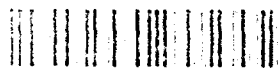


AD-A284 311



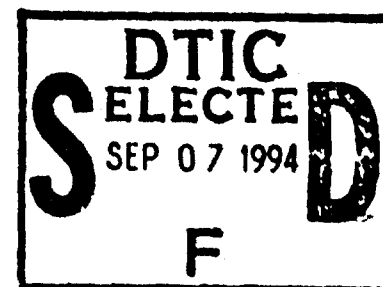
AD

AD-E402 532

Technical Report ARAED-TR-94011

**DESIGN TOOL FOR ARTILLERY SAFETY AND ARMING
MECHANISMS CONTAINING CLOCK GEARS AND A
STRAIGHT-SIDED VERGE RUNAWAY ESCAPEMENT AND
OPERATING IN AN AEROBALLISTIC ENVIRONMENT**

F. R. Tepper, ARDEC
G. G. Lowen, City College of New York



August 1994



**U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND
ENGINEERING CENTER**

Armament Engineering Directorate

Picatinny Arsenal, New Jersey

U.S. ARMY
ARMAMENT RESEARCH, DEVELOPMENT AND
ENGINEERING CENTER
PICATINNY ARSENAL, NEW JERSEY

Approved for public release; distribution is unlimited.

94-29155



DTIC QUALITY INSPECTED 3

94 9 06 215

The views, opinions, and/or findings contained in this report are those of the authors(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

The citation in this report of the names of commercial firms or commercially available products or services does not constitute official endorsement by or approval of the U.S. Government.

Destroy this report when no longer needed by any method that will prevent disclosure of its contents or reconstruction of the document. Do not return to the originator.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operation and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE August 1994		3. REPORT TYPE AND DATES COVERED
4. TITLE AND SUBTITLE DESIGN TOOL FOR ARTILLERY SAFETY AND ARMING MECHANISMS CONTAINING CLOCK GEARS AND A STRAIGHT-SIDED VERGE RUNAWAY ESCAPEMENT AND OPERATING IN AN AEROBALLISTIC ENVIRONMENT			5. FUNDING NUMBERS	
6. AUTHOR(S) F. R. Tepper, ARDEC G. G. Lowen, City College of New York				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSES(S) REPORT NUMBER ARDEC, AED Fuze Division (SMCAR-AEF-C) Picatinny Arsenal, NJ 07806-5000			8. PERFORMING ORGANIZATION Technical Report ARAED-TR-94011	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(S) AGENCY REPORT NUMBER ARDEC, IMD STINFO Br (SMCAR-IMI-I) Picatinny Arsenal, NJ 07806-5000			10. SPONSORING/MONITORING	
11. SUPPLEMENTARY NOTES Parts of this material appeared originally in ARDC Technical Report ARLCD-CR-84003.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This investigation developed a computer simulation, which serves as a design tool for a complete safety and arming mechanism, which operates in a projectile that experiences spin, precession, and nutation. This mechanism contains a straight-sided verge runaway escapement, a two-pass clock gear step-up train, and is powered by a spin-driven rotor. The mathematical model of the escapement recognizes three motion regimes, i.e., coupled motion, free motion, and impact. The model of the clock gear meshes differentiates between round-on-round and round-on-flat contact of the mating teeth. The use as a design tool is furnished by the fact that the computer program allows an infinite variation in verge and rotor mass properties as well as in component center distances and clock tooth geometries with the circular arc and radial flank geometries. Similarly, the limits of operation of the mechanism when used in conjunction with a projectile having pathological aeroballistic motion may be observed.				
14. SUBJECT TERMS Clock gears, Safety and arming, Artillery, Escapement, M577 fuze, Fuze Verge escapement			15. NUMBER OF PAGES 369	
16. PRICE CODE				
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR	

