG3*B3*COS(PHI3I+DELG3-BE  A 436
         1TA3))/(2.*ACP3)                                             A 437
          ROOT3R=A3R*A3R+B3R*B3R-C3R*C3R                              A 438
          Y3R1=A3R+SQRT(ROOT3R)                                       A 439
          Y3R2=A3R-SQRT(ROOT3R)                                       A 440
          X3R=B3R+C3R                                                 A 441
          PSI3R1=2.*ATAN2(Y3R1,X3R)                                   A 442
          PSI3R2=2.*ATAN2(Y3R2,X3R)                                   A 443
          IF (PSI3R1.LT.0.) PSI3R1=PSI3R1+2.*PI                       A 444
          IF (PSI3R2.LT.0.) PSI3R2=PSI3R2+2.*PI                       A 445
          IF (ABS(PSI3I-PSI3R1).LT.ABS(PSI3I-PSI3R2)) GO TO 27        A 446
          SIGN3R=-1.                                                  A 447
          GO TO 28                                                    A 448
       27 SIGN3R=1.                                                   A 449
C                                                                     A 450
C         GEAR TRAIN MOTION MODEL, KINEMATICS                         A 451
C                                                                     A 452
       28 DDPHI1=NP2*NP3*(PHI3I-PHI3F)/(K*NG1*NG2)                    A 453
          PHI1A=PHI1I+(PHI1F-PHI1I)*J1                                A 454
          PHI1=PHI1A+DDPHI1                                           A 455
          J4=0.                                                       A 456
          J5=0.                                                       A 457
          WRITE (6,52)                                                A 458
       29 PHI1=PHI1-DDPHI1                                            A 459
          IF (PHI1.LE.PHI1F) J5=1.                                    A 460
          IF (PHI1.LE.PHI1F) PHI1=PHI1I                               A 461
          PHI1D=PHI1/Z                                                A 462
          IF ((J5.EQ.1..AND.PHI1.LE.PHI1A+DDPHI1).OR.(J1.EQ.0..AND.PHI1.LE.P  A 463
         1HI1F+DDPHI1)) GO TO 45                                      A 464
C                                                                     A 465
C         MESH 1                                                      A 466
C                                                                     A 467
          IF (PHI1.LE.PHI1T) GO TO 30                                 A 468
          A1R=ACG1*SIN(PHI1+DELG1-DELP1)-B1*SIN(BETA1-DELP1)          A 469
          B1R=ACG1*COS(PHI1+DELG1-DELP1)-B1*COS(BETA1-DELP1)          A 470
          C1R=(ACP1*ACP1+ACG1*ACG1+B1*B1-L1*L1-2.*ACG1*B1*COS(PHI1+DELG1-BET  A 471
         1A1))/(2.*ACP1)                                              A 472
          ROOT1R=A1R*A1R+B1R*B1R-C1R*C1R                              A 473
          Y1R=A1R+SIGN1R*SQRT(ROOT1R)                                 A 474
          X1R=B1R+C1R                                                 A 475
          PSI1=2.*ATAN2(Y1R,X1R)                                      A 476
          IF (PSI1.LT.0.) PSI1=PSI1+2.*PI                             A 477
```

Computer program CLOCK3 (cont)


```
      IF (PSI1.GT.2.*PI) PSI1=PSI1-2.*PI
      PSI1D=PSI1/Z
      IF (ABS(PHI1-PHI1I).LT..0001) PSI1P=PSI1I
      IF (J4.EQ.0.) PSI1P=PSI1
      SLAM1=(B1*SIN(BETA1)+ACP1*SIN(PSI1+DELP1)-ACG1*SIN(PHI1+DELG1))/L1
      CLAM1=(B1*COS(BETA1)+ACP1*COS(PSI1+DELP1)-ACG1*COS(PHI1+DELG1))/L1
      LAMDA1=ATAN2(SLAM1,CLAM1)
      IF (LAMDA1.LT.0.) LAMDA1=LAMDA1+2.*PI
      PSDOT1=PHDOT1*ACG1*(B1/ACP1*SIN(PHI1+DELG1-BETA1)+SIN(PHI1-PSI1+DE
     1LG1-DELP1))/(A1R*COS(PSI1)-B1R*SIN(PSI1))
      VST1R=PHDOT1*(ACG1*COS(PHI1+DELG1-LAMDA1)+RHOG1)-PSDOT1*(ACP1*COS(
     1PSI1+DELP1-LAMDA1)-RHOP1)
      S1R=VST1R/ABS(VST1R)
      GO TO 31
   30 A1F=ACG1*COS(PHI1+DELG1+ALPHP1)-B1*COS(BETA1+ALPHP1)
      B1F=-ACG1*SIN(PHI1+DELG1+ALPHP1)+B1*SIN(BETA1+ALPHP1)
      C1F=RHOG1
      ROOT1F=A1F*A1F+B1F*B1F-C1F*C1F
      Y1F=A1F+SIGN1F*SQRT(ROOT1F)
      X1F=B1F+C1F
      PSI1=2.*ATAN2(Y1F,X1F)
      IF (PSI1.LT.0.) PSI1=PSI1+2.*PI
      IF (PSI1.GT.2.*PI) PSI1=PSI1-2.*PI
      IF (J4.EQ.0.) PSI1P=PSI1
      PSI1D=PSI1/Z
      G1=(ACG1*SIN(PHI1+DELG1)+RHOG1*COS(PSI1-ALPHP1)-B1*SIN(BETA1))/SIN
     1(PSI1-ALPHP1)
      PSDOT1=PHDOT1*(ACG1*COS(PHI1-PSI1+DELG1+ALPHP1))/(A1F*COS(PSI1)-B1
     1F*SIN(PSI1))
      VST1F=PHDOT1*(ACG1*SIN(PSI1-ALPHP1-PHI1-DELG1)-RHOG1)
      S1F=VST1F/ABS(VST1F)
C
C     MESH 2
C
   31 DDPHI2=PSI1-PSI1P
      IF (J4.EQ.0.) PHI2=PHI2I+(PHI2F-PHI2I)*J2
      PHI2=PHI2+DDPHI2
      IF (PHI2.GT.2.*PI) PHI2=PHI2-2.*PI
      PSI1P=PSI1
      IF (PHI2.GT.PHI2F) PHI2=PHI2I
      PHI2D=PHI2/Z
      IF (PHI2.GE.PHI2T) GO TO 32
      A2R=B2*SIN(BETA2+DELP2)-ACG2*SIN(PHI2-DELG2+DELP2)
      B2R=B2*COS(BETA2+DELP2)-ACG2*COS(PHI2-DELG2+DELP2)
      C2R=(L2*L2-B2*B2-ACG2*ACG2-ACP2*ACP2+2.*ACG2*B2*COS(PHI2-DELG2-BET
     1A2))/(2.*ACP2)
      ROOT2R=A2R*A2R+B2R*B2R-C2R*C2R
      Y2R=A2R+SIGN2R*SQRT(ROOT2R)
      X2R=B2R+C2R
      PSI2=2.*ATAN2(Y2R,X2R)
      IF (PSI2.LT.0.) PSI2=PSI2+2.*PI
      IF (PSI2.GT.2.*PI) PSI2=PSI2-2.*PI
      PSI2D=PSI2/Z
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Computer program CLOCK3 (cont)

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          IF (ABS(PHI2-PHI2I).LT..0001) PSI2P=PSI2I                                       A 531
          IF (J4.EQ.0.) PSI2P=PSI2                                                        A 532
          SLAM2=(B2*SIN(BETA2)+ACP2*SIN(PSI2-DELP2)-ACG2*SIN(PHI2-DELG2))/L2              A 533
          CLAM2=(B2*COS(BETA2)+ACP2*COS(PSI2-DELP2)-ACG2*COS(PHI2-DELG2))/L2              A 534
          LAMDA2=ATAN2(SLAM2,CLAM2)                                                       A 535
          IF (LAMDA2.LT.0.) LAMDA2=LAMDA2+2.*PI                                           A 536
          PHDOT2=PSDOT1                                                                   A 537
          PSDOT2=PHDOT2*ACG2*(-SIN(PHI2-PSI2-DELG2+DELP2)-B2/ACP2*SIN(PHI2-D              A 538
         1ELG2-BETA2))/(A2R*COS(PSI2)-B2R*SIN(PSI2))                                      A 539
          VST2R=PHDOT2*(ACG2*COS(PHI2-DELG2-LAMDA2)+RHOG2)-PSDOT2*(ACP2*COS(              A 540
         1PSI2-DELP2-LAMDA2)-RHOP2)                                                       A 541
          S2R=VST2R/ABS(VST2R)                                                            A 542
          GO TO 33                                                                        A 543
       32 A2F=ACG2*COS(PHI2-DELG2-ALPHP2)-B2*COS(BETA2-ALPHP2)                            A 544
          B2F=-ACG2*SIN(PHI2-DELG2-ALPHP2)+B2*SIN(BETA2-ALPHP2)                           A 545
          C2F=-RHOG2                                                                      A 546
          ROOT2F=A2F*A2F+B2F*B2F-C2F*C2F                                                  A 547
          Y2F=A2F+SIGN2F*SQRT(ROOT2F)                                                     A 548
          X2F=B2F+C2F                                                                     A 549
          PSI2=2.*ATAN2(Y2F,X2F)                                                          A 550
          IF (PSI2.LT.0.) PSI2=PSI2+2.*PI                                                 A 551
          IF (PSI2.GT.2.*PI) PSI2=PSI2-2.*PI                                              A 552
          IF (J4.EQ.0.) PSI2P=PSI2                                                        A 553
          PSI2D=PSI2/Z                                                                    A 554
          G2=(ACG2*SIN(PHI2-DELG2)-RHOG2*COS(PSI2+ALPHP2)-B2*SIN(BETA2))/SIN              A 555
         1(PSI2+ALPHP2)                                                                   A 556
          PHDOT2=PSDOT1                                                                   A 557
          PSDOT2=(PHDOT2*ACG2*COS(PHI2-DELG2-ALPHP2-PSI2))/(A2F*COS(PSI2)-B2              A 558
         1F*SIN(PSI2))                                                                    A 559
          VST2F=PHDOT2*(ACG2*SIN(PSI2+ALPHP2-PHI2+DELG2)+RHOG2)                           A 560
          S2F=VST2F/ABS(VST2F)                                                            A 561
C                                                                                         A 562
C         MESH 3                                                                          A 563
C                                                                                         A 564
       33 DDPHI3=PSI2-PSI2P                                                               A 565
          IF (J4.EQ.0.) PHI3=PHI3I+(PHI3F-PHI3I)*J3                                       A 566
          PHI3=PHI3+DDPHI3                                                                A 567
          IF (PHI3.GT.2.*PI) PHI3=PHI3-2.*PI                                              A 568
          PSI2P=PSI2                                                                      A 569
          IF (PHI3.LT.PHI3F) PHI3=PHI3I                                                   A 570
          PHI3D=PHI3/Z                                                                    A 571
          IF (PHI3.LE.PHI3T) GO TO 34                                                     A 572
          A3R=ACG3*SIN(PHI3+DELG3-DELP3)-B3*SIN(BETA3-DELP3)                              A 573
          B3R=ACG3*COS(PHI3+DELG3-DELP3)-B3*COS(BETA3-DELP3)                              A 574
          C3R=(ACP3*ACP3+ACG3*ACG3+B3*B3-L3*L3-2.*ACG3*B3*COS(PHI3+DELG3-BET              A 575
         1A3))/(2.*ACP3)                                                                  A 576
          ROOT3R=A3R*A3R+B3R*B3R-C3R*C3R                                                  A 577
          Y3R=A3R+SIGN3R*SQRT(ROOT3R)                                                     A 578
          X3R=B3R+C3R                                                                     A 579
          PSI3=2.*ATAN2(Y3R,X3R)                                                          A 580
          IF (PSI3.LT.0.) PSI3=PSI3+2.*PI                                                 A 581
          PSI3D=PSI3/Z                                                                    A 582
          SLAM3=(B3*SIN(BETA3)+ACP3*SIN(PSI3+DELP3)-ACG3*SIN(PHI3+DELG3))/L3              A 583
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Computer program CLOCK3 (cont)

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      CLAM3=(B3*COS(BETA3)+ACP3*COS(PSI3+DELP3)-ACG3*COS(PHI3+DELG3))/L3
      LAMDA3=ATAN2(SLAM3,CLAM3)
      IF (LAMDA3.LT.0.0) LAMDA3=LAMDA3+2.*PI
      PHDOT3=PSDOT2
      PSDOT3=PHDOT3*ACG3*(B3/ACP3*SIN(PHI3+DELG3-BETA3)+SIN(PHI3-PSI3+DE
     1LG3-DELP3))/(A3R*COS(PSI3)-B3R*SIN(PSI3))
      VST3R=PHDOT3*(ACG3*COS(PHI3+DELG3-LAMDA3)+RHOG3)-PSDOT3*(ACP3*COS(
     1PSI3+DELP3-LAMDA3)-RHOP3)
      S3R=VST3R/ABS(VST3R)
      GO TO 35
   34 A3F=ACG3*COS(PHI3+DELG3+ALPHP3)-B3*COS(BETA3+ALPHP3)
      B3F=-ACG3*SIN(PHI3+DELG3+ALPHP3)+B3*SIN(BETA3+ALPHP3)
      C3F=RHOG3
      ROOT3F=A3F*A3F+B3F*B3F-C3F*C3F
      Y3F=A3F+SIGN3F*SQRT(ROOT3F)
      X3F=B3F+C3F
      PSI3=2.*ATAN2(Y3F,X3F)
      IF (PSI3.LT.0.) PSI3=PSI3+2.*PI
      PSI3D=PSI3/Z
      G3=(ACG3*SIN(PHI3+DELG3)+RHOG3*COS(PSI3-ALPHP3)-B3*SIN(BETA3))/SIN
     1(PSI3-ALPHP3)
      PHDOT3=PSDOT2
      PSDOT3=PHDOT3*ACG3*COS(PHI3-PSI3+DELG3+ALPHP3)/(A3F*COS(PSI3)-B3F*
     1SIN(PSI3))
      VST3F=PHDOT3*(ACG3*SIN(PSI3-ALPHP3-PHI3-DELG3)-RHOG3)
      S3F=VST3F/ABS(VST3F)
C
C     MOMENT COMPUTATIONS
C
   35 DN=1.+MU*MU
      A1=ABS((MU*SIN(GAMMA4)+COS(GAMMA4))/DN)
      A2=ABS((MU*(S3R-1.)*SIN(LAMDA3)-(1.+MU*MU*S3R)*COS(LAMDA3))/DN)
      A3=ABS((SIN(GAMMA4)-MU*COS(GAMMA4))/DN)
      A4=ABS(((1.+MU*MU*S3R)*SIN(LAMDA3)+MU*(S3R-1.)*COS(LAMDA3))/DN)
      A5=ABS(((1.-MU*MU*S3R)*COS(LAMDA3)-MU*(1.+S3R)*SIN(LAMDA3))/DN)
      A6=ABS((MU*(1.+S2R)*SIN(LAMDA2)-(1.-MU*MU*S2R)*COS(LAMDA2))/DN)
      A7=ABS((MU*SIN(GAMMA3)-COS(GAMMA3))/DN)
      A8=ABS(((1.-MU*MU*S3R)*SIN(LAMDA3)+MU*(1.+S3R)*COS(LAMDA3))/DN)
      A9=ABS(((MU*MU*S2R-1.)*SIN(LAMDA2)-MU*(1.+S2R)*COS(LAMDA2))/DN)
      A10=ABS((SIN(GAMMA3)+MU*COS(GAMMA3))/DN)
      A11=ABS(((1.+MU*MU*S2R)*COS(LAMDA2)-MU*(S2R-1.)*SIN(LAMDA2))/DN)
      A12=ABS((MU*(S1R-1.)*SIN(LAMDA1)-(1.+MU*MU*S1R)*COS(LAMDA1))/DN)
      A13=ABS((-COS(GAMMA2)-MU*SIN(GAMMA2))/DN)
      A14=ABS(((1.+MU*MU*S2R)*SIN(LAMDA2)-MU*(1.-S2R)*COS(LAMDA2))/DN)
      A15=ABS((MU*(1.-S1R)*COS(LAMDA1)-(1.+MU*MU*S1R)*SIN(LAMDA1))/DN)
      A16=ABS((MU*COS(GAMMA2)-SIN(GAMMA2))/DN)
      A17=ABS(((1.-MU*MU*S1R)*COS(LAMDA1)-MU*(1.+S1R)*SIN(LAMDA1))/DN)
      A18=ABS(1./DN)
      A19=ABS(((1.-MU*MU*S1R)*SIN(LAMDA1)+MU*(1.+S1R)*COS(LAMDA1))/DN)
      A20=ABS(MU/DN)
      A21=ABS((MU*(1.-S2R)*SIN(LAMDA2)+(1.-MU*MU*S2R)*COS(LAMDA2))/DN)
      A22=ABS(((1.-MU*MU*S1F)*SIN(PSI1-ALPHP1)-MU*(1.+S1F)*COS(PSI1-ALPH
     1P1))/DN)
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Computer program CLOCK3 (cont)

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      A23=ABS((MU*SIN(GAMMA2)+COS(GAMMA2))/DN)                                          A 637
      A24=ABS(((1.+MU*MU*S2R)*SIN(LAMDA2)-MU*(1.-S2R)*COS(LAMDA2))/DN)                  A 638
      A25=ABS((-MU*(1.+S1F)*SIN(PSI1-ALPHP1)+(MU*MU*S1F-1.)*COS(PSI1-ALP                A 639
     1HP1))/DN)                                                                         A 640
      A26=ABS((-SIN(GAMMA2)+MU*COS(GAMMA2))/DN)                                         A 641
      A27=ABS((-(1.+MU*MU*S1F)*SIN(PSI1-ALPHP1)+MU*(S1F-1.)*COS(PSI1-ALP                A 642
     1HP1))/DN)                                                                         A 643
      A28=ABS(1./DN)                                                                    A 644
      A29=ABS((MU*(S1F-1.)*SIN(PSI1-ALPHP1)+(1.+MU*MU*S1F)*COS(PSI1-ALPH                A 645
     1P1))/DN)                                                                          A 646
      A30=ABS(MU/DN)                                                                    A 647
      A31=ABS(((1.-MU*MU*S3R)*COS(LAMDA3)-MU*(1.+S3R)*SIN(LAMDA3))/DN)                  A 648
      A32=ABS((-MU*(1.+S2F)*COS(PSI2+ALPHP2)-(1.-MU*MU*S2F)*SIN(PSI2+ALP                A 649
     1HP2))/DN)                                                                         A 650
      A33=ABS((MU*SIN(GAMMA3)-COS(GAMMA3))/DN)                                          A 651
      A34=ABS((MU*(1.+S3R)*COS(LAMDA3)+(1.-MU*MU*S3R)*SIN(LAMDA3))/DN)                  A 652
      A35=ABS(((1.-MU*MU*S2F)*COS(PSI2+ALPHP2)-MU*(1.+S2F)*SIN(PSI2+ALPH                A 653
     1P2)) DN)                                                                          A 654
      A36=ABS((SIN(GAMMA3)+MU*COS(GAMMA3))/DN)                                          A 655
      A37=ABS(((1.+MU*MU*S2F)*SIN(PSI2+ALPHP2)+MU*(S2F-1.)*COS(PSI2+ALPH                A 656
     1P2))/DN)                                                                          A 657
      A38=ABS(((1.-MU*MU*S1F)*SIN(PSI1-ALPHP1)-MU*(1.+S1F)*COS(PSI1-ALPH                A 658
     1P1))/DN)                                                                          A 659
      A39=ABS((MU*SIN(GAMMA2)+COS(GAMMA2))/DN)                                          A 660
      A40=ABS((MU*(S2F-1.)*SIN(PSI2+ALPHP2)-(1.+MU*MU*S2F)*COS(PSI2+ALPH                A 661
     1P2))/DN)                                                                          A 662
      A41=ABS((-MU*(1.+S1F)*SIN(PSI1-ALPHP1)+(MU*MU*S1F-1.)*COS(PSI1-ALP                A 663
     1HP1))/DN)                                                                         A 664
      A42=ABS((MU*COS(GAMMA2)-SIN(GAMMA2))/DN)                                          A 665
      A43=ABS(((1.+MU*MU*S2F)*SIN(PSI2+ALPHP2)-MU*(1.-S2F)*COS(PSI2+ALPH                A 666
     1P2)), DN)                                                                         A 667
      A44=ABS((MU*(S1R-1.)*SIN(LAMDA1)-(1.+MU*MU*S1R)*COS(LAMDA1))/DN)                  A 668
      A45=ABS((MU*SIN(GAMMA2)+COS(GAMMA2))/DN)                                          A 669
      A46=ABS((MU*(S2F-1.)*SIN(PSI2+ALPHP2)-(1.+MU*MU*S2F)*COS(PSI2+ALPH                A 670
     1P2))/DN)                                                                          A 671
      A47=ABS((-(1.+MU*MU*S1R)*SIN(LAMDA1)+MU*(1.-S1R)*COS(LAMDA1))/DN)                 A 672
      A48=ABS((-SIN(GAMMA2)+MU*COS(GAMMA2))/DN)                                         A 673
      A49=ABS(((1.-MU*MU*S3F)*SIN(PSI3-ALPHP3)-MU*(1.+S3F)*COS(PSI3-ALPH                A 674
     1P3))/DN)                                                                          A 675
      A50=ABS((-MU*SIN(GAMMA4)-COS(GAMMA4))/DN)                                         A 676
      A51=ABS((-MU*(1.+S3F)*SIN(PSI3-ALPHP3)-(1.-MU*MU*S3F)*COS(PSI3-ALP                A 677
     1HP3))/DN)                                                                         A 678
      A52=ABS((-SIN(GAMMA4)+MU*COS(GAMMA4))/DN)                                         A 679
      A53=ABS((-(1.+MU*MU*S3F)*SIN(PSI3-ALPHP3)+MU*(S3F-1.)*COS(PSI3-ALP                A 680
     1HP3))/DN)                                                                         A 681
      A54=ABS(((MU*MU*S2F-1.)*SIN(PSI2+ALPHP2)-MU*(1.+S2F)*COS(PSI2+ALPH                A 682
     1P2))/DN)                                                                          A 683
      A55=ABS((MU*SIN(GAMMA3)-COS(GAMMA3))/DN)                                          A 684
      A56=ABS((MU*(S3F-1.)*SIN(PSI3-ALPHP3)+(1.+MU*MU*S3F)*COS(PSI3-ALPH                A 685
     1P3))/DN)                                                                          A 686
      A57=ABS((-MU*(1.+S2F)*SIN(PSI2+ALPHP2)+(1.-MU*MU*S2F)*COS(PSI2+ALP                A 687
     1HP2))/DN)                                                                         A 688
      A58=ABS((-SIN(GAMMA3)-MU*COS(GAMMA3))/DN)                                         A 689
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      A59=ABS((-(1.+MU*MU*S3F)*SIN(PSI3-ALPHP3)+MU*(S3F-1.)*COS(PSI3-ALP   A 690
     1HP3))/DN)                                                             A 691
      A60=ABS((MU*(1.+S2R)*SIN(LAMDA2)+(MU*MU*S2R-1.)*COS(LAMDA2))/DN)      A 692
      A61=ABS((MU*SIN(GAMMA3)-COS(GAMMA3))/DN)                              A 693
      A62=ABS((MU*(S3F-1.)*SIN(PSI3-ALPHP3)+(1.+MU*MU*S3F)*COS(PSI3-ALPH   A 694
     1P3))/DN)                                                              A 695
      A63=ABS(((MU*MU*S2R-1.)*SIN(LAMDA2)-MU*(1.+S2R)*COS(LAMDA2))/DN)      A 696
      A64=ABS((-SIN(GAMMA3)-MU*COS(GAMMA3))/DN)                             A 697
      C1=MU*RHO4*(A1+A3)                                                    A 698
      C2=ACP3*(MU*S3R*COS(PSI3+DELP3-LAMDA3)-SIN(PSI3+DELP3-LAMDA3))-MU*   A 699
     1(RHOP3*S3R+RHO4*(A2+A4))                                              A 700
      C3=MU*RHO3*(A5+A8)-MU*S3R*RHOG3+ACG3*(SIN(PHI3-DELG3-LAMDA3)-MU*S3   A 701
     1R*COS(PHI3+DELG3-LAMDA3))                                             A 702
      C4=MU*RHO3*(A7+A10)                                                   A 703
      C5=MU*RHO3*(A6+A9)-MU*S2R*RHOP2+ACP2*(MU*S2R*COS(PSI2-DELP2-LAMDA2   A 704
     1)-SIN(PSI2-DELP2-LAMDA2))                                             A 705
      C6=ACG2*(SIN(PHI2-DELG2-LAMDA2)-MU*S2R*COS(PHI2-DELG2-LAMDA2))-MU*   A 706
     1RHO2*(A11+A14)-MU*RHOG2*S2R                                           A 707
      C7=MU*RHO2*(A13+A16)                                                  A 708
      C8=-(ACP1*(SIN(PSI1+DELP1-LAMDA1)-MU*S1R*COS(PSI1+DELP1-LAMDA1))+M   A 709
     1U*RHO2*(A12+A15)+MU*S1R*RHOP1)                                        A 710
      C9=MU*RHO1*(A18+A20)                                                  A 711
      C10=MU*RHO1*(A17+A19)+ACG1*(SIN(PHI1+DELG1-LAMDA1)-MU*S1R*COS(PHI1   A 712
     1+DELG1-LAMDA1))-MU*S1R*RHOG1                                          A 713
      C11=ACG2*(SIN(PHI2-DELG2-LAMDA2)-MU*S2R*COS(PHI2-DELG2-LAMDA2))-MU   A 714
     1*RHO2*(A21+A24)-MU*RHOG2*S2R                                          A 715
      C12=MU*RHO2*(A23+A26)                                                 A 716
      C13=G1-MU*RHO2*(A22+A25)                                              A 717
      C14=MU*RHO1*(A28+A30)                                                 A 718
      C15=MU*RHO1*(A27+A29)+MU*S1F*RHOG1+ACG1*(MU*S1F*SIN(PHI1+DELG1-PSI   A 719
     11+ALPHP1)-COS(PHI1+DELG1-PSI1+ALPHP1))                                A 720
      C16=MU*RHO3*(A31+A34)+ACG3*(SIN(PHI3+DELG3-LAMDA3)-MU*S3R*COS(PHI3   A 721
     1+DELG3-LAMDA3))-RHOG3*MU*S3R                                          A 722
      C17=MU*RHO3*(A33+A36)                                                 A 723
      C18=MU*RHO3*(A32+A35)-G2                                              A 724
      C19=-MU*RHO2*(A37+A40)+ACG2*(COS(PHI2-DELG2-PSI2-ALPHP2)+MU*S2F*SI   A 725
     1N(PHI2-DELG2-PSI2-ALPHP2))-MU*S2F*RHOG2                               A 726
      C20=MU*RHO2*(A39+A42)                                                 A 727
      C21=-MU*RHO2*(A38+A41)+G1                                             A 728
      C22=-MU*RHO2*(A43+A46)+ACG2*(COS(PHI2-DELG2-PSI2-ALPHP2)+MU*S2F*SI   A 729
     1N(PHI2-DELG2-PSI2-ALPHP2))-MU*S2F*RHOG2                               A 730
      C23=MU*RHO2*(A45+A48)                                                 A 731
      C24=-MU*RHO2*(A44+A47)+ACP1*(MU*S1R*COS(PSI1+DELP1-LAMDA1)-SIN(PSI   A 732
     11+DELP1-LAMDA1))-MU*S1R*RHOP1                                         A 733
      C25=MU*RHO4*(A50+A52)                                                 A 734
      C26=G3-MU*RHO4*(A49+A51)                                              A 735
      C27=MU*RHO3*(A53+A56)+ACG3*(-COS(PHI3+DELG3-PSI3+ALPHP3)+MU*S3F*SI   A 736
     1N(PHI3+DELG3-PSI3+ALPHP3))+MU*S3F*RHOG3                               A 737
      C28=MU*RHO3*(A55+A58)                                                 A 738
      C29=MU*RHO3*(A54+A57)-G2                                              A 739
      C30=MU*RHO3*(A59+A62)-ACG3*(COS(PHI3+DELG3-PSI3+ALPHP3)-MU*S3F*SIN   A 740
     1(PHI3+DELG3-PSI3+ALPHP3))+MU*S3F*RHOG3                                A 741
      C31=MU*RHO3*(A61+A64)                                                 A 742
```

Computer program CLOCK3 (cont)


```
      C32=MU*RHO3*(A60+A63)-ACP2*(SIN(PSI2-DELP2-LAMDA2)-MU*S2R*COS(PSI2
     1-DELP2-LAMDA2))-MU*S2R*RHOP2
C
C     MOMENT CONTROL
C
      IF ((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T).AND.(PHI3.GE.PHI3T)) GO TO
     1 36
      IF ((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T).AND.(PHI3.GE.PHI3T)) GO TO
     1 37
      IF ((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T).AND.(PHI3.GE.PHI3T)) GO TO
     1 38
      IF ((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T).AND.(PHI3.GE.PHI3T)) GO TO
     1 39
      IF ((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T).AND.(PHI3.LE.PHI3T)) GO TO
     1 40
      IF ((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T).AND.(PHI3.LE.PHI3T)) GO TO
     1 41
      IF ((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T).AND.(PHI3.LE.PHI3T)) GO TO
     1 42
      IF ((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T).AND.(PHI3.LE.PHI3T)) GO TO
     1 43
C
C     MOMENT EXPRESSIONS
C
   36 MO41=MIN*C2*C5*C8/(C3*C6*C10)-Q4*C1-Q2*C2*C5*C7/(C3*C6)-Q3*C2*C4/C
     13-Q1*C2*C5*C8*C9/(C3*C6*C10)
      MO4=MO41
      POINTEF=ABS(PSDOT3)*MO4/MIN
      WRITE (6,53) PHI1D,PHI2D,PHI3D,PSI1D,PSI2D,PSI3D,PSDOT1,PSDOT2,PSD
     1OT3,S1R,S2R,S3R,POINTEF
      GO TO 44
   37 MO42=MIN*C2*C5*C13/(C3*C11*C15)-Q1*C2*C5*C13*C14/(C3*C11*C15)-Q2*C
     12*C5*C12/(C3*C11)-Q3*C2*C4/C3-Q4*C1
      MO4=MO42
      POINTEF=ABS(PSDOT3)*MO4/MIN
      WRITE (6,54) PHI1D,PHI2D,PHI3D,PSI1D,PSI2D,PSI3D,PSDOT1,PSDOT2,PSD
     1OT3,S2R,S3R,S1F,G1,POINTEF
      GO TO 44
   38 MO43=MIN*C2*C18*C21/(C15*C16*C19)-Q1*C2*C14*C18*C21/(C15*C16*C19)-
     1Q2*C2*C18*C20/(C16*C19)-Q3*C2*C17/C16-Q4*C1
      MO4=MO43
      POINTEF=ABS(PSDOT3)*MO4/MIN
      WRITE (6,55) PHI1D,PHI2D,PHI3D,PSI1D,PSI2D,PSI3D,PSDOT1,PSDOT2,PSD
     1OT3,S3R,S1F,G1,S2F,G2,POINTEF
      GO TO 44
   39 MO44=MIN*C2*C18*C24/(C10*C16*C22)-Q1*C2*C9*C18*C24/(C10*C16*C22)-Q
     12*C2*C18*C23/(C16*C22)-Q3*C2*C17/C16-Q4*C1
      MO4=MO44
      POINTEF=ABS(PSDOT3)*MO4/MIN
      WRITE (6,56) PHI1D,PHI2D,PHI3D,PSI1D,PSI2D,PSI3D,PSDOT1,PSDOT2,PSD
     1OT3,S1R,S3R,S2F,G2,POINTEF
      GO TO 44
   40 MO45=MIN*C21*C26*C29/(C15*C19*C27)-Q1*C14*C21*C26*C29/(C15*C19*C27
```

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      1)-Q2-C20*C26*C29/(C19*C27)-Q3*C26*C28/C27-Q4*C25                   A 796
       W04=W045                                                            A 797
       POINTEF=ABS(PSDOT3)*W04/WIN                                         A 798
       WRITE (6,57) PHI1D,PHI2D,PHI3D,PSI1D,PSI2D,PSI3D,PSDOT1,PSDOT2,PSD  A 799
      1OT3,S1F,G1,S2F,G2,S3F,G3,POINTEF                                    A 800
       GO TO 44                                                            A 801
   41 W046=WIN*C24*C26*C29/(C10*C22*C27)-Q1*C9*C24*C26*C29/(C10*C22*C27)   A 802
      1-Q2*C23*C26*C29/(C22*C27)-Q3*C26*C28/C27-Q4*C25                     A 803
       W04=W046                                                            A 804
       POINTEF=ABS(PSDOT3)*W04/WIN                                         A 805
       WRITE (6,58) PHI1D,PHI2D,PHI3D,PSI1D,PSI2D,PSI3D,PSDOT1,PSDOT2,PSD  A 806
      1OT3,S1R,S2F,G2,S3F,G3,POINTEF                                       A 807
       GO TO 44                                                            A 808
   42 W047=WIN*C8*C26*C32/(C6*C10*C30)-Q1*C8*C9*C26*C32/(C6*C10*C30)-Q2*   A 809
      1C7*C26*C32/(C6*C30)-Q3*C26*C31/C30-Q4*C25                           A 810
       W04=W047                                                            A 811
       POINTEF=ABS(PSDOT3)*W04/WIN                                         A 812
       WRITE (6,59) PHI1D,PHI2D,PHI3D,PSI1D,PSI2D,PSI3D,PSDOT1,PSDOT2,PSD  A 813
      1OT3,S1R,S2R,S3F,G3,POINTEF                                          A 814
       GO TO 44                                                            A 815
   43 W048=WIN*C13*C26*C32/(C11*C15*C30)-Q1*C13*C14*C26*C32/(C11*C15*C30   A 816
      1)-Q2*C12*C26*C32/(C11*C30)-Q3*C26*C31/C30-Q4*C25                    A 817
       W04=W048                                                            A 818
       POINTEF=ABS(PSDOT3)*W04/WIN                                         A 819
       WRITE (6,60) PHI1D,PHI2D,PHI3D,PSI1D,PSI2D,PSI3D,PSDOT1,PSDOT2,PSD  A 820
      1OT3,S2R,S1F,G1,S3F,G3,POINTEF                                       A 821
   44 WTOT=WTOT+POINTEF                                                    A 822
       J4=1.                                                               A 823
       GO TO 29                                                            A 824
   45 CYCLEFF=-WTOT*DDPHI1/(PHI1F-PHI1I)                                   A 825
       WRITE (6,81) CYCLEFF                                                A 826
       WTOT=0.                                                             A 827
       IF (ISTOP.NE.0) GO TO 1                                             A 828
       STOP                                                                A 829
C                                                                          A 830
C                                                                          A 831
C                                                                          A 832
   46 FORMAT (6X,9HPSI1T1D =,F9.4,3X,8HTEST11 =,F9.4)                      A 833
   47 FORMAT (6X,9HPSI1T2D =,F9.4,3X,8HTEST12 =,F9.4//)                    A 834
   48 FORMAT (6X,9HPSI2T1D =,F9.4,3X,8HTEST21 =,F9.4)                      A 835
   49 FORMAT (6X,9HPSI2T2D =,F9.4,3X,8HTEST22 =,F9.4//)                    A 836
   50 FORMAT (6X,9HPSI3T1D =,F9.4,3X,8HTEST31 =,F9.4)                      A 837
   51 FORMAT (6X,9HPSI3T2D =,F9.4,3X,8HTEST32 =,F9.4//)                    A 838
   52 FORMAT (132H0      PHI1     PHI2     PHI3     PSI1     PSI2     PSI3 A 839
      1DPSI1   DPSI2   DPSI3   S1R   S2R   S3R   S1F    G1    S2F   G2   S3F  A 840
      2G3    POINTEF/)                                                     A 841
   53 FORMAT (6X,6(F6.2,2X),3(F5.0,2X),3(F3.0,2X),36X,F5.3)                A 842
   54 FORMAT (6X,6(F6.2,2X),3(F5.0,2X),5X,3(F3.0,2X),F5.3,26X,F5.3)        A 843
   55 FORMAT (6X,6(F6.2,2X),3(F5.0,2X),10X,F3.0,2X,F3.0,2X,F5.3,2X,F3.0,   A 844
      12X,F5.3,14X,F5.3)                                                   A 845
   56 FORMAT (6X,6(F5.2,2X),3(F5.0,2X),F3.0,7X,F3.0,14X,F3.0,2X,F5.3,14X   A 846
      1,F5.3)                                                              A 847
   57 FORMAT (6X,6(F6.2,2X),3(F5.0,2X),15X,3(F3.0,2X,F5.3,2X),F5.3)        A 848
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   58 FORMAT (6X,6(F6.2,2X),3(F5.0,2X),F3.0,24X,F3.0,2X,F5.3,2X,F3.0,2X,  A 849
     1F5.3,2X,F5.3)                                                        A 850
   59 FORMAT (6X,6(F5.2,2X),3(F5.0,2X),2(F3.0,2X),29X,F3.0,2X,F5.3,2X,F5  A 851
     1.3)                                                                  A 852
   60 FORMAT (6X,6(F6.2,2X),3(F5.0,2X),5X,F3.0,7X,F3.0,2X,F5.3,14X,F3.0,  A 853
     12X,F5.3,2X,F5.3)                                                     A 854
   61 FORMAT (3F10.4/6F10.0)                                               A 855
   62 FORMAT (6F10.4)                                                      A 856
   63 FORMAT (6F10.4)                                                      A 857
   64 FORMAT (F10.3,F10.0/6F10.5/6F10.5/I1)                                A 858
   65 FORMAT (4F10.4/F10.4/F10.6/3F10.2)                                   A 859
   66 FORMAT (1H1,5X,8HPSUBD1 =,F5.0,3X,8HPSUBD2 =,F5.0,3X,8HPSUBD3 =,F5  A 860
     1.0//6X,5HMIN =,F9.6,3X,4HMU =,F6.3,3X,5HRPM =,F6.0//6X,8HCAPRP1 =,   A 861
     2F8.5,3X,8HCAPRP2 =,F8.5,3X,8HCAPRP3 =,F8.5//6X,5HRP2 =,F8.5,3X,5HR  A 862
     3P3 =,F8.5,3X,5HRP4 =,F8.5//6X,6HACG1 =,F8.5,3X,6HACG2 =,F8.5,3X,6H  A 863
     4ACG3 =,F8.5//6X,6HACP1 =,F8.5,3X,6HACP2 =,F8.5,3X,6HACP3 =,F8.5/)   A 864
   67 FORMAT (6X,7HRHOG1 =,F8.5,3X,7HRHOG2 =,F8.5,3X,7HRHOG3 =,F8.5,3X,7  A 865
     1HRHOP1 =,F8.5,3X,7HRHOP2 =,F8.5,3X,7HRHOP3 =,F8.5/)                  A 866
   68 FORMAT (6X,5HTG1 =,F8.5,3X,5HTG2 =,F8.5,3X,5HTG3 =,F8.5,3X,5HTP1 =  A 867
     1,F8.5,3X,5HTP2 =,F8.5,3X,5HTP3 =,F8.5/)                              A 868
   69 FORMAT (6X,5HNG1 =,F5.0,3X,5HNG2 =,F5.0,3X,5HNG3 =,F5.0,3X,5HNP2 =  A 869
     1,F5.0,3X,5HNP3 =,F5.0,3X,5HNP4 =,F5.0/)                              A 870
   70 FORMAT (6X,6HRHO1 =,F6.3,3X,6HRHO2 =,F6.3,3X,6HRHO3 =,F6.3,3X,6HRH  A 871
     1O4 =,F6.3//6X,4HMD =,E12.4//6X,3HK =,F6.1//6X,8HPHDOT1 =,F5.1//6X,   A 872
     24HJ1 =,F4.2,3X,4HJ2 =,F4.2,3X,4HJ3 =,F4.2/)                          A 873
   71 FORMAT (6X,8HBETA1D =,F8.4,3X,8HBETA2D =,F8.4,3X,8HBETA3D =,F8.4//  A 874
     1)                                                                    A 875
   72 FORMAT (6X,30HSOMETHING IS WRONG WITH MESH 1)                        A 876
   73 FORMAT (6X,8HPHI1TD =,F8.4,3X,8HPSI1TD =,F8.4)                       A 877
   74 FORMAT (6X,8HPHI1ID =,F8.4,3X,8HPSI1ID =,F8.4,3X,8HPHI1FD =,F8.4,3  A 878
     1X,8HPSI1FD =,F8.4//)                                                 A 879
   75 FORMAT (6X,30HSOMETHING IS WRONG WITH MESH 2)                        A 880
   76 FORMAT (6X,8HPHI2TD =,F8.4,3X,8HPSI2TD =,F8.4)                       A 881
   77 FORMAT (6X,8HPHI2ID =,F8.4,3X,8HPSI2ID =,F8.4,3X,8HPHI2FD =,F8.4,3  A 882
     1X,8HPSI2FD =,F8.4//)                                                 A 883
   78 FORMAT (6X,30HSOMETHING IS WRONG WITH MESH 3)                        A 884
   79 FORMAT (6X,8HPHI3TD =,F8.4,3X,8HPSI3TD =,F8.4)                       A 885
   80 FORMAT (6X,8HPHI3ID =,F8.4,3X,8HPSI3ID =,F8.4,3X,8HPHI3FD =,F8.4,3  A 886
     1X,8HPSI3FD =,F8.4//)                                                 A 887
   81 FORMAT (1H0,5X,18HCYCLE EFFICIENCY =,F5.3)                           A 888
   82 FORMAT (4F10.5)                                                      A 889
   83 FORMAT (6X,4HR1 =,F8.5,3X,4HR2 =,F8.5,3X,4HR3 =,F8.5,3X,4HR4 =,F8.  A 890
     15/)                                                                  A 891
   84 FORMAT (6X,5HFP1 =,F8.5,3X,5HFP2 =,F8.5,3X,5HFP3 =,F8.5/)            A 892
   85 FORMAT (4E15.5)                                                      A 893
   86 FORMAT (6X,4HM1 =,E15.5,3X,4HM2 =,E15.5,3X,4HM3 =,E15.5,3X,4HM4 =,  A 894
     1E15.5/)                                                              A 895
      END                                                                  A 896-
```