CONTENTS

	Page
Introduction	1
Geometry of Clock Gear Teeth and Kinematics of Step-up Clock Gear Trains	1
Description of Computer Program Aercloc	6
Preliminary Computations for Mesh No. 1	7
Preliminary Computations for Mesh No. 2	9
Data for Runge-Kutta	11
Coupled Motion	13
Free Motion	18
Impact	20
Reversal of Gear Train Motion Due to Impact	21
Termination of Computations	21
Computer Simulation of Example Mechanism	21
Input Data	22
Escapement Parameters	22
Clock Gear and Pinion Parameters	22
Mass Parameters of Components	24
General Parameters	26
Projectile Kinematics and Parameters	27
Output Data	28
Fuze Geometry and Contact Angles of Both Meshes	29
Coupled Motion	
Free Motion	30
Impact	31
Number of Turns-to-Arm and Maximum Contract Forces	32
Conclusions	32
References	33
Appendices	
A Kinematics of Aeroballistic Systems	35
B Angular Momentum and Its Derivatives in Various Coordinate Systems	47

CONTENTS (cont)

	Page
C Absolute Acceleration of Geometric Center C of the S&A Plane	55
D Dynamics of Rotor-Driven S&A Mechanism with a Two-Pass Clock Gear Train and A Verge Runaway Escapement Operating in an Aeroballistic Environment	59
E Projectile Kinematics	265
F Forward and Reverse Kinematics of Clock Gear Meshes No. 1 and No. 2	269
G Projectile Kinematics in Terms of Coordinate System Fixed to Underside of Mechanism Plane (Applicable to M577 S&A)	295
H Program Aercloc	301
Distribution List	365

Accession For	
NTIS CRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

INTRODUCTION

The present report describes the development of a computer simulation of a complete artillery safety and arming (S&A) mechanism, which must operate in a projectile that experiences spin, precession, and nutation. This mechanism consists of a straight-sided verge runaway escapement, a two pass step-up clock gear train and a spin-driven rotor.

Top views of the mechanism planes of the two possible configurations of this device are shown in figures 1 and 2, respectively. One of the feasible positions of this mechanism plane with respect to a projectile which experiences aeroballistic motion is given in figure 3.

The clock gear step-up meshes, whose kinematics and dynamics were developed in references 1 and 2, have been incorporated into the present verge type fuze simulation. It represents the latest fuze simulation work of the authors which began with the pin pallet escapement (ref 3). This initial effort was followed by a simulation of a complete S&A mechanism (ref 4) in which the motion of a spin-driven rotor is retarded by a pin pallet escapement that is driven through a involute gear train. The development of the dynamics of a straight-sided verge runaway escapement as well as the inclusion of this type of escapement into a S&A simulation where again a spin-driven rotor and an involute gear train are involved is given in reference 5. In both these computer models, the mechanisms experience only spin fields. In contrast, reference 6, which is the predecessor of the present work, represents for the first time a simulation of a S&A device with a verge type escapement and involute gears which operates in a full aeroballistic environment. The necessary background on the reverse kinematics of clock gear meshes was first stated in reference 7.

The kinematics of the aeroballistic system are described in appendix A, the angular momentum and its derivatives are given in appendix B, the absolute acceleration of the center of the S&A plane is provided in appendix C, the dynamics of the entire system are derived in appendix D, the projectile kinematics are discussed in appendix E, the kinematics of the clock gear meshes are shown in appendix F, the projectile kinematics in terms of a specific coordinate system is presented in appendix G, and the associated computer program is listed in appendix H.

GEOMETRY OF CLOCK GEAR TEETH AND KINEMATICS OF STEP-UP CLOCK GEAR TRAINS

The basic shape of a clock gear tooth, as used in the present work, consists of a circular arc or ogive type tip, which blends into a straight line (radial) flank that theoretically originates at the center of the gear blank. As in involute gearing, the intertooth spaces are designed such that there is sufficient clearance for a meshing set of clock gears. (Possible design methods are given by British Standard 978, Part 2, 1952: Gears for Instruments and Clockwork Mechanisms. Also see references 1 and 2.)