Computer program CLOCK3 (cont)

```
SUBROUTINE TRANS1      74/74    OPT=1                    FTN 4.6+420        07/31/79  08.15.34        PAGE      1

      SUBROUTINE TRANS1 (RHOG,ALPHP,BETA,FP,ACG,B,DELG,Z,PSIT,PHIT,G)
      PI=3.14159
      ST=(-RHOG*COS(PSIT-ALPHP)+B*SIN(BETA)+FP*SIN(PSIT-ALPHP))/ACG
      CT=(RHOG*SIN(PSIT-ALPHP)+B*COS(BETA)+FP*COS(PSIT-ALPHP))/ACG
      PHIT=ATAN2(ST,CT)-DELG
      PHINEXT=PHIT-.1*Z
      AF=ACG*COS(PHINEXT+DELG+ALPHP)-B*COS(BETA+ALPHP)
      BF=-ACG*SIN(PHINEXT+DELG+ALPHP)+B*SIN(BETA+ALPHP)
      CF=RHOG
      ROOTF=AF*AF+BF*BF-CF*CF
      YF1=AF+SQRT(ROOTF)
      YF2=AF-SQRT(ROOTF)
      XF=BF+CF
      PSINEX1=2.*ATAN2(YF1,XF)
      PSINEX2=2.*ATAN2(YF2,XF)
      IF (PSINEX1.LT.0.) PSINEX1=PSINEX1+2.*PI
      IF (PSINEX2.LT.0.) PSINEX2=PSINEX2+2.*PI
      IF (ABS(PSINEX1-PSIT).LT.ABS(PSINEX2-PSIT)) GO TO 1
      PSINEXT=PSINEX2
      GO TO 2
    1 PSINEXT=PSINEX1
    2 G=(ACG*SIN(PHINEXT+DELG)+RHOG*COS(PSINEXT-ALPHP)-B*SIN(BETA))/SIN(
     1PSINEXT-ALPHP)
      RETURN
      END
```

Computer program CLOCK3 (cont)

SUBROUTINE TRANS2   74/74   OPT=1   FTN 4.6+420   07/31/79 08.15.34   PAGE   1

```
      SUBROUTINE TRANS2 (RHOG,ALPHP,BETA,FP,ACG,B,DELG,Z,PSIT,PHIT,G)
      PI=3.14159
      ST=(RHOG*COS(PSIT+ALPHP)+B*SIN(BETA)+FP*SIN(PSIT+ALPHP))/ACG
      CT=(-RHOG*SIN(PSIT+ALPHP)+B*COS(BETA)+FP*COS(PSIT+ALPHP))/ACG
      PHIT=ATAN2(ST,CT)+DELG
      PHINEXT=PHIT+.1*Z
      AF=ACG*COS(PHINEXT-DELG-ALPHP)-B*COS(BETA-ALPHP)
      BF=-ACG*SIN(PHINEXT-DELG-ALPHP)+B*SIN(BETA-ALPHP)
      CF=-RHOG
      ROOTF=AF*AF+BF*BF-CF*CF
      YF1=AF+SQRT(ROOTF)
      YF2=AF-SQRT(ROOTF)
      XF=BF+CF
      PSINEX1=2.*ATAN2(YF1,XF)
      PSINEX2=2.*ATAN2(YF2,XF)
      IF (PSINEX1.LT.0.) PSINEX1=PSINEX1+2.*PI
      IF (PSINEX2.LT.0.) PSINEX2=PSINEX2+2.*PI
      IF (ABS(PSINEX1-PSIT).LT.ABS(PSINEX2-PSIT)) GO TO 1
      PSINEXT=PSINEX2
      GO TO 2
    1 PSINEXT=PSINEX1
    2 G=(ACG*SIN(PHINEXT-DELG)-RHOG*COS(PSINEXT+ALPHP)-B*SIN(BETA))/SIN(
     1PSINEXT+ALPHP)
      RETURN
      END
```

```
PSUBD1 =  44.   PSUBD2 =  65.   PSUBD3 =  77.

MIN =  .030157   MU =  .200   RPM = 1000.

CAPRP1 =  .47727   CAPRP2 =  .20769   CAPRP3 =  .17532

RP2 =  .09091   RP3 =  .06923   RP4 =  .05844

ACG1 =  .47343   ACG2 =  .20559   ACG3 =  .17355

ACP1 =  .09083   ACP2 =  .06917   ACP3 =  .05839

NG1 =  42.   NG2 =  27.   NG3 =  27.   NP2 =   8.   NP3 =   9.   NP4 =   9.

R1 =  .22500   R2 =  .43600   R3 =  .50400   R4 =  .52000

RHOG1 =  .04857   RHOG2 =  .03323   RHOG3 =  .02805   RHOP1 =  .01591   RHOP2 =  .01077   RHOP3 =  .00909

TG1 =  .03609   TG2 =  .02438   TG3 =  .02058   TP1 =  .02382   TP2 =  .01613   TP3 =  .01362

M1 =      .12000E-03   M2 =      .85000E-05   M3 =      .34000E-05   M4 =      .15000E-05

RHO1 =  .062   RHO2 =  .025   RHO3 =  .018   RHO4 =  .016

MD =  .2750E-05

K =  25.0

PHDOT1 = -1.0

J1 = .90   J2 = .90   J3 = .93

FP1 =  .08943   FP2 =  .06833   FP3 =  .05766

BETA1D =135.8183   BETA2D =207.7654   BETA3D =247.3601

PSI1T1D = 332.4403   TEST11 =   9.0E47
PSI1T2D =  11.3250   TEST12 =  47.9494

PHI1TD =136.2544   PSI1TD =332.4403
PHI1ID =140.2158   PSI1ID =311.7042   PHI1FD =131.6444   PSI1FD =356.7042

PSI2T1D = 337.8854   TEST21 =  43.1735
PSI2T2D =  12.3618   TEST22 =   8.6971

PHI2TD =207.2958   PSI2TD = 12.3618
PHI2ID =200.9124   PSI2ID = 31.4084   PHI2FD =214.2458   PSI2FD =351.4084

PSI3T1D -  82.7609   TEST31 =   8.6883
PSI3T2D = 117.2516   TEST32 =  43.1790

PHI3TD =247.6360   PSI3TD = 32.7609
PHI3ID =254.2093   PSI3ID = 63.7458   PHI3FD =240.8760   PSI3FD =103.7458
```

Computer program CLOCK3 (cont)

PHI1	PHI2	PHI3	PSI1	PSI2	FSI3	DPSI1	DPSI2	DPSI3	S1R	S2R	S3R	S1F	G1	S2F	G2	S3F	G3	POINTEF
132.50	212.91	242.21	352.45	355.25	99.91	5.	-15.	44.				1.	.081	1.	.063	1.	.053	.320
132.47	213.68	241.70	352.62	354.74	101.39	5.	-15.	43.				1.	.081	1.	.063	1.	.053	.317
132.43	213.26	241.20	352.79	354.24	102.83	5.	-15.	42.				1.	.081	1.	.063	1.	.053	.315
132.40	213.43	254.21	352.96	353.74	63.75	5.	-15.	44.			1.	1.	.081	1.	.063			.345
132.37	213.10	253.71	353.13	353.24	65.24	5.	-15.	44.			1.	1.	.081	1.	.063			.348
132.33	213.77	253.22	353.30	352.75	66.71	5.	-14.	43.			1.	1.	.081	1.	.063			.350
132.30	213.94	252.73	353.48	352.27	68.17	5.	-14.	43.			1.	1.	.081	1.	.063			.353
132.26	214.11	252.25	353.65	351.78	69.61	5.	-14.	42.			1.	1.	.081	1.	.063			.355
132.23	200.91	252.25	353.82	31.41	69.61	5.	-15.	45.		-1.	1.	1.	.081					.391
132.20	201.08	251.74	353.99	30.89	71.13	5.	-15.	45.		-1.	1.	1.	.081					.356
132.16	201.25	251.23	354.16	30.38	72.65	5.	-15.	45.		-1.	1.	1.	.081					.400
132.13	201.42	250.72	354.32	29.88	74.16	5.	-15.	45.		-1.	-1.	1.	.081					.401
132.10	201.59	250.21	354.49	29.37	75.66	5.	-15.	44.		-1.	-1.	1.	.081					.399
132.06	201.76	249.71	354.66	28.87	77.16	5.	-15.	44.		-1.	-1.	1.	.081					.397
132.03	201.93	249.21	354.83	28.36	78.56	5.	-15.	44.		-1.	-1.	1.	.081					.395
131.99	202.09	248.70	355.00	27.86	80.16	5.	-15.	44.		-1.	-1.	1.	.081					.393
131.96	202.26	248.21	355.16	27.36	81.66	5.	-15.	44.		-1.	-1.	1.	.081					.391
131.93	202.43	247.71	355.33	26.87	83.15	5.	-15.	44.		-1.		1.	.081			1.	.058	.389
131.89	202.59	247.21	355.50	26.37	84.65	5.	-15.	44.		-1.		1.	.081			1.	.057	.387
131.86	202.76	246.72	355.65	25.88	86.15	5.	-15.	45.		-1.		1.	.081			1.	.056	.385
131.82	202.93	246.23	355.83	25.38	87.67	5.	-15.	45.		-1.		1.	.081			1.	.056	.383
131.79	203.09	245.73	356.00	24.89	89.18	5.	-14.	45.		-1.		1.	.081			1.	.055	.381
131.76	203.26	245.24	356.16	24.40	90.69	5.	-14.	45.		-1.		1.	.081			1.	.055	.379
131.72	203.42	244.75	356.33	23.91	92.20	5.	-14.	44.		-1.		1.	.081			1.	.054	.377
131.69	203.59	244.27	356.49	23.42	93.70	5.	-14.	44.		-1.		1.	.081			1.	.054	.376
131.65	203.75	243.78	356.65	22.94	95.19	5.	-14.	44.		-1.		1.	.081			1.	.054	.374
140.22	203.75	243.77	311.71	22.93	95.22	5.	-16.	48.	1.	-1.						1.	.054	.413
140.18	203.93	243.24	311.89	22.40	96.83	5.	-16.	47.	1.	-1.						1.	.054	.413
140.15	204.11	242.71	312.07	21.87	98.43	5.	-16.	47.	1.	-1.						1.	.053	.411
140.11	204.29	242.16	312.24	21.33	100.00	5.	-16.	46.	1.	-1.						1.	.053	.410
140.08	204.47	241.65	312.42	20.80	101.55	5.	-16.	45.	1.	1.						1.	.052	.404
140.05	204.65	241.12	312.60	20.27	103.07	5.	-16.	44.	1.	1.						1.	.053	.400
140.01	204.82	254.21	312.78	19.74	63.75	5.	-16.	47.	1.	1.	1.							.438
139.98	205.06	253.68	312.96	19.21	65.34	5.	-16.	47.	1.	1.	1.							.442
139.94	205.13	253.15	313.14	18.68	66.93	5.	-16.	47.	1.	1.	1.							.446
139.91	205.36	252.62	313.31	18.15	68.51	5.	-16.	47.	1.	1.	1.							.450
139.88	205.54	252.03	313.49	17.62	70.09	5.	-16.	47.	1.	1.	1.							.453
139.84	205.71	251.56	313.67	17.09	71.67	5.	-16.	47.	1.	1.	1.							.457
139.81	205.89	251.03	313.85	16.56	73.24	5.	-16.	47.	1.	1.	1.							.460
139.78	206.07	250.50	314.02	16.03	74.82	5.	-16.	47.	1.	1.	-1.							.455
139.74	206.25	249.56	314.20	15.50	76.40	5.	-16.	47.	1.	1.	-1.							.450
139.71	206.42	249.43	314.38	14.97	77.99	5.	-16.	47.	1.	1.	-1.							.445
139.67	206.60	248.90	314.56	14.44	79.57	5.	-16.	47.	1.	1.	-1.							.441
139.64	206.78	248.37	314.73	13.90	81.17	5.	-16.	47.	1.	1.	-1.							.436
139.61	206.96	247.84	314.91	13.37	82.76	5.	-16.	47.	1.	1.	-1.							.431
139.57	207.13	247.31	315.09	12.84	84.37	5.	-16.	48.	1.	1.						1.	.057	.426
139.54	207.31	246.73	315.27	12.31	85.95	5.	-16.	48	1.					1.	.068	1.	.056	.421
139.50	207.49	246.25	315.44	11.78	87.60	5.	-16.	49.	1.					1.	.068	1.	.056	.417
139.47	207.67	245.71	315.62	11.25	89.25	5.	-16.	49.	1.					1.	.068	1.	.055	.412
139.44	207.84	245.17	315.80	10.71	90.91	5.	-16.	49.	1.					1.	.067	1.	.055	.408
139.40	208.02	244.64	315.97	10.17	92.56	5.	-16.	49.	1.					1.	.067	1.	.054	.403
139.37	208.20	244.10	316.15	9.63	94.22	5.	-16.	49.	1.					1.	.067	1.	.054	.399
139.34	208.37	243.56	316.33	9.09	95.87	5.	-16.	49.	1.					1.	.067	1.	.054	.396
139.30	208.55	243.01	316.51	6.55	97.51	5.	-16.	48.	1.					1.	.067	1.	.054	.392
139.27	208.73	242.47	316.68	8.01	99.13	5.	-16.	48.	1.					1.	.066	1.	.053	.388
139.23	208.90	241.93	316.86	7.46	100.73	5.	-16.	47.	1.					1.	.066	1.	.053	.384
139.20	209.08	241.38	317.04	6.92	102.30	5.	-16.	46.	1.					1.	.066	1.	.053	.381
139.17	209.26	254.21	317.21	6.37	63.75	5.	-16.	49.	1.		1.			1.	.066			.416

Computer program CLOCK3 (cont)

139.13	209.43	253.66	317.39	5.83	65.39	5.	-16.	48.	1.		1.	1.	.065			.420
139.10	209.61	253.12	317.57	5.29	67.02	5.	-16.	48.	1.		1.	1.	.065			.423
139.06	209.79	252.57	317.74	4.74	68.64	5.	-16.	48.	1.		1.	1.	.065			.427
139.03	209.96	252.03	317.92	4.20	70.26	5.	-16.	48.	1.		1.	1.	.065			.430
139.00	210.14	251.49	318.10	3.65	71.88	5.	-16.	48.	1.		1.	1.	.065			.434
138.96	210.32	250.94	318.27	3.11	73.50	5.	-16.	48.	1.		1.	1.	.065			.437
138.93	210.45	250.40	318.45	2.56	75.11	5.	-16.	48.	1.		-1.	1.	.064			.431
[illegible]	210.67	249.85	318.63	2.02	76.73	5.	-16.	48.	1.		-1.	1.	.064			.427
138.86	210.85	249.31	318.80	1.48	78.34	5.	-16.	48.	1.		-1.	1.	.064			.422
138.83	211.02	248.77	318.98	.94	79.96	5.	-16.	48.	1.		-1.	1.	.064			.418
138.79	211.20	248.23	319.16	.40	81.58	5.	-16.	48.	1.		-1.	1.	.064			.413
138.76	211.38	247.69	319.33	359.86	83.19	5.	-16.	48.	1.			1.	.064	1.	.057	.409
138.73	211.55	247.16	319.51	359.32	84.82	5.	-16.	48.	1.			1.	.064	1.	.057	.405
138.69	211.73	246.62	319.68	358.79	86.45	5.	-16.	48.	1.			1.	.064	1.	.056	.400
138.66	211.91	246.09	319.86	358.25	88.09	5.	-16.	48.	1.			1.	.064	1.	.056	.396
138.62	212.08	245.55	320.04	357.72	89.73	5.	-16.	48.	1.			1.	.063	1.	.055	.393
138.59	212.26	245.02	320.21	357.19	91.37	5.	-16.	48.	1.			1.	.063	1.	.055	.389
138.56	212.44	244.50	320.39	356.66	92.99	5.	-16.	48.	1.			1.	.063	1.	.054	.386
138.52	212.61	243.97	320.57	356.14	94.60	5.	-15.	47.	1.			1.	.063	1.	.054	.383
138.49	212.79	243.45	320.74	355.61	96.20	5.	-15.	47.	1.			1.	.063	1.	.054	.380
138.45	212.97	242.93	320.92	355.09	97.77	5.	-15.	46.	1.			1.	.063	1.	.053	.377
138.42	213.14	242.41	321.10	354.58	99.31	5.	-15.	45.	1.			1.	.063	1.	.053	.374
138.39	213.32	241.89	321.27	354.06	100.83	5.	-15.	44.	1.			1.	.063	1.	.053	.371
138.35	213.50	241.38	321.45	353.55	102.31	5.	-15.	43.	1.			1.	.063	1.	.053	.368
138.32	213.67	254.21	321.63	353.04	63.75	5.	-15.	45.	1.		1.	1.	.063			.402
138.29	213.85	253.70	321.80	352.53	65.27	5.	-15.	45.	1.		1.	1.	.063			.406
138.25	214.02	253.20	321.98	352.03	66.77	5.	-15.	44.	1.		1.	1.	.063			.410
138.22	214.20	252.70	322.16	351.53	68.26	5.	-15.	44.	1.		1.	1.	.063			.413
138.18	200.91	252.70	322.33	31.41	68.27	5.	-16.	47.	1.	-1.	1.					.455
138.15	201.09	252.17	322.51	30.87	69.85	5.	-16.	47.	1.	-1.	1.					.462
138.12	201.27	251.64	322.69	30.34	71.43	5.	-16.	47.	1.	-1.	1.					.469
138.08	201.44	251.11	322.86	29.81	73.01	5.	-16.	47.	1.	-1.	1.					.475
138.05	201.62	250.58	323.04	29.28	74.58	5.	-16.	46.	1.	-1.	-1.					.475
138.01	201.80	250.05	323.22	28.75	76.15	5.	-16.	46.	1.	-1.	-1.					.473
137.98	201.97	249.52	323.39	28.22	77.73	5.	-16.	47.	-1.	-1.	-1.					.473
137.95	202.15	248.99	323.57	27.70	79.31	5.	-16.	47.	-1.	-1.	-1.					.470
137.91	202.33	248.46	323.75	27.17	80.88	5.	-16.	47.	-1.	-1.	-1.					.467
137.88	202.50	247.94	323.92	26.64	82.46	5.	-16.	47.	-1.	-1.	-1.					.464
137.85	202.68	247.41	324.10	26.12	84.04	5.	-16.	47.	-1.	-1.				1.	.057	.461
137.81	202.86	246.89	324.28	25.59	85.64	5.	-16.	47.	-1.	-1.				1.	.056	.458
137.78	203.03	246.36	324.45	25.07	87.26	5.	-16.	48.	-1.	-1.				1.	.056	.455
137.74	203.21	245.83	324.63	24.54	88.87	5.	-16.	48.	-1.	-1.				1.	.055	.453
137.71	203.39	245.31	324.81	24.01	90.49	5.	-16.	48.	-1.	-1.				1.	.055	.450
137.68	203.56	244.78	324.98	23.49	92.11	5.	-16.	48.	-1.	-1.				1.	.054	.448
137.64	203.74	244.26	325.16	22.96	93.73	5.	-16.	48.	-1.	-1.				1.	.054	.445
137.61	203.92	243.73	325.34	22.44	95.34	5.	-16.	47.	-1.	-1.				1.	.054	.443
137.57	204.10	243.21	325.52	21.91	96.93	5.	-16.	47.	-1.	-1.				1.	.054	.441
137.54	204.27	242.68	325.69	21.38	98.51	5.	-16.	46.	-1.	-1.				1.	.053	.439
137.51	204.45	242.15	325.87	20.86	100.07	5.	-16.	46.	-1.	1.				1.	.053	.431
137.47	204.63	241.63	326.05	20.33	101.61	5.	-16.	45.	-1.	1.				1.	.053	.426
137.44	204.80	241.10	326.22	19.80	103.12	5.	-16.	44.	-1.	1.				1.	.053	.421
137.41	204.98	254.21	326.40	19.28	63.75	5.	-16.	47.	-1.	1.	1.					.460
137.37	205.16	253.68	326.58	18.75	65.34	5.	-16.	47.	-1.	1.	1.					.464
137.34	205.34	253.15	326.76	18.22	66.92	5.	-16.	47.	-1.	1.	1.					.466
137.30	205.51	252.62	326.93	17.69	68.49	5.	-16.	47.	-1.	1.	1.					.469
137.27	205.69	252.10	327.11	17.16	70.07	5.	-16.	46.	-1.	1.	1.					.471
137.24	205.87	251.57	327.29	16.63	71.64	5.	-16.	46.	-1.	1.	1.					.474
137.20	206.05	251.04	327.47	16.10	73.22	5.	-16.	47.	-1.	1.	1.					.476
137.17	206.22	250.50	327.64	15.57	74.79	5.	-16.	47.	-1.	1.	-1.					.470
137.13	206.40	249.97	327.82	15.04	76.38	5.	-16.	47.	-1.	1.	-1.					.464
137.10	206.58	249.44	328.00	14.51	77.96	5.	-16.	47.	-1.	1.	-1.					.458

Computer program CLOCK3 (cont)

137.07	206.76	248.91	328.18	13.98	79.55	5.	-16.	47.	-1.	1.	-1.							.452
137.03	206.93	248.38	328.35	13.44	81.15	5.	-16.	47.	-1.	1.	-1.							.446
137.00	207.11	247.84	328.53	12.91	82.75	5.	-16.	47.	-1.	1.	-1.							.440
136.97	207.29	247.31	328.71	12.38	84.36	5.	-16.	48.	-1.	1.						1.	.057	.434
136.93	207.47	246.78	328.89	11.85	85.97	5.	-16.	48.	-1.					1.	.068	1.	.056	.428
136.90	207.64	246.24	329.07	11.31	87.61	5.	-16.	49.	-1.					1.	.068	1.	.056	.422
136.86	207.82	245.70	329.24	10.77	89.27	5.	-16.	49.	-1.					1.	.068	1.	.055	.417
136.83	208.00	245.16	329.42	10.23	90.94	5.	-16.	49.	-1.					1.	.067	1.	.055	.411
136.80	208.18	244.62	329.60	9.69	92.61	5.	-16.	49.	-1.					1.	.067	1.	.054	.406
136.76	208.36	244.08	329.78	9.14	94.28	5.	-16.	49.	-1.					1.	.067	1.	.054	.401
136.73	208.53	243.53	329.95	8.60	95.94	5.	-16.	49.	-1.					1.	.067	1.	.054	.397
136.69	208.71	242.99	330.13	3.05	97.60	5.	-16.	49.	-1.					1.	.066	1.	.054	.392
136.66	208.89	242.44	330.31	7.51	99.23	5.	-16.	48.	-1.					1.	.066	1.	.053	.387
136.63	209.07	241.89	330.49	6.96	100.84	5.	-16.	47.	-1.					1.	.066	1.	.053	.382
136.59	209.25	241.34	330.67	6.41	102.43	5.	-16.	46.	-1.					1.	.066	1.	.053	.378
136.56	209.43	254.21	330.85	5.86	63.75	5.	-16.	49.	-1.		1.			1.	.065			.412
136.52	209.60	253.66	331.02	5.31	65.40	5.	-16.	49.	-1.		1.			1.	.065			.415
136.49	209.78	253.11	331.20	4.76	67.05	5.	-16.	49.	-1.		1.			1.	.065			.418
136.46	209.96	252.56	331.38	4.21	68.69	5.	-16.	48.	-1.		1.			1.	.065			.421
136.42	210.14	252.01	331.56	3.66	70.32	5.	-16.	48.	-1.		1.			1.	.065			.423
136.39	210.32	251.46	331.74	3.11	71.96	5.	-16.	48.	-1.		1.			1.	.065			.426
136.36	210.50	250.91	331.92	2.56	73.59	5.	-16.	48.	-1.		1.			1.	.064			.428
136.32	210.67	250.36	332.09	2.01	73.22	5.	-16.	48.	-1.		-1.			1.	.064			.421
135.29	210.85	249.81	332.27	1.46	76.85	5.	-16.	48.	-1.		-1.			1.	.064			.415
136.25	211.02	249.29	332.44	.94	78.40	5.	-16.	49.			-1.	1.	.089	1.	.064			.410
136.22	211.20	248.75	332.62	.40	80.04	5.	-16.	48.			-1.	1.	.089	1.	.064			.405
136.19	211.38	248.20	332.80	359.85	81.67	5.	-16.	48.			-1.	1.	.089	1.	.064			.400
136.15	211.56	247.66	332.98	359.31	83.30	5.	-16.	49.				1.	.089	1.	.064	1.	.057	.394
136.12	211.74	247.11	333.16	358.76	84.35	5.	-16.	49.				1.	.089	1.	.064	1.	.057	.389
136.08	211.92	246.57	333.34	358.22	86.51	5.	-16.	49.				1.	.089	1.	.063	1.	.056	.384
136.05	212.10	246.03	333.52	357.68	89.27	5.	-16.	49.				1.	.089	1.	.063	1.	.056	.379
136.02	212.28	245.49	333.70	357.14	89.94	5.	-16.	49.				1.	.089	1.	.063	1.	.055	.375
135.98	212.46	244.95	333.88	356.60	91.60	5.	-16.	49				1.	.088	1.	.063	1.	.055	.370
135.95	212.64	244.41	334.06	356.06	93.25	5.	-16.	49.				1.	.088	1.	.063	1.	.054	.366
135.92	212.82	243.88	334.24	355.53	94.88	5	-16.	49.				1.	.088	1.	.063	1.	.054	.362
135.88	213.00	243.35	334.42	355.00	96.50	5.	-16.	47.				1.	.088	1.	.063	1.	.054	.359
135.85	213.18	242.82	334.60	354.47	98.09	5.	-16.	47.				1.	.088	1.	.063	1.	.053	.355
135.81	213.36	242.29	334.78	353.94	99.66	5.	-16.	46.				1.	.088	1.	.063	1.	.053	.351
135.78	213.54	241.77	334.96	353.42	101.19	5.	-15.	45.				1.	.088	1.	.063	1.	.053	.348
135.75	213.72	241.25	335.14	352.90	102.69	5.	-15.	44.				1.	.088	1.	.063	1.	.053	.344
135.71	213.90	254.21	335.32	352.36	63.75	5.	-15.	46.			1.	1.	.088	1.	.063			.376
135.68	214.08	253.69	335.50	351.87	65.30	5.	-15.	45.			1.	1.	.087	1.	.063			.379
135.64	200.91	253.69	335.69	31.41	65.30	5.	-16.	49.		-1.	1.	1.	.087					.416
135.61	201.09	253.15	335.87	30.86	66.94	5.	-16.	48.		-1.	1.	1.	.087					.422
135.58	201.28	252.60	336.05	30.31	68.57	5.	-16.	49.		-1.	1.	1.	.087					.428
135.54	201.46	252.05	336.23	29.77	70.19	5.	-16.	48.		-1.	1.	1.	.087					.433
135.51	201.64	251.51	336.41	29.22	71.82	5.	-16.	48.		-1.	1.	1.	.087					.439
135.48	201.82	250.96	336.59	28.68	73.43	5.	-16.	48.		-1.	1.	1.	.087					.444
135.44	202.00	250.42	335.78	28.13	75.05	5.	-16.	48.		-1.	-1.	1.	.087					.440
135.41	202.19	249.87	336.96	27.59	76.67	5.	-16.	48.		-1.	-1.	1.	.087					.438
135.37	202.37	249.33	337.14	27.04	78.29	5.	-16.	48.		-1.	-1.	1.	.086					.435
135.34	202.55	248.79	337.32	26.50	79.92	5.	-16.	48.		-1.	-1.	1.	.086					.432
135.31	202.73	248.24	337.51	25.96	81.54	5.	-16.	48.		-1.	-1.	1.	.086					.429
135.27	202.92	247.70	337.69	25.42	83.17	5.	-16.	48.		-1.		1.	.086			1.	.057	.426
135.24	203.10	247.16	337.87	24.87	84.81	5.	-16.	49.		-1.		1.	.086			1.	.057	.423
135.20	203.28	246.62	338.05	24.33	86.47	5.	-16.	49.		-1.		1.	.086			1.	.056	.420
135.17	203.46	246.07	338.24	23.79	88.14	5.	-16.	49.		-1.		1.	.086			1.	.056	.417
135.14	203.65	245.53	338.42	23.24	89.81	5.	-16.	49.		-1.		1.	.086			1.	.055	.415
135.10	203.83	244.99	338.60	22.70	91.49	5.	-16.	49.		-1.		1.	.086			1.	.055	.412
135.07	204.01	244.44	338.79	22.16	93.16	5.	-16.	49.		-1.		1.	.086			1.	.054	.410
135.03	204.20	243.90	338.97	21.61	94.82	5.	-16.	49.		-1.		1.	.085			1.	.054	.408

Computer program CLOCK3 (cont)

135.00	204.38	243.36	339.15	21.07	95.48	5.	-16.	49.	1.		1.	.085			1.	.054	.402
134.97	204.56	242.81	339.33	20.52	98.13	5.	-16.	48.	1.		1.	.085			1.	.053	.397
134.93	204.74	242.27	339.52	19.98	99.74	5.	-16.	47.	1.		1.	.085			1.	.053	.392
134.90	204.93	241.72	339.70	19.44	101.33	5.	-16.	47.	1.		1.	.085			1.	.053	.387
134.87	205.11	241.18	339.88	18.89	102.90	5.	-16.	46.	1.		1.	.085			1.	.053	.383
134.83	205.29	254.21	340.07	18.34	53.75	5.	-16.	49.	1.	1.	1.	.085					.418
134.80	205.48	253.65	340.25	17.80	65.39	5.	-16.	48.	1.	1.	1.	.085					.421
134.76	205.66	253.12	340.43	17.25	67.03	5.	-16.	48.	1.	1.	1.	.085					.424
134.73	205.84	252.57	340.62	16.70	68.66	5.	-16.	48.	1.	1.	1.	.085					.426
134.70	206.03	252.02	340.80	16.15	70.29	5.	-16.	48.	1.	1.	1.	.085					.428
134.66	206.21	251.47	340.98	15.61	71.91	5.	-16.	48.	1.	1.	1.	.084					.431
134.63	206.39	250.93	341.17	15.06	73.54	5.	-16.	48.	1.	1.	1.	.084					.433
134.59	206.58	250.38	341.35	14.51	75.17	5.	-16.	48.	1.	-1.	1.	.084					.426
134.56	206.76	249.83	341.53	13.96	76.81	5.	-16.	48.	1.	-1.	1.	.084					.420
134.53	206.94	249.28	341.72	13.41	78.45	5.	-16.	48.	1.	-1.	1.	.084					.414
134.49	207.13	248.73	341.90	12.86	80.09	5.	-16.	49.	1.	-1.	1.	.084					.408
134.46	207.31	248.19	342.08	12.32	81.72	5.	-16.	49.		-1.	1.	.084	1.	.068			.403
134.43	207.49	247.63	342.27	11.77	83.37	5.	-16.	49.			1.	.084	1.	.068	1.	.057	.397
134.39	207.68	247.08	342.45	11.22	85.05	5.	-16.	50.			1.	.084	1.	.068	1.	.057	.391
134.36	207.86	246.53	342.63	10.66	86.74	5.	-16.	50.			1.	.084	1.	.067	1.	.056	.385
134.32	208.04	245.97	342.81	10.10	88.45	5.	-16.	51.			1.	.084	1.	.067	1.	.055	.380
134.29	208.22	245.41	343.00	9.55	90.17	5.	-16.	51.			1.	.084	1.	.067	1.	.055	.375
134.26	208.41	244.85	343.18	8.99	91.90	5.	-17.	51.			1.	.084	1.	.067	1.	.055	.370
134.22	208.59	244.29	343.36	8.43	93.62	5.	-17.	51.			1.	.083	1.	.066	1.	.054	.365
134.19	208.77	243.73	343.55	7.87	95.33	5.	-17.	50.			1.	.083	1.	.066	1.	.054	.361
134.15	208.96	243.17	343.73	7.31	97.04	5.	-17.	50.			1.	.083	1.	.066	1.	.054	.356
134.12	209.14	242.61	343.91	6.74	98.72	5.	-17.	49.			1.	.083	1.	.066	1.	.053	.352
134.09	209.32	242.05	344.09	6.18	100.38	5.	-17.	49.			1.	.083	1.	.066	1.	.053	.348
134.05	209.50	241.49	344.28	5.62	102.01	5.	-17.	48.			1.	.083	1.	.065	1.	.053	.344
134.02	209.69	240.92	344.46	5.06	103.61	5.	-17.	47.			1.	.083	1.	.065	1.	.053	.340
133.99	209.87	254.21	344.64	4.50	63.75	5.	-17.	50.		1.	1.	.083	1.	.065			.373
133.95	210.05	253.65	344.82	3.93	65.44	5.	-17.	50.		1.	1.	.083	1.	.065			.376
133.92	210.23	253.09	345.00	3.37	67.11	5.	-17.	49.		1.	1.	.083	1.	.065			.379
133.88	210.41	252.53	345.19	2.81	68.78	5.	-17.	49.		1.	1.	.083	1.	.064			.381
133.85	210.59	251.97	345.37	2.26	70.45	5.	-16.	49.		1.	1.	.083	1.	.064			.384
133.82	210.78	251.41	345.55	1.70	72.10	5.	-16.	49.		1.	1.	.083	1.	.064			.386
133.78	210.96	250.85	345.73	1.14	73.76	5.	-16.	49.		1.	1.	.083	1.	.064			.388
133.75	211.14	250.30	345.91	.59	75.41	5.	-16.	49.		-1.	1.	.083	1.	.064			.381
133.71	211.32	249.75	346.09	.03	77.05	5.	-16.	49.		-1.	1.	.083	1.	.064			.376
133.68	211.50	249.20	346.27	359.48	78.70	5.	-16.	49.		-1.	1.	.083	1.	.064			.372
133.65	211.68	248.65	346.45	358.93	80.34	5.	-15.	48.		-1.	1.	.082	1.	.064			.367
133.61	211.86	248.10	346.64	358.39	81.98	5.	-16.	48.		-1.	1.	.082	1.	.064			.363
133.58	212.04	247.55	346.82	357.84	83.61	5.	-16.	49.			1.	.082	1.	.063	1.	.057	.358
133.54	212.22	247.01	347.00	357.30	85.26	5.	-16.	49.			1.	.082	1.	.063	1.	.057	.353
133.51	212.40	246.47	347.18	356.76	86.91	5.	-16.	49.			1.	.082	1.	.063	1.	.056	.349
133.48	212.58	245.94	347.36	356.22	88.55	5.	-16.	49.			1.	.082	1.	.063	1.	.055	.345
133.44	212.76	245.40	347.54	355.69	90.20	5.	-16.	48.			1.	.082	1.	.063	1.	.055	.341
133.41	212.94	244.87	347.72	355.16	91.83	5.	-16.	48.			1.	.082	1.	.063	1.	.055	.338
133.38	213.12	244.35	347.90	354.63	93.46	5.	-15.	48.			1.	.082	1.	.063	1.	.054	.334
133.34	213.30	243.82	348.07	354.11	95.06	5.	-15.	47.			1.	.082	1.	.063	1.	.054	.331
133.31	213.48	243.30	348.25	353.59	96.64	5.	-15.	46.			1.	.082	1.	.063	1.	.054	.328
133.27	213.66	242.79	348.43	353.08	98.19	5.	-15.	45.			1.	.082	1.	.063	1.	.053	.325
133.24	213.84	242.28	348.61	352.56	99.71	5.	-15.	44.			1.	.082	1.	.063	1.	.053	.322
133.21	214.02	241.77	348.79	352.06	101.19	5.	-15.	43.			1.	.082	1.	.063	1.	.053	.319
133.17	214.19	241.27	348.97	351.55	102.64	5.	-15.	42.			1.	.082	1.	.063	1.	.053	.316
133.14	200.91	241.26	349.15	31.41	102.65	5.	-16.	45.	-1.		1.	.082			1.	.053	.348
133.10	201.09	254.21	349.32	30.87	63.75	5.	-16.	46.	-1.	1.	1.	.082					.383
133.07	201.27	253.68	349.50	30.34	65.36	5.	-16.	47.	-1.	1.	1.	.082					.389
133.04	201.44	253.14	349.68	29.80	66.95	5.	-16.	47.	-1.	1.	1.	.082					.394
133.00	201.52	252.61	349.86	29.27	68.53	5.	-16.	47.	-1.	1.	1.	.082					.400
132.97	201.60	252.06	350.03	28.74	70.11	5.	-16.	46.	-1.	1.	1.	.082					.405