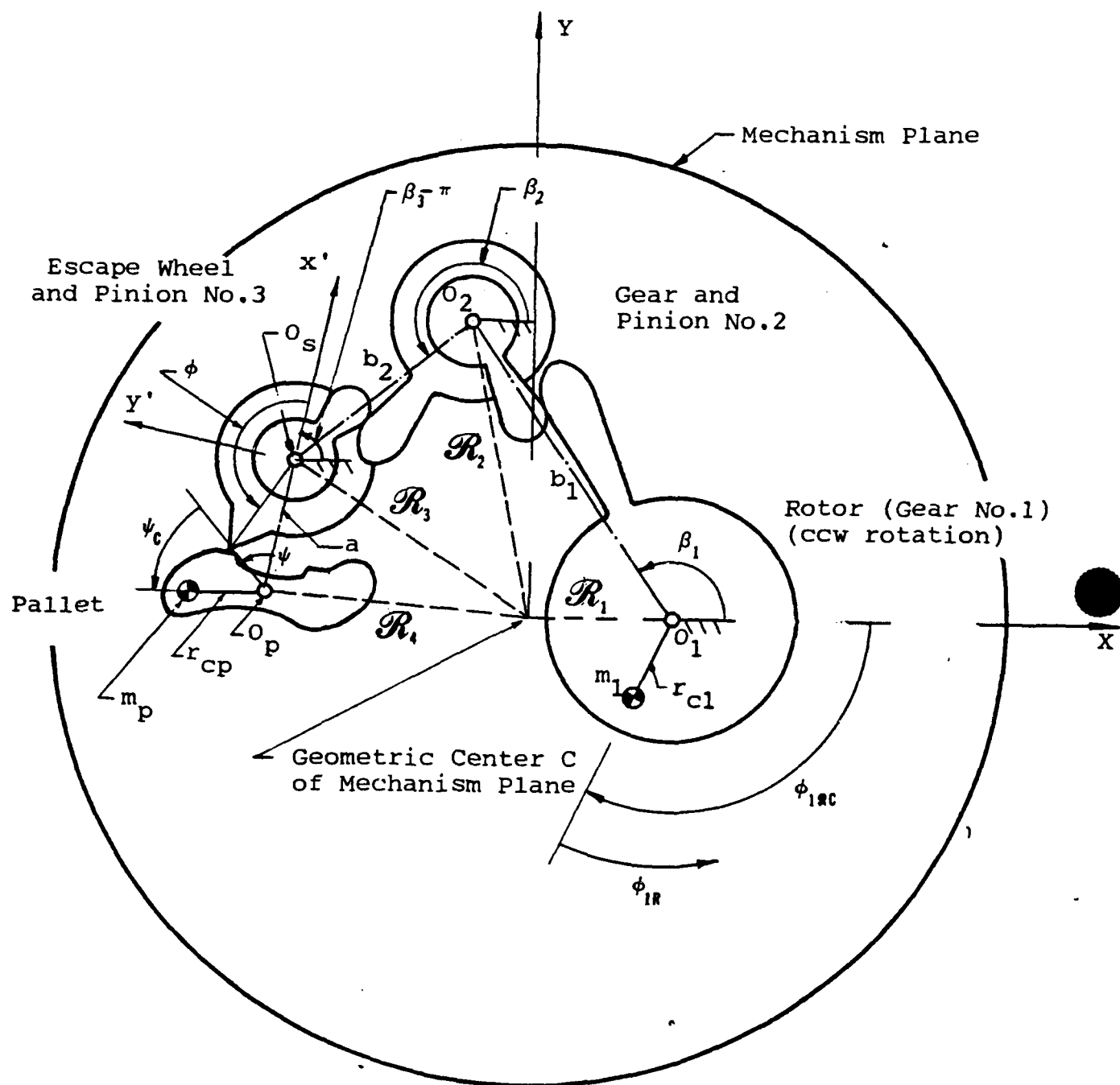


Figure 1. Rotor-driven S&A device with verge configuration no. 1

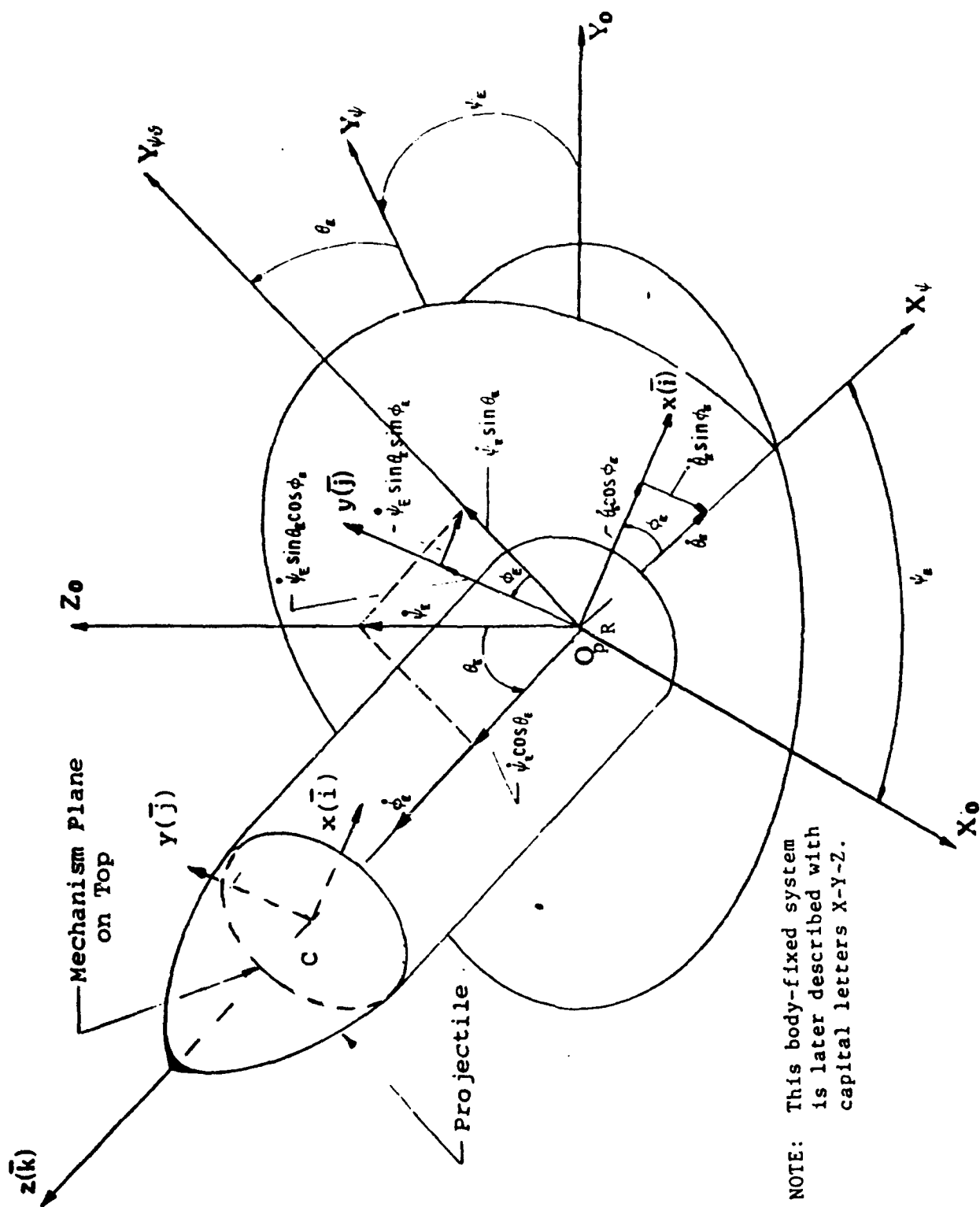


Figure 3. Mechanism plane in projectile which experiences aeroballistic motion

When meshed in step-up trains, where the gear drives the pinion, the initial contact is made between the circular arc tips of both components. This contact mode has been called round-on-round contact. As the motion continues, past a transition point on the pinion, the circular arc of the gear makes contact with the straight flank of the pinion. This contact mode has been designated as round-on-flat contact. During this regime the contact point between gear and pinion first proceeds inward with respect to the pinion flank. Subsequently, it moves outward and disengagement, i.e., transfer of motion to the next set of teeth occurs long before round-on-round contact could be reestablished. (Since the velocity ratio of such meshes is not constant, only one set of teeth can be in contact at any one time.)