Computer program CLOCK3 (cont)

132.94	201.98	251.56	350.21	28.22	71.67	5.	-16.	46.	-1.	1.	1.	.082			.410
132.90	202.15	251.03	350.38	27.69	73.24	5.	-16.	46.	-1.	1.	1.	.082			.415
132.87	202.33	250.50	350.55	27.17	74.79	5.	-15.	46.	-1.	-1.	1.	.082			.413
132.83	202.50	249.98	350.74	26.64	76.35	5.	-15.	46.	-1.	-1.	1.	.082			.410
132.80	202.68	249.46	350.91	26.12	77.91	5.	-15.	46.	-1.	-1.	1.	.082			.408
132.77	202.85	248.94	351.09	25.60	79.47	5.	-15.	46.	-1.	-1.	1.	.082			.406
132.73	203.03	248.42	351.26	25.08	81.02	5.	-15.	46.	-1.	-1.	1.	.082			.403
132.70	203.20	247.90	351.44	24.56	82.58	5.	-15.	46.	-1.	-1.	1.	.082			.401
132.66	203.38	247.38	351.61	24.04	84.13	5.	-15.	46.	-1.		1.	.081	1.	.057	.398
132.63	203.55	246.86	351.79	23.53	85.71	5.	-15.	47.	-1.		1.	.081	1.	.056	.396
132.60	203.73	246.35	351.96	23.01	87.29	5.	-15.	47.	-1.		1.	.081	1.	.056	.394
132.56	203.90	245.83	352.13	22.50	88.87	5.	-15.	47.	-1.		1.	.081	1.	.055	.391

CYCLE EFFICIENCY = .404

REFERENCE

D-1 G.G. Lowen, City College of N.Y., and F.R. Tepper, ARRADCOM, "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

APPENDIX E

COMPUTER PROGRAM CLOCK4 (REVISED)

The original program descriptions were given in appendix I of Fuze Gear Train Analysis (ref E-1). The following appendix contains revised descriptions, listings and sample outputs of computer program CLOCK4, which computes point and cycle efficiencies for two pass clock gear trains in a spin environment.

The following changes were made:

1. The diametral pitches of both meshes are given as data and printed in the output.

2. The initialization parameters J (one for each of the two meshes) are introduced. They are given as part of the data and are printed in the output. Again, these parameters allow the arbitrary choice of the initial point of contact anywhere within the possible range of contact points.

The kinematics of computer program CLOCK4 is again based on the work in appendix G (ref E-1). The moment input-output relationships are derived in appendix H (ref E-1). This program is in many ways very similar to computer program CLOCK3 with the exception that only two meshes are involved, and therefore, wherever possible, reference will be made to computer program CLOCK3. Again, it is assumed that the two meshes will have been tested by computer program CLOCK1 for their geometric suitability. The format of the following is identical to that used in appendix D.

Input Parameters

The following parameters represent the input data for the program (appendix D):

PSUBD1, PSUBD2

MU

RPM

CAPRP1, CAPRP2, RP2, RP3

RHOG1, RHOG2, RHOP1, RHOP2

ACG1, ACG2, ACP1, ACP2

R1, R2, R3

TG1, TG2, TP1, TP2

NG1, NG2, NP2, NP3

RHO1, RHO2, RHO3

M1, M2, M3

MD

K

J1, J2

The angular velocity of the input gear is incorporated into the program as PHDOT1 = -1. All velocity computations are based on this model. The input motion in the fuze gearing model is negative (fig. A-10, ref E-1).

Computations

Computations of Gear Tooth Parameters

The required computations are identical to those for the revised computer program CLOCK3 in appendix D, with the exception that only two meshes are considered.

Computation of MIN, GAMMAS and BETAS

The input moment is computed in the manner of equation D-1 of appendix D. In addition, the angles γ_2, γ_3, β_1 and β_2 are found according to the expressions given in appendix A (ref E-1).

Computations of Other Parameters

The computations of the angles $\Delta\phi_1$ and $\Delta\psi_1$, the length L_1 as well as the centrifugal forces Q_1, Q_2 and Q_3 (called Q_{3p} by equation H-245, ref E-1) are identical to those described in the parallel section dealing with computer program CLOCK3 in appendix D.

Preliminary Computations for Mesh 1

The preliminary computations for mesh 1 are similar to those discussed in appendix D.

Preliminary Computations for Mesh 2

The preliminary computations for mesh 2 are similar to those discussed in appendix D.

Gear Train Motion Model: Initial Contact Angles, Kinematics, Point and Cycle Efficiencies

The simulation of the gear train model, which is necessary for the determination of both POINTEF and CYCLEFF, is found in a loop starting with statement label no. 20 and ending with card no. 542. The motions of the individual driving gears are initialized at the angles PHI1 and PHI2, respectively, with the help of the initialization parameters J_i (i=1,2) according to equation D-17 (app D).

The additional parameter J_3 is set equal to zero to mark the first cycle of computations (statement no. 318). J_3 becomes equal to unity for all subsequent computations (see statement no. 541).

The parameter J_4 is used to distinguish between the two possible contact conditions of mesh no. 1. $J_4 = 0$ whenever the first set of teeth is in contact. $J_4 = 1$ once the latest possible value of ϕ_1 has been reached, and contact must be transferred to the second set of teeth in order to obtain a complete cycle of motion for this mesh. $J_4 = 0$ at all times if $J_1 = 0$, i.e., contact is made in mesh no. 1 at the earliest possible point.

Both meshes will be in round on round contact until either reaches its respective transition angle PHI1T or PHI2T. Once the transition angles are past, the meshes will be in round on flat contact. These regimes continue until the final angles PHI1F and PHI2F are reached.

The increment DDPHI1 of the input gear 1 is obtained from an adaptation of equations A-207 and A-208 (ref E-1), in which tooth numbers, rather than base circle radii are used. The increment DDPHI2 of gear 2 is related to the increment of the pinion angle PSI1.

While the motion of gear 1 is terminated when the angle PHI1 reaches one increment before the starting angle, gear 2 must be reset to its earliest possible angle PHI2I whenever its latest angle PHI2F has been reached.*

---

* If $J_1 = 0$, the computation is terminated for PHI1 < PHI1F + DDPHI1. If $J_1 \neq 0$, and therefore $J_4 = 1$, computation is terminated when PHI1 < PHI1A + DDPHI1. In the above, PHI1A represents the starting angle of mesh 1 in the manner of equation D-17. (Card no. 316).

The appropriate choice of moment equation depends upon which of the four possible combinations of contact conditions, as indicated by table H-2 (ref E-1), is applicable.

The following discusses the kinematics of the individual meshes as well as the determination of the point and cycle efficiencies where they differ from the description in appendix D.

Kinematics. The program only utilizes the kinematics of meshes 1 and 2. These are identical with those for the revised computer program CLOCK3, as given in appendix D.

Moment Computations, Point and Cycle Efficiencies. Regardless of the combination of contact conditions, the point efficiency is computed according to equation 3 (ref E-1), i.e.,

$$\varepsilon_p = \text{POINTEF} = K_{RATIO} \frac{M_{o3i}}{M_{in}} \qquad \text{(E-1)}$$

where, with $\dot{\phi}_1 = -1$

$$K_{RATIO} = \left| \dot{\psi}_2 \right| \qquad \text{(E-2)}$$

The cycle efficiency determination is based on equation I-21 through I-23 (ref E-1).

The moment computations begin with the statement label no. 24, and initially consist of the determination of selected variables between A11 and A72 and selected variables between C6 and C36, as applicable to the analyses of appendix H (ref E-1). The governing contact combination (table H-2, ref E-1) is determined with the help of the four moment control statements, which start with card no. 508. Once the appropriate combination is established, the program is directed to one of the four associated moment expressions. These expressions for M_{o3i} coincide with those given by equation H-260, H-261, H-277 and H-278 (ref E-1). They are listed in the above order beginning with statement label no. 25 and ending with statement label no. 28.

The rationale of the control statements for meshes 1 and 2 is identical to that given for revised computer program CLOCK3 (appendix D).

Output

The output of the program is best explained with the help of the sample problem at the end of the program.

Input Parameters (see fourth and fifth sets of gear data of appendix C)

Mesh 1

CAPRP1	= R_{p1}	= 0.55000 in. (1.397 cm)	PSUBD1	= P_{d1}	= 50
RP2	= r_{p2}	= 0.08000 in. (0.2032 cm)	J1	= 0.90	
ACG1	= a_{G1}	= 0.54656 in. (1.3883 cm)			
ACP1	= a_{p1}	= 0.07998 in. (0.2031 cm)			
RHOG1	= ρ_{G1}	= 0.04322 in. (0.1098 cm)			
RHOP1	= ρ_{P1}	= 0.01400 in. (0.0356 cm)			
TG1	= t_{G1}	= 0.03175 in. (0.0806 cm)			
TP1	= t_{P1}	= 0.02096 in. (0.0532 cm)			
NG1	= n_{G1}	= 55			
NP2	= n_{P2}	= 8			

Mesh 2

CAPRP2	= R_{p2}	= 0.39286 in. (0.9978 cm)	PSUBD2	= P_{d2}	= 70
RP3	= r_{p3}	= 0.05714 in. (0.1451 cm)	J2	= 0.90	
ACG2	= a_{G2}	= 0.39040 in. (0.9916 cm)			
ACP2	= a_{P2}	= 0.05709 in. (0.1450 cm)			
RHOG2	= ρ_{G2}	= 0.03087 in. (0.0784 cm)			
RHOP2	= ρ_{P2}	= 0.01000 in. (0.0254 cm)			
TG2	= t_{G2}	= 0.02268 in. (0.0576 cm)			
TP2	= t_{P2}	= 0.01497 in. (0.0380 cm)			
NG2	= n_{G2}	= 55			
NP3	= n_{P3}	= 8			

In addition

MU	=	0.2	
RPM	=	1000	
M1	= m_1	=	0.12×10^{-3} lb-sec^2/in. (2.101×10^{-2} kg)
M2	= m_2	=	0.253×10^{-4} lb-sec^2/in. (4.430×10^{-3} kg)
M3	= m_3	=	0.153×10^{-5} lb-sec^2/in. (2.679×10^{-4} kg)
R1	= $\mathcal{R}_1$	=	0.225 in. (0.572 cm)
R2	= $\mathcal{R}_2$	=	0.497 in. (1.2624 cm)
R3	= $\mathcal{R}_3$	=	0.640 in. (1.6256 cm)
RHO1	= ρ_1	=	0.062 in. (0.157 cm)
RHO2	= ρ_2	=	0.025 in. (0.064 cm)
RHO3	= ρ_3	=	0.018 in. (0.041 cm)
MD	= md^2	=	0.275×10^{-5} lb-sec^2-in. (3.105×10^{-7} kg-m^2)
K	=	25	

Computed Values

At the beginning of the output, one finds MIN = M_{in}. Subsequently, the following are listed for each mesh:

ℓ_{pi}, the length of the pinion flats

β_i, the fuze body pivot to pivot line angles

ψ_{Ti} and ϕ_{Ti}, the transition angles

ϕ_{Ii}, and ψ_{Ii}, the earliest angles

ϕ_{Fi} and ψ_{Fi}, the latest angles

Finally, for the full range of the input angles ϕ_1, the point efficiency POINTEF is listed, in addition to other parameters which are useful for checking purposes. Note that DPSI1 and DPSI2 represent $\dot{\psi}_1$ and $\dot{\psi}_2$, respectively. The cycle efficiency CYCLEFF is found at the end of the output.

Computer program CLOCK4


```
      PROGRAM CLOCK4(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C     POINT AND CYCLE EFFICIENCIES FOR TWO PASS CLOCK (OSIVAL) STEP-UP
C     GEAR TRAIN IN SPIN ENVIRONMENT
C
      REAL MU,LAMDA1,LAMDA2,LX1,LY1,L1,LX2,LY2,L2,NP2,NP3,NG1,NG2,MIN,M1
     1,M2,M3,MO3,MO31,MO32,MO33,MO34,MTOT,MD,LL1,LL2,K,J1,J2,J3,J4
    1 READ (5,40) PSUBG1,PSUBG2,NG1,NP2,NG2,NP3
      READ (5,43) MU,RPM,CAPRP1,CAPRP2,RP2,RP3,ACG1,ACG2,ACP1,ACP2,ISTOP
      READ (5,58) R1,R2,R3
      READ (5,41) RHOG1,RHOG2,RHOP1,RHOP2
      READ (5,42) TG1,TG2,TP1,TP2
      READ (5,61) M1,M2,M3
      READ (5,44) RHO1,RHO2,RHO3,MD,K,J1,J2
      PI=3.14159
      Z=PI/180.
      OMEGA=RPM*2.*PI/60.
      OM2=OMEGA*OMEGA
      PHODT1=-1.
C
C     COMPUTATION OF GEAR TOOTH PARAMETERS FOR BOTH MESHES
C
      CXG1=RHOG1-TG1/2.
      DELG1=ASIN(CXG1/CAPRP1)
      CXP1=RHOP1-TP1/2.
      DELP1=ASIN(CXP1/RP2)
      GAMMP1=ASIN(RHOP1/RP2)
      ALPHP1=GAMMP1-DELP1
      FP1=ACP1*COS(GAMMP1)
      B1=CAPRP1+RP2
      CXG2=RHOG2-TG2/2.
      DELG2=ASIN(CXG2/CAPRP2)
      CXP2=RHOP2-TP2/2.
      DELP2=ASIN(CXP2/RP3)
      GAMMP2=ASIN(RHOP2/RP3)
      ALPHP2=GAMMP2-DELP2
      FP2=ACP2*COS(GAMMP2)
      B2=CAPRP2+RP3
C
C     COMPUTATION OF MIN, GAMMAS AND BETAS
C
      MIN=MD*OM2
      DELTA2=ACOS(((CAPRP1+RP2)*(CAPRP1+RP2)+R1*R1-R2*R2)/(2.*R1*(CAPRP1
     1+RP2)))
      DELTA3=ACOS(((CAPRP2+RP3)*(CAPRP2+RP3)+R2*R2-R3*R3)/(2.*R2*(CAPRP2
     1+RP3)))
      GAMMA2=ACOS((R1*R1+R2*R2-(CAPRP1+RP2)*(CAPRP1+RP2))/(2.*R1*R2))
      GAMM3P=ACOS((R2*R2+R3*R3-(CAPRP2+RP3)*(CAPRP2+RP3))/(2.*R2*R3))
      GAMMA3=GAMMA2+GAMM3P
      BETA1=PI-DELTA2
      BETA2=GAMMA2+PI-DELTA3
      BETA1D=BETA1/Z
      BETA2D=BETA2/Z
```

Computer program CLOCK4 (cont)


```
      WRITE (6,45) PSUBD1,PSUBD2,MIN,MU,RPM,CAPRP1,CAPRP2,RP2,RP3,ACG1,A
     1CG2,ACP1,ACP2
      WRITE (6,48) NG1,NG2,NP2,NP3
      WRITE (6,59) R1,R2,R3
      WRITE (6,46) RHOG1,RHOG2,RHOP1,RHOP2
      WRITE (6,47) TG1,TG2,TP1,TP2
      WRITE (6,62) M1,M2,M3
      WRITE (6,49) RHO1,RHO2,RHO3,MD,K,PHDOT1,J1,J2
      WRITE (6,60) FP1,FP2
      WRITE (6,50) BETA1D,BETA2D
C
C     COMPUTATION OF OTHER PARAMETERS
C
      DPHI1=360./NG1*Z
      DPSI1=360./NP2*Z
      DPHI2=360./NG2*Z
      DPSI2=360./NP3*Z
      L1=RHOG1+RHOP1
      L2=RHOG2+RHOP2
      Q1=M1*R1*OM2
      Q2=M2*R2*OM2
      Q3=M3*R3*OM2
C
C     PRELIMINARY COMPUTATIONS FOR MESH 1
C
C     DETERMINATION OF TRANSITION ANGLE OF MESH 1
C
      A1T=RHOG1*COS(BETA1+ALPHP1)+FP1*SIN(BETA1+ALPHP1)
      B1T=-RHOG1*SIN(BETA1+ALPHP1)+FP1*COS(BETA1+ALPHP1)
      C1T=(ACG1*ACG1-RHOG1*RHOG1-B1*B1-FP1*FP1)/(2.*B1)
      ROOT1T=A1T*A1T+B1T*B1T-C1T*C1T
      Y1T1=A1T+SQRT(ROOT1T)
      Y1T2=A1T-SQRT(ROOT1T)
      X1T=B1T+C1T
      PSI1T1=2.*ATAN2(Y1T1,X1T)
      PSI1T2=2.*ATAN2(Y1T2,X1T)
      PSITE11=PSI1T1
      PSITE12=PSI1T2
      IF (PSI1T1.GT.PI) PSITE11=PSITE11-2.*PI
      IF (PSI1T1.LT.PI) PSITE11=PSITE11+2.*PI
      IF (PSI1T2.GT.PI) PSITE12=PSITE12-2.*PI
      IF (PSI1T2.LT.PI) PSITE12=PSITE12+2.*PI
      IF (PSITE11.GE.0.) TEST11=ABS(PI-BETA1+PSITE11-ALPHP1)/Z
      IF (PSITE11.LT.0.) TEST11=ABS(PI+BETA1-(PSITE11+2.*PI-ALPHP1))/Z
      IF (PSITE12.GE.0.) TEST12=ABS(PI-BETA1+PSITE12-ALPHP1)/Z
      IF (PSITE12.LT.0.) TEST12=ABS(PI+BETA1-(PSITE12+2.*PI-ALPHP1))/Z
      IF (PSI1T1.LT.0.) PSI1T1=PSI1T1+2.*PI
      IF (PSI1T2.LT.0.) PSI1T2=PSI1T2+2.*PI
      PSI1T1D=PSI1T1/Z
      PSI1T2D=PSI1T2/Z
      WRITE (6,31) PSI1T1D,TEST11
      WRITE (6,32) PSI1T2D,TEST12
      CALL TRANS1 (RHOG1,ALPHP1,BETA1,FP1,ACG1,B1,DELG1,Z,PSI1T1,PHI1T1,
```

Computer program CLOCK4 (cont)

```
PROGRAM CLOCK4      74/74    OPT=1                        FTN 4.6+420        07/31/79  08.11.05        PAGE    3

     1G11)
      IF (G11.GT.FP1) GO TO 2
      PHI1T=PHI1T1
      PSI1T=PSI1T1
      GO TO 4
    2 CALL TRANS1 (RHOG1,ALPHP1,BETA1,FP1,ACG1,B1,DELG1,Z,PSI1T2,PHI1T2,
     1G12)
      IF (G12.LT.FP1) GO TO 3
      WRITE (6,51)
      STOP
    3 PHI1T=PHI1T2
      PSI1T=PSI1T2
    4 IF (PHI1T.LT.0.) PHI1T=PHI1T+2.*PI
      IF (PSI1T.LT.0.) PSI1T=PSI1T+2.*PI
      PHI1TD=PHI1T/Z
      PSI1TD=PSI1T/Z
      WRITE (6,52) PHI1TD,PSI1TD
C
C     DETERMINATION OF CORRECT SIGN FOR ROUND ON FLAT REGIME OF MESH 1
C
      A1F=ACG1*COS(PHI1T+DELG1+ALPHP1)-B1*COS(BETA1+ALPHP1)
      B1F=-ACG1*SIN(PHI1T+DELG1+ALPHP1)+B1*SIN(BETA1+ALPHP1)
      C1F=RHOG1
      ROOT1F=A1F*A1F+B1F*B1F-C1F*C1F
      Y1F1=A1F+SQRT(ROOT1F)
      Y1F2=A1F-SQRT(ROOT1F)
      X1F=B1F+C1F
      PSI1F1=2.*ATAN2(Y1F1,X1F)
      PSI1F2=2.*ATAN2(Y1F2,X1F)
      IF (PSI1F1.LT.0.) PSI1F1=PSI1F1+2.*PI
      IF (PSI1F2.LT.0.) PSI1F2=PSI1F2+2.*PI
      IF (ABS(PSI1F1-PSI1T).LT.ABS(PSI1F2-PSI1T)) GO TO 5
      SIGN1F=-1.
      GO TO 6
    5 SIGN1F=1.
C
C     LATEST AND EARLIEST POSSIBLE VALUES OF PHI AND PSI FOR MESH 1
C
    6 DO 7 I=1,2000
      PHID1=PHI1TD-(I-1.)/100.
      PHI1=PHID1*Z
      A1F=ACG1*COS(PHI1+DELG1+ALPHP1)-B1*COS(BETA1+ALPHP1)
      B1F=-ACG1*SIN(PHI1+DELG1+ALPHP1)+B1*SIN(BETA1+ALPHP1)
      C1F=RHOG1
      ROOT1F=A1F*A1F+B1F*B1F-C1F*C1F
      Y1F=A1F+SIGN1F*SQRT(ROOT1F)
      X1F=B1F+C1F
      PSI1F=2.*ATAN2(Y1F,X1F)
      IF (PSI1F.LT.0.) PSI1F=PSI1F+2.*PI
      LX1=B1*COS(BETA1)+ACP1*COS(PSI1F-DPSI1+DELP1)-ACG1*COS(PHI1+DPHI1+
     1DELG1)
      LY1=B1*SIN(BETA1)+ACP1*SIN(PSI1F-DPSI1+DELP1)-ACG1*SIN(PHI1+DPHI1+
     1DELG1)
```

Computer program CLOCK4 (cont)


```
      LL1=SQRT(LX1*LX1+LY1*LY1)
      DELEL1=LL1-L1
      IF (DELEL1.LE.0.) GO TO 8
    7 CONTINUE
    8 PHI1F=PHI1
      PSI1FF=PSI1F
      PHI1I=PHI1F+DPHI1
      PSI1I=PSI1FF-DPSI1
      IF (PSI1I.LT.0.) PSI1I=PSI1I+2.*PI
      PHI1ID=PHI1I/Z
      PSI1ID=PSI1I/Z
      PHI1FD=PHI1F/Z
      PSI1FD=PSI1FF/Z
      WRITE (6,53) PHI1ID,PSI1ID,PHI1FD,PSI1FD
C
C     DETERMINATION OF CORRECT SIGN FOR ROUND ON ROUND REGIME OF MESH 1
C
      A1R=ACG1*SIN(PHI1I+DELG1-DELP1)-B1*SIN(BETA1-DELP1)
      B1R=ACG1*COS(PHI1I+DELG1-DELP1)-B1*COS(BETA1-DELP1)
      C1R=(ACP1*ACP1+ACG1*ACG1+B1*B1-L1*L1-2.*ACG1*B1*COS(PHI1I+DELG1-BE
     1TA1))/(2.*ACP1)
      ROOT1R=A1R*A1R+B1R*B1R-C1R*C1R
      Y1R1=A1R+SQRT(ROOT1R)
      Y1R2=A1R-SQRT(ROOT1R)
      X1R=B1R+C1R
      PSI1R1=2.*ATAN2(Y1R1,X1R)
      PSI1R2=2.*ATAN2(Y1R2,X1R)
      IF (PSI1R1.LT.0.) PSI1R1=PSI1R1+2.*PI
      IF (PSI1R2.LT.0.) PSI1R2=PSI1R2+2.*PI
      IF (ABS(PSI1I-PSI1R1).LT.ABS(PSI1I-PSI1R2)) GO TO 9
      SIGN1R=-1.
      GO TO 10
    9 SIGN1R=1.
C
C     PRELIMINARY COMPUTATIONS FOR MESH 2
C
C     DETERMINATION OF TRANSITION ANGLE OF MESH 2
C
   10 A2T=-RHOG2*COS(BETA2-ALPHP2)+FP2*SIN(BETA2-ALPHP2)
      B2T=RHOG2*SIN(BETA2-ALPHP2)+FP2*COS(BETA2-ALPHP2)
      C2T=(ACG2*ACG2-RHOG2*RHOG2-B2*B2-FP2*FP2)/(2.*B2)
      ROOT2T=A2T*A2T+B2T*B2T-C2T*C2T
      Y2T1=A2T+SQRT(ROOT2T)
      Y2T2=A2T-SQRT(ROOT2T)
      X2T=B2T+C2T
      PSI2T1=2.*ATAN2(Y2T1,X2T)
      PSI2T2=2.*ATAN2(Y2T2,X2T)
      PSITE21=PSI2T1
      PSITE22=PSI2T2
      IF (PSI2T1.GT.PI) PSITE21=PSITE21-2.*PI
      IF (PSI2T1.LT.PI) PSITE21=PSITE21+2.*PI
      IF (PSI2T2.GT.PI) PSITE22=PSITE22-2.*PI
      IF (PSI2T2.LT.PI) PSITE22=PSITE22+2.*PI
```

Computer program CLOCK4 (cont)


```
      IF (PSITE21.GE.0.) TEST21=ABS(PI-BETA2+PSITE21+ALPHP2)/Z
      IF (PSITE21.LT.0.) TEST21=ABS(PI+BETA2-(PSITE21+2.*PI+ALPHP2))/Z
      IF (PSITE22.GE.0.) TEST22=ABS(PI-BETA2+PSITE22+ALPHP2)/Z
      IF (PSITE22.LT.0.) TEST22=ABS(PI+BETA2-(PSITE22+2.*PI+ALPHP2))/Z
      IF (PSI2T1.LT.0.) PSI2T1=PSI2T1+2.*PI
      IF (PSI2T2.LT.0.) PSI2T2=PSI2T2+2.*PI
      PSI2T1D=PSI2T1/Z
      PSI2T2D=PSI2T2/Z
      WRITE (6,33) PSI2T1D,TEST21
      WRITE (6,34) PSI2T2D,TEST22
      CALL TRANS2 (RHOG2,ALPHP2,BETA2,FP2,ACG2,B2,DELG2,Z,PSI2T1,PHI2T1,
     1G21)
      IF (G21.GT.FP2) GO TO 11
      PHI2T=PHI2T1
      PSI2T=PSI2T1
      GO TO 13
   11 CALL TRANS2 (RHOG2,ALPHP2,BETA2,FP2,ACG2,B2,DELG2,Z,PSI2T2,PHI2T2,
     1G22)
      IF (G22.LT.FP2) GO TO 12
      WRITE (6,54)
      STOP
   12 PHI2T=PHI2T2
      PSI2T=PSI2T2
   13 IF (PHI2T.LT.0.) PHI2T=PHI2T+2.*PI
      IF (PSI2T.LT.0.) PSI2T=PSI2T+2.*PI
      PHI2TD=PHI2T/Z
      PSI2TD=PSI2T/Z
      WRITE (6,55) PHI2TD,PSI2TD
C
C     DETERMINATION OF CORRECT SIGN FOR ROUND ON FLAT REGIME OF MESH 2
C
      A2F=ACG2*COS(PHI2T-DELG2-ALPHP2)-B2*COS(BETA2-ALPHP2)
      B2F=-ACG2*SIN(PHI2T-DELG2-ALPHP2)+B2*SIN(BETA2-ALPHP2)
      C2F=-RHOG2
      ROOT2F=A2F*A2F+B2F*B2F-C2F*C2F
      Y2F1=A2F+SQRT(ROOT2F)
      Y2F2=A2F-SQRT(ROOT2F)
      X2F=B2F+C2F
      PSI2F1=2.*ATAN2(Y2F1,X2F)
      PSI2F2=2.*ATAN2(Y2F2,X2F)
      IF (PSI2F1.LT.0.) PSI2F1=PSI2F1+2.*PI
      IF (PSI2F2.LT.0.) PSI2F2=PSI2F2+2.*PI
      IF (ABS(PSI2F1-PSI2T).LT.ABS(PSI2F2-PSI2T)) GO TO 14
      PSI2F1D=PSI2F1/Z
      PSI2F2D=PSI2F2/Z
      SIGN2F=-1.
      GO TO 15
   14 SIGN2F=1.
C
C     LATEST AND EARLIEST POSSIBLE VALUES OF PHI AND PSI FOR MESH 2
C
   15 DO 16 I=1,1000
      PHID2=PHI2TD+(I-1.)/100.
```

Computer program CLOCK4 (cont)

```
PROGRAM CLOCK4      74/74    OPT=1                        FTN 4.6+420        07/31/79  08.11.05         PAGE     6

          PHI2=PHID2*Z
          A2F=ACG2*COS(PHI2-DELG2-ALPHP2)-B2*COS(BETA2-ALPHP2)
          B2F=-ACG2*SIN(PHI2-DELG2-ALPHP2)+B2*SIN(BETA2-ALPHP2)
          C2F=-RHOG2
          ROOT2F=A2F*A2F+B2F*B2F-C2F*C2F
          Y2F=A2F+SIGN2F*SQRT(ROOT2F)
          X2F=B2F+C2F
          PSI2F=2.*ATAN2(Y2F,X2F)
          IF (PSI2F.LT.0.) PSI2F=PSI2F+2.*PI
          LX2=B2*COS(BETA2)+ACP2*COS(PSI2F+DPSI2-DELP2)-ACG2*COS(PHI2-DPHI2-
         1DELG2)
          LY2=B2*SIN(BETA2)+ACP2*SIN(PSI2F+DPSI2-DELP2)-ACG2*SIN(PHI2-DPHI2-
         1DELG2)
          LL2=SQRT(LX2*LX2+LY2*LY2)
          DELEL2=LL2-L2
          IF (DELEL2.LE.0.) GO TO 17
       16 CONTINUE
       17 PHI2F=PHI2
          PSI2FF=PSI2F
          PHI2I=PHI2F-DPHI2
          PSI2I=PSI2FF+DPSI2
          IF (PSI2I.GT.2.*PI) PSI2I=PSI2I-2.*PI
          PHI2ID=PHI2I/Z
          PSI2ID=PSI2I/Z
          PHI2FD=PHI2F/Z
          PSI2FD=PSI2FF/Z
          WRITE (6,56) PHI2ID,PSI2ID,PHI2FD,PSI2FD
      C
      C   DETERMINATION OF CORRECT SIGN FOR ROUND ON ROUND REGIME OF MESH 2
      C
          A2R=B2*SIN(BETA2+DELP2)-ACG2*SIN(PHI2I-DELG2+DELP2)
          B2R=B2*COS(BETA2+DELP2)-ACG2*COS(PHI2I-DELG2+DELP2)
          C2R=(L2*L2-B2*B2-ACG2*ACG2-ACP2*ACP2+2.*ACG2*B2*COS(PHI2I-DELG2-BE
         1TA2))/(2.*ACP2)
          ROOT2R=A2R*A2R+B2R*B2R-C2R*C2R
          Y2R1=A2R+SQRT(ROOT2R)
          Y2R2=A2R-SQRT(ROOT2R)
          X2R=B2R+C2R
          PSI2R1=2.*ATAN2(Y2R1,X2R)
          PSI2R2=2.*ATAN2(Y2R2,X2R)
          IF (PSI2R1.LT.0.) PSI2R1=PSI2R1+2.*PI
          IF (PSI2R2.LT.0.) PSI2R2=PSI2R2+2.*PI
          IF (ABS(PSI2I-PSI2R1).LT.ABS(PSI2I-PSI2R2)) GO TO 18
          SIGN2R=-1.
          GO TO 19
       18 SIGN2R=1.
      C
      C   GEAR TRAIN MOTION MODEL, KINEMATICS
      C
       19 DDPHI1=NP2*(PHI2F-PHI2I)/(K*NG1)
          PHI1A=PHI1I+(PHI1F-PHI1I)*J1
          PHI1=PHI1A+DDPHI1
          J3=0.
```

Computer program CLOCK4 (cont)

```
PROGRAM CLOCK4      74/74    OPT=1                      FTN 4.6+420         07/31/79  08.11.05        PAGE     7

      J4=0.
      WRITE (6,35)
   20 PHI1=PHI1-DDPHI1
      IF (PHI1.LE.PHI1F) J4=1.
      IF (PHI1.LE.PHI1F) PHI1=PHI1I
      PHI1D=PHI1/Z
      IF ((J4.EQ.1..AND.PHI1.LE.PHI1A+DDPHI1).OR.(J1.EQ.0..AND.PHI1.LE.P
     1HI1F+DDPHI1)) GO TO 30
C
C     MESH 1
C
      IF (PHI1.LE.PHI1I) GO TO 21
      A1R=ACG1*SIN(PHI1+DELG1-DELP1)-B1*SIN(BETA1-DELP1)
      B1R=ACG1*COS(PHI1+DELG1-DELP1)-B1*COS(BETA1-DELP1)
      C1R=(ACP1*ACP1+ACG1*ACG1+B1*B1-L1*L1-2.*ACG1*B1*COS(PHI1+DELG1-BET
     1A1))/(2.*ACP1)
      ROOT1R=A1R*A1R+B1R*B1R-C1R*C1R
      Y1R=A1R+SIGN1R*SQRT(ROOT1R)
      X1R=B1R+C1R
      PSI1=2.*ATAN2(Y1R,X1R)
      IF (PSI1.LT.0.) PSI1=PSI1+2.*PI
      IF (PSI1.GT.2.*PI) PSI1=PSI1-2.*PI
      PSI1D=PSI1/Z
      IF (ABS(PHI1-PHI1I).LT.0.0001) PSI1P=PSI1I
      IF (J3.EQ.0.) PSI1P=PSI1
      SLAM1=(B1*SIN(BETA1)+ACP1*SIN(PSI1+DELP1)-ACG1*SIN(PHI1+DELG1))/L1
      CLAM1=(B1*COS(BETA1)+ACP1*COS(PSI1+DELP1)-ACG1*COS(PHI1+DELG1))/L1
      LAMDA1=ATAN2(SLAM1,CLAM1)
      IF (LAMDA1.LT.0.) LAMDA1=LAMDA1+2.*PI
      PSDOT1=PHDOT1*ACG1*(B1/ACP1*SIN(PHI1+DELG1-BETA1)+SIN(PHI1-PSI1+DE
     1LG1-DELP1))/(A1R*COS(PSI1)-B1R*SIN(PSI1))
      VST1R=PHDOT1*(ACG1*COS(PHI1+DELG1-LAMDA1)+RHOG1)-PSDOT1*(ACP1*COS(
     1PSI1+DELP1-LAMDA1)-RHOP1)
      S1R=VST1R/ABS(VST1R)
      GO TO 22
   21 A1F=ACG1*COS(PHI1+DELG1+ALPHP1)-B1*COS(BETA1+ALPHP1)
      B1F=-ACG1*SIN(PHI1+DELG1+ALPHP1)+B1*SIN(BETA1+ALPHP1)
      C1F=RHOG1
      ROOT1F=A1F*A1F+B1F*B1F-C1F*C1F
      Y1F=A1F+SIGN1F*SQRT(ROOT1F)
      X1F=B1F+C1F
      PSI1=2.*ATAN2(Y1F,X1F)
      IF (PSI1.LT.0.) PSI1=PSI1+2.*PI
      IF (PSI1.GT.2.*PI) PSI1=PSI1-2.*PI
      PSI1D=PSI1/Z
      IF (J3.EQ.0.) PSI1P=PSI1
      G1=(ACG1*SIN(PHI1+DELG1)+RHOG1*COS(PSI1-ALPHP1)-B1*SIN(BETA1))/SIN
     1(PSI1-ALPHP1)
      PSDOT1=PHDOT1*(ACG1*COS(PHI1-PSI1+DELG1+ALPHP1))/(A1F*COS(PSI1)-B1
     1F*SIN(PSI1))
      VST1F=PHDOT1*(ACG1*SIN(PSI1-ALPHP1-PHI1-DELG1)-RHOG1)
      S1F=VST1F/ABS(VST1F)
C
```

Computer program CLOCK4 (cont)


```
C     MESH 2
C
   22 DDPHI2=PSI1-PSI1P
      IF (J3.EQ.0.) PHI2=PHI2I+(PHI2F-PHI2I)*J2
      PHI2=PHI2+DDPHI2
      PSI1P=PSI1
      IF (PHI2.GT.PHI2F) PHI2=PHI2I
      PHI2D=PHI2/Z
      IF (PHI2.GE.PHI2T) GO TO 23
      A2R=B2*SIN(BETA2+DELP2)-ACG2*SIN(PHI2-DELG2+DELP2)
      B2R=B2*COS(BETA2+DELP2)-ACG2*COS(PHI2-DELG2+DELP2)
      C2R=(L2*L2-B2*B2-ACG2*ACG2-ACP2*ACP2+2.*ACG2*B2*COS(PHI2-DELG2-BET
     1A2))/(2.*ACP2)
      ROOT2R=A2R*A2R+B2R*B2R-C2R*C2R
      Y2R=A2R+SIGN2R*SQRT(ROOT2R)
      X2R=B2R+C2R
      PSI2=2.*ATAN2(Y2R,X2R)
      IF (PSI2.LT.0.) PSI2=PSI2+2.*PI
      PSI2D=PSI2/Z
      IF (ABS(PHI2-PHI2I).LT.0.0001) PSI2P=PSI2I
      IF (J3.EQ.0.) PSI2P=PSI2
      SLAM2=(B2*SIN(BETA2)+ACP2*SIN(PSI2-DELP2)-ACG2*SIN(PHI2-DELG2))/L2
      CLAM2=(B2*COS(BETA2)+ACP2*COS(PSI2-DELP2)-ACG2*COS(PHI2-DELG2))/L2
      LAMDA2=ATAN2(SLAM2,CLAM2)
      IF (LAMDA2.LT.0.) LAMDA2=LAMDA2+2.*PI
      PHDOT2=PSDOT1
      PSDOT2=PHDOT2*ACG2*(-SIN(PHI2-PSI2-DELG2+DELP2)-B2/ACP2*SIN(PHI2-D
     1ELG2-BETA2))/(A2R*COS(PSI2)-B2R*SIN(PSI2))
      VST2R=PHDOT2*(ACG2*COS(PHI2-DELG2-LAMDA2)+RHOG2)-PSDOT2*(ACP2*COS(
     1PSI2-DELP2-LAMDA2)-RHOP2)
      S2R=VST2R/ABS(VST2R)
      GO TO 24
   23 A2F=ACG2*COS(PHI2-DELG2-ALPHP2)-B2*COS(BETA2-ALPHP2)
      B2F=-ACG2*SIN(PHI2-DELG2-ALPHP2)+B2*SIN(BETA2-ALPHP2)
      C2F=-RHOG2
      ROOT2F=A2F*A2F+B2F*B2F-C2F*C2F
      Y2F=A2F+SIGN2F*SQRT(ROOT2F)
      X2F=B2F+C2F
      PSI2=2.*ATAN2(Y2F,X2F)
      IF (PSI2.LT.0.) PSI2=PSI2+2.*PI
      PSI2D=PSI2/Z
      G2=(ACG2*SIN(PHI2-DELG2)-RHOG2*COS(PSI2+ALPHP2)-B2*SIN(BETA2))/SIN
     1(PSI2+ALPHP2)
      PHDOT2=PSDOT1
      PSDOT2=(PHDOT2*ACG2*COS(PHI2-DELG2-ALPHP2-PSI2))/(A2F*COS(PSI2)-B2
     1F*SIN(PSI2))
      VST2F=PHDOT2*(ACG2*SIN(PSI2+ALPHP2-PHI2+DELG2)+RHOG2)
      S2F=VST2F/ABS(VST2F)
C
C     MOMENT COMPUTATIONS
C
   24 DN=1.+MU*MU
      A12=ABS((MU*(S1R-1.)*SIN(LAMDA1)-(1.+MU*MU*S1R)*COS(LAMDA1))/DN)
```

Computer program CLOCK4 (cont)


```
      A11=ABS(((1.+MU*MU*S2R)*COS(LAMDA2)-MU*(S2R-1.)*SIN(LAMDA2))/DN)       A 425
      A13=ABS((-COS(GAMMA2)-MU*SIN(GAMMA2))/DN)                               A 426
      A14=ABS(((1.+MU*MU*S2R)*SIN(LAMDA2)-MU*(1.-S2R)*COS(LAMDA2))/DN)       A 427
      A15=ABS((MU*(1.-S1R)*COS(LAMDA1)-(1.+MU*MU*S1R)*SIN(LAMDA1))/DN)       A 428
      A16=ABS((MU*COS(GAMMA2)-SIN(GAMMA2))/DN)                                A 429
      A17=ABS(((1.-MU*MU*S1R)*COS(LAMDA1)-MU*(1.+S1R)*SIN(LAMDA1))/DN)       A 430
      A18=ABS(1./DN)                                                           A 431
      A19=ABS(((1.-MU*MU*S1R)*SIN(LAMDA1)+MU*(1.+S1R)*COS(LAMDA1))/DN)       A 432
      A20=ABS(MU/DN)                                                           A 433
      A21=ABS((MU*(1.-S2R)*SIN(LAMDA2)+(1.+MU*MU*S2R)*COS(LAMDA2))/DN)       A 434
      A22=ABS(((1.-MU*MU*S1F)*SIN(PSI1-ALPHP1)-MU*(1.+S1F)*COS(PSI1-ALPH     A 435
     1P1))/DN)                                                                 A 436
      A23=ABS((MU*SIN(GAMMA2)+COS(GAMMA2))/DN)                                A 437
      A24=ABS(((1.+MU*MU*S2R)*SIN(LAMDA2)-MU*(1.-S2R)*COS(LAMDA2))/DN)       A 438
      A25=ABS((-MU*(1.+S1F)*SIN(PSI1-ALPHP1)+(MU*MU*S1F-1.)*COS(PSI1-ALP     A 439
     1HP1))/DN)                                                                A 440
      A26=ABS((-SIN(GAMMA2)+MU*COS(GAMMA2))/DN)                               A 441
      A27=ABS((-(1.+MU*MU*S1F)*SIN(PSI1-ALPHP1)+MU*(S1F-1.)*COS(PSI1-ALP     A 442
     1HP1))/DN)                                                                A 443
      A28=ABS(1./DN)                                                           A 444
      A29=ABS((MU*(S1F-1.)*SIN(PSI1-ALPHP1)+(1.+MU*MU*S1F)*COS(PSI1-ALPH     A 445
     1P1))/DN)                                                                 A 446
      A30=ABS(MU/DN)                                                           A 447
      A37=ABS(((1.+MU*MU*S2F)*SIN(PSI2+ALPHP2)+MU*(S2F-1.)*COS(PSI2+ALPH     A 448
     1P2))/DN)                                                                 A 449
      A38=ABS(((1.-MU*MU*S1F)*SIN(PSI1-ALPHP1)-MU*(1.+S1F)*COS(PSI1-ALPH     A 450
     1P1))/DN)                                                                 A 451
      A39=ABS((MU*SIN(GAMMA2)+COS(GAMMA2))/DN)                                A 452
      A40=ABS((MU*(S2F-1.)*SIN(PSI2+ALPHP2)-(1.+MU*MU*S2F)*COS(PSI2+ALPH     A 453
     1P2))/DN)                                                                 A 454
      A41=ABS((-MU*(1.+S1F)*SIN(PSI1-ALPHP1)+(MU*MU*S1F-1.)*COS(PSI1-ALP     A 455
     1HP1))/DN)                                                                A 456
      A42=ABS((MU*COS(GAMMA2)-SIN(GAMMA2))/DN)                                A 457
      A43=ABS(((1.+MU*MU*S2F)*SIN(PSI2+ALPHP2)-MU*(1.-S2F)*COS(PSI2+ALPH     A 458
     1P2))/DN)                                                                 A 459
      A44=ABS((MU*(S1R-1.)*SIN(LAMDA1)-(1.+MU*MU*S1R)*COS(LAMDA1))/DN)       A 460
      A45=ABS((MU*SIN(GAMMA2)+COS(GAMMA2))/DN)                                A 461
      A46=ABS((MU*(S2F-1.)*SIN(PSI2+ALPHP2)-(1.+MU*MU*S2F)*COS(PSI2+ALPH     A 462
     1P2))/DN)                                                                 A 463
      A47=ABS((-(1.+MU*MU*S1R)*SIN(LAMDA1)+MU*(1.-S1R)*COS(LAMDA1))/DN)      A 464
      A48=ABS((-SIN(GAMMA2)+MU*COS(GAMMA2))/DN)                               A 465
      A65=ABS((MU*(1.+S2R)*SIN(LAMDA2)+(MU*MU*S2R-1.)*COS(LAMDA2))/DN)       A 466
      A66=ABS((MU*SIN(GAMMA3)-COS(GAMMA3))/DN)                                A 467
      A67=ABS(((MU*MU*S2R-1.)*SIN(LAMDA2)-MU*(1.+S2R)*COS(LAMDA2))/DN)       A 468
      A68=ABS((-SIN(GAMMA3)-MU*COS(GAMMA3))/DN)                               A 469
      A69=ABS(((MU*MU*S2F-1.)*SIN(PSI2+ALPHP2)-MU*(1.+S2F)*COS(PSI2+ALPH     A 470
     1P2))/DN)                                                                 A 471
      A70=ABS((MU*SIN(GAMMA3)-COS(GAMMA3))/DN)                                A 472
      A71=ABS((-MU*(1.+S2F)*SIN(PSI2+ALPHP2)+(1.-MU*MU*S2F)*COS(PSI2+ALP     A 473
     1HP2))/DN)                                                                A 474
      A72=ABS((-SIN(GAMMA3)-MU*COS(GAMMA3))/DN)                               A 475
      C6=ACG2*(SIN(PHI2-DELG2-LAMDA2)-MU*S2R*COS(PHI2-DELG2-LAMDA2))-MU*     A 476
     1RHC2*(A11+A14)-MU*RHOG2*S2R                                             A 477
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      C7=MU*RHO2*(A13+A16)                                                 A 478
      C8=-(ACP1*(SIN(PSI1+DELP1-LAMDA1)-MU*S1R*COS(PSI1+DELP1-LAMDA1))+M   A 479
     1U*RHO2*(A12+A15)+MU*S1R*RHOP1)                                       A 480
      CS=MU*RHO1*(A18+A20)                                                 A 481
      C10=MU*RHO1*(A17+A19)+ACG1*(SIN(PHI1+DELG1-LAMDA1)-MU*S1R*COS(PHI1   A 482
     1+DELG1-LAMDA1))-MU*S1R*RHOG1                                         A 483
      C11=ACG2*(SIN(PHI2-DELG2-LAMDA2)-MU*S2R*COS(PHI2-DELG2-LAMDA2))-MU   A 484
     1*RHO2*(A21+A24)-MU*RHOG2*S2R                                         A 485
      C12=MU*RHO2*(A23+A26)                                                A 486
      C13=G1-MU*RHO2*(A22+A25)                                             A 487
      C14=MU*RHO1*(A28+A30)                                                A 488
      C15=MU*RHO1*(A27+A29)+MU*S1F*RHOG1+ACG1*(MU*S1F*SIN(PHI1+DELG1-PSI   A 489
     11+ALPHP1)-COS(PHI1+DELG1-PSI1+ALPHP1))                               A 490
      C1S=-MU*RHO2*(A37+A40)+ACG2*(COS(PHI2-DELG2-PSI2-ALPHP2)+MU*S2F*SI   A 491
     1N(PHI2-DELG2-PSI2-ALPHP2))-MU*S2F*RHOG2                              A 492
      C20=MU*RHO2*(A39+A42)                                                A 493
      C21=-MU*RHO2*(A38+A41)+G1                                            A 494
      C22=-MU*RHO2*(A43+A46)+ACG2*(COS(PHI2-DELG2-PSI2-ALPHP2)+MU*S2F*SI   A 495
     1N(PHI2-DELG2-PSI2-ALPHP2))-MU*S2F*RHOG2                              A 496
      C23=MU*RHO2*(A45+A48)                                                A 497
      C24=-MU*RHO2*(A44+A47)+ACP1*(MU*S1R*COS(PSI1+DELP1-LAMDA1)-SIN(PSI   A 498
     11+DELP1-LAMDA1))-MU*S1R*RHOP1                                        A 499
      C33=MU*RHO3*(A66+A68)                                                A 500
      C34=MU*RHO3*(A65+A67)-MU*S2R*RHOP2+ACP2*(MU*S2R*COS(PSI2-DELP2-LAM   A 501
     1DA2)-SIN(PSI2-DELP2-LAMDA2))                                         A 502
      C35=MU*RHO3*(A70+A72)                                                A 503
      C36=MU*RHO3*(A69+A71)-G2                                             A 504
C                                                                          A 505
C     MOMENT CONTROL                                                       A 506
C                                                                          A 507
      IF ((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T)) GO TO 25                    A 508
      IF ((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T)) GO TO 26                    A 509
      IF ((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T)) GO TO 27                    A 510
      IF ((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T)) GO TO 28                    A 511
C                                                                          A 512
C     MOMENT EXPRESSIONS                                                   A 513
C                                                                          A 514
   25 MO31=MIN*C8*C34/(C6*C10)-Q1*C8*C9*C34/(C6*C10)-Q2*C7*C34/C6-Q3*C33   A 515
      MO3=MO31                                                             A 516
      POINTEF=ABS(PSDOT2)*MO3/MIN                                          A 517
      WRITE (6,36) PHI1D,PHI2D,PSI1D,PSI2D,PSDOT1,PSDOT2,S1R,S2R,POINTEF   A 518
      GO TO 29                                                             A 519
   26 MO32=MIN*C13*C34/(C11*C15)-Q1*C13*C14*C34/(C11*C15)-Q2*C12*C34/C11   A 520
     1-Q3*C33                                                              A 521
      MO3=MO32                                                             A 522
      POINTEF=ABS(PSDOT2)*MO3/MIN                                          A 523
      WRITE (6,37) PHI1D,PHI2D,PSI1D,PSI2D,PSDOT1,PSDOT2,S2R,S1F,G1,POIN   A 524
     1TEF                                                                  A 525
      GO TO 29                                                             A 526
   27 MO33=MIN*C21*C36/(C15*C19)-Q1*C14*C21*C36/(C15*C19)-Q2*C20*C36/C19   A 527
     1-Q3*C35                                                              A 528
      MO3=MO33                                                             A 529
      POINTEF=ABS(PSDOT2)*MO3/MIN                                          A 530
```

Computer program CLOCK4 (cont)


```
      WRITE (6,38) PHI1D,PHI2D,PSI1D,PSI2D,PSDOT1,PSDOT2,S1F,G1,S2F,G2,P
     1OINTEF
      GO TO 29
   28 MO34=MIN*C24*C36/(C10*C22)-Q1*C9*C24*C36/(C10*C22)-Q2*C23*C36/C22-
     1O3*C35
      MO3=MO34
      POINTEF=ABS(PSDOT2)*MO3/MIN
      WRITE (6,39) PHI1D,PHI2D,PSI1D,PSI2D,PSDOT1,PSDOT2,S1R,S2F,G2,POIN
     1TEF
   29 MTOT=MTOT+POINTEF
      J3=1.
      GO TO 20
   30 CYCLEFF=-MTOT*DDPHI1/(PHI1F-PHI1I)
      WRITE (6,57) CYCLEFF
      MTOT=0.
      IF (ISTOP.NE.0) GO TO 1
      STOP
C
C
C
   31 FORMAT (6X,9HPSI1T1D =,F9.4,3X,8HTEST11 =,F9.4)
   32 FORMAT (6X,9HPSI1T2D =,F9.4,3X,8HTEST12 =,F9.4//)
   33 FORMAT (6X,9HPSI2T2D =,F9.4,3X,8HTEST21 =,F9.4)
   34 FORMAT (6X,9HPSI2T2D =,F9.4,3X,8HTEST22 =,F9.4//)
   35 FORMAT (93H        PHI1     PHI2     PSI1     PSI2    DPSI1   DPSI2   S1R
     1  S2R  S1F     G1    S2F     G2    POINTEF/)
   36 FORMAT (6X,4(F6.2,2X),2(F5.0,2X),2(F3.0,2X),24X,F5.3)
   37 FORMAT (6X,4(F6.2,2X),2(F5.0,2X),5X,F3.0,2X,F3.0,2X,F5.3,14X,F5.3)
   38 FORMAT (6X,4(F6.2,2X),2(F5.0,2X),10X,2(F3.0,2X,F5.3,2X),F5.3)
   39 FORMAT (6X,4(F6.2,2X),2(F5.0,2X),F3.0,19X,F3.0,2X,F5.3,2X,F5.3)
   40 FORMAT (2F10.4/4F10.0)
   41 FORMAT (4F10.4)
   42 FORMAT (4F10.4)
   43 FORMAT (F10.3,F10.0/4F10.5/4F10.5/I1)
   44 FORMAT (3F10.4/F10.6/F10.4/2F10.2)
   45 FORMAT (1H1,5X,8HPSUBD1 =,F5.0,3X,8HPSUBD2 =,F5.0//6X,5HMIN =,F9.6
     1,3X,4HMU =,F6.3,3X,5HRPM =,F6.0//6X,8HCAPRP1 =,F8.5,3X,8HCAPRP2 =,
     2F8.5//6X,5HRP2 =,F8.5,3X,5HRP3 =,F8.5//6X,6HACG1 =,F8.5,3X,6HACG2
     3=,F8.5,3X,6HACP1 =,F8.5,3X,6HACP2 =,F8.5/)
   46 FORMAT (6X,7HRHOG1 =,F8.5,3X,7HRHOG2 =,F8.5,3X,7HRHOP1 =,F8.5,3X,7
     1HRHOP2 =,F8.5/)
   47 FORMAT (6X,5HTG1 =,F8.5,3X,5HTG2 =,F8.5,3X,5HTP1 =,F8.5,3X,5HTP2 =
     1,F8.5/)
   48 FORMAT (6X,5HNG1 =,F5.0,3X,5HNG2 =,F5.0,3X,5HNP2 =,F5.0,3X,5HNP3 =
     1,F5.0/)
   49 FORMAT (6X,6HRHO1 =,F6.3,3X,6HRHO2 =,F6.3,3X,6HRHO3 =,F6.3//6X,4HM
     1D =,E12.4//6X,3HK =,F6.1//6X,8HPHDOT1 =,F5.1//6X,4HJ1 =,F4.2,3X,4H
     2J2 =,F4.2//)
   50 FORMAT (6X,8HBETA1D =,F8.4,3X,8HBETA2D =,F8.4/)
   51 FORMAT (6X,30HSOMETHING IS WRONG WITH MESH 1)
   52 FORMAT (6X,8HPHI1TD =,F8.4,3X,8HPSI1TD =,F8.4)
   53 FORMAT (6X,8HPHI1ID =,F8.4,3X,8HPSI1ID =,F8.4,3X,8HPHI1FD =,F8.4,3
     1X,8HPSI1FD =,F8.4//)
```

Computer program CLOCK4 (cont)

```
PROGRAM CLOCK4      74/74    OPT=1                      FTN 4.6+420        07/31/79  08.11.05        PAGE    12

          54 FORMAT (6X,30HSOMETHING IS WRONG WITH MESH 2)                        A 584
          55 FORMAT (6X,8HPHI2TD =,F8.4,3X,8HPSI2TD =,F8.4)                       A 585
          56 FORMAT (6X,8HPHI2ID =,F8.4,3X,8HPSI2ID =,F8.4,3X,8HPHI2FD =,F8.4,3   A 586
         1X,8HPSI2FD =,F8.4//)                                                    A 587
          57 FORMAT (1H0,5X,18HCYCLE EFFICIENCY =,F5.3)                           A 588
          58 FORMAT (3F10.5)                                                      A 589
          59 FORMAT (6X,4HR1 =,F8.5,3X,4HR2 =,F8.5,3X,4HR3 =,F8.5/)               A 590
          60 FORMAT (6X,5HFP1 =,F8.5,3X,5HFP2 =,F8.5/)                            A 591
          61 FORMAT (3E15.5)                                                      A 592
          62 FORMAT (6X,4HM1 =,E15.5,3X,4HM2 =,E15.5,3X,4HM3 =,E15.5/)            A 593
             END                                                                  A 594-
```

Computer program CLOCK4 (cont)

```
SUBROUTINE TRANS1      74/74    OPT=1                    FTN 4.6+420        07/31/79  08.11.05        PAGE      1

      SUBROUTINE TRANS1 (RHOG,ALPHP,BETA,FP,ACG,B,DELG,Z,PSIT,PHIT,G)
      PI=3.14159
      ST=(-RHOG*COS(PSIT-ALPHP)+B*SIN(BETA)+FP*SIN(PSIT-ALPHP))/ACG
      CT=(RHOG*SIN(PSIT-ALPHP)+B*COS(BETA)+FP*COS(PSIT-ALPHP))/ACG
      PHIT=ATAN2(ST,CT)-DELG
      PHINEXT=PHIT-.1*Z
      AF=ACG*COS(PHINEXT+DELG+ALPHP)-B*COS(BETA+ALPHP)
      BF=-ACG*SIN(PHINEXT+DELG+ALPHP)+B*SIN(BETA+ALPHP)
      CF=RHOG
      ROOTF=AF*AF+BF*BF-CF*CF
      YF1=AF+SQRT(ROOTF)
      YF2=AF-SQRT(ROOTF)
      XF=BF+CF
      PSINEX1=2.*ATAN2(YF1,XF)
      PSINEX2=2.*ATAN2(YF2,XF)
      IF (PSINEX1.LT.0.) PSINEX1=PSINEX1+2.*PI
      IF (PSINEX2.LT.0.) PSINEX2=PSINEX2+2.*PI
      IF (ABS(PSINEX1-PSIT).LT.ABS(PSINEX2-PSIT)) GO TO 1
      PSINEXT=PSINEX2
      GO TO 2
    1 PSINEXT=PSINEX1
    2 G=(ACG*SIN(PHINEXT+DELG)+RHOG*COS(PSINEXT-ALPHP)-B*SIN(BETA))/SIN(
     1PSINEXT-ALPHP)
      RETURN
      END
```

Computer program CLOCK4 (cont)

```
SUBROUTINE TRANS2     74/74    OPT=1                    FTN 4.6+420        07/31/79  08.11.05        PAGE    1

      SUBROUTINE TRANS2 (RHOG,ALPHP,BETA,FP,ACG,B,DELG,Z,PSIT,PHIT,G)
      PI=3.14159
      ST=(RHOG*COS(PSIT+ALPHP)+B*SIN(BETA)+FP*SIN(PSIT+ALPHP))/ACG
      CT=(-RHOG*SIN(PSIT+ALPHP)+B*COS(BETA)+FP*COS(PSIT+ALPHP))/ACG
      PHIT=ATAN2(ST,CT)+DELG
      PHINEXT=PHIT+.1*Z
      AF=ACG*COS(PHINEXT-DELG-ALPHP)-B*COS(BETA-ALPHP)
      BF=-ACG*SIN(PHINEXT-DELG-ALPHP)+B*SIN(BETA-ALPHP)
      CF=-RHOG
      ROOTF=AF*AF+BF*BF-CF*CF
      YF1=AF+SQRT(ROOTF)
      YF2=AF-SQRT(ROOTF)
      XF=BF+CF
      PSINEX1=2.*ATAN2(YF1,XF)
      PSINEX2=2.*ATAN2(YF2,XF)
      IF (PSINEX1.LT.0.) PSINEX1=PSINEX1+2.*PI
      IF (PSINEX2.LT.0.) PSINEX2=PSINEX2+2.*PI
      IF (ABS(PSINEX1-PSIT).LT.ABS(PSINEX2-PSIT)) GO TO 1
      PSINEXT=PSINEX2
      GO TO 2
    1 PSINEXT=PSINEX1
    2 G=(ACG*SIN(PHINEXT-DELG)-RHOG*COS(PSINEXT+ALPHP)-B*SIN(BETA))/SIN(
     1PSINEXT+ALPHP)
      RETURN
      END
```

Computer program CLOCK4 (cont)

```
PSUBD1 =  50.   PSUBD2 =  70.

MIN =  .030157   MU =  .200   RPM = 1000.

CAPRP1 =  .55000   CAPRP2 =  .39286

RP2 =  .08000   RP3 =  .05714

ACG1 =  .54656   ACG2 =  .39040   ACP1 =  .07998   ACP2 =  .05769

NG1 =  55.   NG2 =  55.   NP2 =   8.   NP3 =   8.

R1 =  .22500   R2 =  .49700   R3 =  .64000

RHOG1 =  .04322   RHOG2 =  .03087   RHOP1 =  .01400   RHOP2 =  .01000

TG1 =  .03175   TG2 =  .02268   TP1 =  .02096   TP2 =  .01497

W1 =     .12000E-03   W2 =     .25300E-04   W3 =     .15300E-05

RHO1 =  .062   RHO2 =  .025   RHO3 =  .018

WD =   .2750E-05

K =  25.0

PHDOT1 = -1.0

J1 = .90   J2 = .90


FP1 =  .07875   FP2 =  .05621

BETA1D =135.0146   BETA2D =211.4664

PSI1T1D = 331.1623   TEST11 =   8.5908
PSI1T2D =  11.5011   TEST12 =  48.9297


PHI1TD =135.4134   PSI1TD =331.1623
PHI1ID =138.2188   PSI1ID =311.9198   PHI1FD =131.6734   PSI1FD =356.9198


PSI2T2D = 335.0370   TEST21 =  48.8749
PSI2T2D =  15.2351   TEST22 =   8.6766


PHI2TD =211.0816   PSI2TD = 15.2351
PHI2ID =208.2761   PSI2ID = 34.4878   PHI2FD =214.8216   PSI2FD =349.4878
```

PHI1	PHI2	PSI1	PSI2	DPSI1	DPSI2	S1R	S2R	S1F	G1	S2F	G2	PGINTEF
132.33	214.17	352.69	353.71	7.	-44.			1.	.071	1.	.051	.319
132.29	214.42	352.94	352.06	7.	-43.			1.	.071	1.	.051	.317
132.25	214.67	353.20	350.44	7.	-42.			1.	.071	1.	.051	.316
132.21	268.28	353.45	34.48	7.	-45.		-1.	1.	.071			.350
132.18	298.53	353.70	32.76	7.	-45.		-1.	1.	.071			.354
132.14	208.78	353.95	31.05	7.	-45.		-1.	1.	.071			.357
132.10	209.02	354.20	29.35	7.	-45.		-1.	1.	.071			.361
132.06	209.27	354.44	27.56	6.	-44.		-1.	1.	.071			.364

Computer program CLOCK4 (cont)

132.02	209.52	354.69	25.97	6.	-44.		-1.	1.	.071			.367
131.99	209.76	354.94	24.28	6.	-44.		-1.	1.	.071			.370
131.95	210.01	355.19	22.63	6.	-44.		1.	1.	.071			.367
131.91	210.25	355.43	20.93	6.	-44.		1.	1.	.071			.363
131.87	210.50	355.67	19.25	6.	-44.		1.	1.	.071			.360
131.83	210.74	355.91	17.58	6.	-44.		1.	1.	.071			.357
131.79	210.98	356.15	15.91	6.	-44.		1.	1.	.071			.354
131.76	211.22	356.40	14.25	6.	-44.			1.	.071	1.	.056	.351
131.72	211.46	356.64	12.57	6.	-44.			1.	.072	1.	.055	.347
131.68	211.70	356.89	10.89	6.	-44.			1.	.072	1.	.054	.344
138.22	211.71	311.92	10.87	7.	-49.	1.				1.	.054	.385
138.18	211.97	312.16	9.01	7.	-49.	1.				1.	.054	.382
138.14	212.23	312.45	7.15	7.	-49.	1.				1.	.053	.379
138.10	212.49	312.71	5.30	7.	-49.	1.				1.	.053	.376
138.07	212.75	312.97	3.44	7.	-49.	1.				1.	.052	.374
138.03	213.02	313.23	1.60	7.	-48.	1.				1.	.052	.372
137.99	213.28	313.49	359.77	7.	-48.	1.				1.	.052	.370
137.95	213.54	313.75	357.96	7.	-47.	1.				1.	.051	.369
137.91	213.80	314.02	356.17	7.	-47.	1.				1.	.051	.367
137.88	214.06	314.28	354.41	7.	-46.	1.				1.	.051	.366
137.84	214.32	314.54	352.69	7.	-45.	1.				1.	.051	.365
137.80	214.58	314.80	351.00	7.	-44.	1.				1.	.051	.364
137.76	208.28	315.06	34.48	7.	-47.	1.	-1.					.403
137.72	208.54	315.32	32.69	7.	-47.	1.	-1.					.409
137.69	208.80	315.58	30.90	7.	-47.	1.	-1.					.414
137.65	209.06	315.84	29.12	7.	-47.	1.	-1.					.418
137.61	209.32	316.10	27.34	7.	-47.	1.	-1.					.423
137.57	209.58	316.36	25.56	7.	-47.	1.	-1.					.428
137.53	209.84	316.62	23.77	7.	-47.	1.	1.					.430
137.50	210.10	316.88	21.99	7.	-47.	1.	1.					.427
137.46	210.36	317.14	20.20	7.	-47.	1.	1.					.423
137.42	210.62	317.40	18.41	7.	-47.	1.	1.					.420
137.38	210.88	317.66	16.62	7.	-47.	1.	1.					.417
137.34	211.14	317.92	14.83	7.	-47.	1.				1.	.056	.414
137.30	211.40	318.18	13.01	7.	-48.	1.				1.	.055	.410
137.27	211.66	318.44	11.19	7.	-48.	1.				1.	.055	.407
137.23	211.92	318.71	9.35	7.	-48.	1.				1.	.054	.403
137.19	212.18	318.97	7.50	7.	-48.	1.				1.	.053	.400
137.15	212.44	319.23	5.56	7.	-48.	1.				1.	.053	.397
137.11	212.70	319.49	3.81	7.	-48.	1.				1.	.052	.394
137.08	212.96	319.75	1.98	7.	-48.	1.				1.	.052	.392
137.04	213.22	320.01	.15	7.	-48.	1.				1.	.052	.390
137.00	213.48	320.27	358.35	7.	-47.	1.				1.	.051	.388
136.96	213.74	320.53	356.56	7.	-47.	1.				1.	.051	.386
136.92	214.00	320.79	354.80	7.	-46.	1.				1.	.051	.384
136.89	214.26	321.05	353.07	7.	-45.	1.				1.	.051	.383
136.85	214.52	321.31	351.36	7.	-44.	1.				1.	.051	.382
136.81	214.78	321.57	349.72	7.	-43.	1.				1.	.051	.380
136.77	208.28	321.83	34.48	7.	-47.	1.	-1.					.423
136.73	208.54	322.09	32.69	7.	-47.	1.	-1.					.428
136.70	208.80	322.35	30.90	7.	-47.	1.	-1.					.433
136.66	209.06	322.61	29.12	7.	-47.	-1.	-1.					.441
136.62	209.32	322.87	27.34	7.	-47.	-1.	-1.					.444
136.58	209.58	323.13	25.56	7.	-47.	-1.	-1.					.448
136.54	209.84	323.39	23.77	7.	-47.	-1.	1.					.448
136.51	210.10	323.65	21.98	7.	-47.	-1.	1.					.445
136.47	210.36	323.91	20.19	7.	-47.	-1.	1.					.438
136.43	210.62	324.18	18.39	7.	-47.	-1.	1.					.433
136.39	210.88	324.44	16.59	7.	-47.	-1.	1.					.428
136.35	211.15	324.70	14.80	7.	-48.	-1.				1.	.056	.423
136.31	211.41	324.96	12.98	7.	-48.	-1.				1.	.055	.418

Computer program CLOCK4 (cont)

136.28	211.67	325.22	11.14	7.	-48.	-1.				1.	.055	.413
136.24	211.93	325.48	9.30	7.	-49.	-1.				1.	.054	.408
136.20	212.19	325.74	7.44	7.	-49.	-1.				1.	.053	.403
136.16	212.45	326.00	5.59	7.	-49.	-1.				1.	.053	.398
136.12	212.71	326.27	3.73	7.	-49.	-1.				1.	.052	.394
136.09	212.98	326.53	1.89	7.	-48.	-1.				1.	.052	.390
136.05	213.24	326.79	.05	7.	-48.	-1.				1.	.052	.387
136.01	213.50	327.05	356.24	7.	-47.	-1.				1.	.051	.383
135.97	213.76	327.31	356.44	7.	-47.	-1.				1.	.051	.380
135.93	214.02	327.58	354.67	7.	-46.	-1.				1.	.051	.377
135.90	214.28	327.84	352.93	7.	-45.	-1				1.	.051	.375
135.86	214.55	328.10	351.23	7.	-44.	-1.				1.	.051	.372
135.82	214.81	328.36	349.57	7.	-43.	-1.				1.	.051	.369
135.78	208.28	328 62	34.48	7.	-47.	-1.	-1.					.409
135.74	208.54	328.89	32.68	7.	-47.	-1.	-1.					.413
135.71	208.80	329.15	30.88	7.	-47.	-1.	-1.					.417
135.67	209.06	329.41	29.08	7.	-47.	-1.	-1.					.420
135.63	209.33	329.67	27.28	7.	-47.	-1.	-1.					.423
135.59	209.59	329.94	25.49	7.	-47.	-1.	-1.					.426
135.55	209.85	330.20	23.69	7.	-47.	-1.	1.					.425
135.51	210.11	330.46	21.89	7.	-47.	-1.	1.					.421
135.48	210.38	330.73	20.08	7.	-47.	-1.	1.					.416
135.44	210.64	330.99	18.27	7.	-48.	-1.	1.					.411
135.40	210.90	331.25	16.47	7.	-48.		1.	1.	.079			.407
135.36	211.17	331.51	14.66	7.	-48.			1.	.079	1.	.056	.401
135.32	211.43	331.78	12.82	7.	-49.			1.	.079	1.	.055	.396
135.29	211.69	332.04	10.96	7.	-49.			1.	.079	1.	.054	.390
135.25	211.96	332.31	9.09	7.	-49.			1.	.078	1.	.054	.385
135.21	212.22	332.57	7.21	7.	-49.			1.	.078	1.	.053	.380
135.17	212.49	332.84	5.33	7.	-49.			1.	.078	1.	.053	.375
135.13	212.75	333.10	3.44	7.	-49.			1.	.078	1.	.052	.371
135.10	213.02	333.37	1.57	7.	-49.			1.	.077	1.	.052	.367
135.06	213.29	333.63	359.70	7.	-49.			1.	.077	1.	.052	.363
135.02	213.55	333.90	357.86	7.	-48.			1.	.077	1.	.051	.36[illegible]
134.98	213.82	334.17	356.02	7.	-48.			1.	.077	1.	.051	.357
134.94	214.09	334.44	354.23	7.	-47.			1.	.077	1.	.051	.354
134.91	214.36	334.70	352.47	7.	-46.			1.	.077	1.	.051	.351
134.87	214.62	334.97	350.74	7.	-45.			1.	.077	1.	.051	.348
134.83	208.28	335.24	34.48	7.	-49.		-1.	1.	.076			.385
134.79	208.54	335.51	32.64	7.	-48.		-1.	1.	.076			.388
134.75	208.81	335.78	30.80	7.	-48.		-1.	1.	.076			.391
134.72	209.08	336.05	28.96	7.	-48.		-1.	1.	.076			.394
134.68	209.35	336.31	27.12	7.	-48.		-1.	1.	.076			.397
134.64	209.62	336.58	25.28	7.	-48.		-1.	1.	.076			.400
134.60	209.89	336.85	23.43	7.	-48.		1.	1.	.076			.399
134.56	210.16	337.12	21.58	7.	-49.		1.	1.	.075			.394
134.52	[illegible]	337.39	19.73	7.	-49.		1.	1.	.075			.389
134.49	210.70	337.65	17.67	7.	-49.		1.	1.	.075			.384
134.45	210.97	337.93	16.01	7.	-49.		1.	1.	.075			.379
134.4	211.24	338.20	14.15	7.	-49.			1.	.075	1.	.056	.374
134.37	211.51	338.47	12.26	7.	-50.			1.	.075	1.	.055	.369
134.33	211.78	338.74	10 36	7.	-50.			1.	.075	1.	.054	.364
134.30	212.05	339.01	8.45	7.	-50.			1.	.075	1.	.054	.360
134.26	212.32	339.28	6.53	7.	-50.			1.	.075	1.	.053	.355
134.22	212.59	339.55	4.61	7.	-50.			1.	.074	1.	.053	.351
134.18	212.86	339.82	2.70	7.	-50.			1.	.074	1.	.052	.347
134.14	213.13	340.09	.80	7.	-50.			1.	.074	1.	.052	.344
134.11	213.40	340.36	358.92	7.	-49.			1.	.074	1.	.051	.341
134.07	213.67	340.63	357.06	7.	-49.			1.	.074	1.	.051	.338
134.03	213.94	340.90	355.22	7.	-48.			1.	.074	1.	.051	.335
133.99	214.21	341.17	353.42	7.	-47.			1.	.074	1.	.051	.333

Computer program CLOCK4 (cont)

133.95	214.48	341.44	351.66	7.	-46.		1.	.074	1.	.051	.331
133.92	214.75	341.71	349.93	7.	-45.		1.	.074	1.	.051	.328
133.88	208.28	341.98	34.48	7.	-49.	-1.	1.	.073			.364
133.64	208.55	342.25	32.63	7.	-49.	-1.	1.	.073			.367
133.80	208.82	342.52	30.78	7.	-48.	-1.	1.	.073			.371
133.76	209.08	342.79	28.94	7.	-48.	-1.	1.	.073			.374
133.73	209.35	343.06	27.09	7.	-48.	-1.	1.	.073			.377
133.69	209.[illegible]2	343.33	25.25	7.	-48.	-1.	1.	.073			.380
133.65	209.89	343.60	23.41	7.	-48.	1.	1.	.073			.379
133.61	210.16	343.87	21.57	7.	-48.	1.	1.	.073			.375
133.57	210.43	344.14	19.73	7.	-48.	1.	1.	.073			.370
133.53	210.70	344.41	17.88	7.	-49.	1.	1.	.073			.366
133.50	210.97	344.67	16.03	7.	-49.	1.	1.	.073			.362
133.46	211.23	344.94	14.19	7.	-49.		1.	.073	1.	.056	.358
133.42	211.50	345.21	12.32	7.	-49.		1.	.073	1.	.055	.353
133.38	211.77	345.48	10.44	7.	-49.		1.	.072	1.	.054	.349
133.34	212.03	345.74	8.55	7.	-50.		1.	.072	1.	.054	.345
133.31	212.30	346.01	6.66	7.	-50.		1.	.072	1.	.053	.341
133.27	212.57	346.27	4.77	7.	-49.		1.	.072	1.	.053	.337
133.23	212.63	346.54	2.89	7.	-49.		1.	.072	1.	.052	.334
133.19	213.10	346.81	1.02	7.	-49.		1.	.072	1.	.052	.331
133.15	213.36	347.07	359.18	7.	-48.		1.	.072	1.	.051	.328
133.12	213.63	347.34	357.35	7.	-48.		1.	.072	1.	.051	.326
133.08	213.89	347.60	355.55	7.	-47.		1.	.072	1.	.051	.324
133.04	214.16	347.86	353.79	7.	-46.		1.	.072	1.	.051	.322
133.00	214.42	348.13	352.06	7.	-45.		1.	.072	1.	.051	.320
132.96	214.68	348.39	350.37	7.	-44.		1.	.072	1.	.051	.318
132.93	208.28	348.65	34.48	7.	-47.	-1.	1.	.072			.353
132.89	208.54	348.91	32.68	7.	-47.	-1.	1.	.072			.356
132.85	208.80	349.17	30.89	7.	-47.	-1.	1.	.072			.360
132.81	209.06	349.44	29.11	7.	-47.	-1.	1.	.072			.363
132.77	209.32	349.70	27.33	7.	-47.	-1.	1.	.072			.366
132.73	209.56	349.96	25.55	7.	-47.	-1.	1.	.072			.369
132.70	209.84	350.21	23.78	7.	-47.	1.	1.	.072			.370
132.66	210.10	350.47	22.00	7.	-47.	1.	1.	.072			.366
132.62	210.36	350.73	20.23	7.	-47.	1.	1.	.072			.363
132.58	210.61	350.99	18.46	7.	-46.	1.	1.	.072			.359
132.54	210.87	351.24	16.69	7.	-46.	1.	1.	.071			.356
132.51	211.13	351.50	14.93	7.	-47.		1.	.071	1.	.056	.352
132.47	211.38	351.76	13.15	7.	-47.		1.	.071	1.	.055	.348
132.43	211.64	352.01	11.37	7.	-47.		1.	.071	1.	.055	.344
132.39	211.89	352.27	9.57	7.	-47.		1.	.071	1.	.054	.341

CYCLE EFFICIENCY = .379

REFERENCE

E-1 G.G. Lowen, City College of N.Y., and F.R. Tepper, ARRADCOM, "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

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