The possible combinations of contact modes which arise cyclically in the two pass step-up clock gear trains shown in figures 1 and 2 are enumerated in table 1. Gear 1 and pinion 2 form mesh no. 1. The combination of gear 2 and pinion 3 is called mesh no. 2. (Note that the condition of mesh no. 2 always precedes that of mesh no. 1 in the chosen designations RR, FF, etc.)

Based on the work in references 1 and 7, appendix F of this report reviews and extends the development of the forward and reverse kinematics of meshes no. 1 and no. 2.

Besides input-output relationships as well as angular velocities and angular accelerations for both gear contact modes, expressions for transition angles and contact sensing equations are given. In addition, the angular velocities and accelerations of the rotor and the gear and pinion no. 2 assembly are derived in terms of the escape wheel angular velocity and acceleration for use in the final system differential equations.

Table 1. Possible contact mode combinations in a two pass step-up clock gear train

<u>Train contact mode</u>	<u>Mesh no. 2 (gear 2 and pinion 3)</u>	<u>Mesh no. 1 (gear 1 and pinion 2)</u>
RR	R	R
FF	F	F
RF	R	F
FR	F	R

NOTE: R = Round-on-round
F = Round-on-flat

DESCRIPTION OF COMPUTER PROGRAM AERCLOC

With the exception of the inclusion of both the kinematics and the dynamics of the clock gear meshes, the programming schemes which make it possible to distinguish between entrance and exit coupled motion, free motion, and impact of the verge escapement run parallel to those first given in reference 6. (It will also be helpful to consult the control details for the pin pallet escapement program, which were originally formulated in reference 3 and later adapted, without much change, to the verge escapement in reference 5). The main program starts with the reading and writing of all physical parameters of the S&A mechanism. Subsequently, subroutine GEAR, which has been written for clock teeth whose ogive centers of curvature lie off the tooth centerlines, provides the distances AG, together with the angles DELG, for both gears. It requires the input parameters CAPRP, CAPRO, RHOG, and TCG. (For explanation of terms, see Computer Simulation of Example Mechanism.)

Subroutine PINION has been written for clock teeth whose tip centers of curvature lie on the tooth centerline. It provides the distances AP and FP, as well as the angles DELP and ALPHP, for both pinions of the train. The needed input parameters are RP, RO, and RHOP. (The expressions used in the above subroutines were derived in references 1 and 2.)

To avoid confusion, it is to be noted that, RP2 and RO2 are the pitch and outside radii, respectively, of pinion no. 2 and belong to mesh no. 1. Similarly, RP3 and RO3 belong to the escape wheel pinion and are part of mesh no. 2. The pitch and outside radii of the rotor gear and gear no. 2 have the same numbers as the meshes they are associated with, i.e., CAPRP1 and CAPRO1, as well as CAPRP2 and CAPRO2, respectively.

The above is followed by the initialization of the escapement and gear contact forces in coupled and free motion, the computation of the sums of the individual mesh radii of curvature, as well as the center distances. Finally, before the clock gear transition angles are determined, the various fuse body angles are obtained (ref 4).

The simulation begins with entrance coupled motion at a starting angle PHID, which represents that angle ϕ of the escape wheel that is associated with the approximate center of the entrance working surface of the verge. This angle then corresponds to a cumulative escape wheel angle PHITOT of zero degree.

Preliminary Computations for Mesh No. 1

Determination of Transition Angles

The transition angle $PH2PT = \phi_{2PT}$ (app F., eq F-25) is established as that angle for which a small change in the direction of continued motion of the rotor angle $PH1 = \phi_1$ will cause the associated value of $G1 = g_1$ (eq F-18) to become smaller than its transition value $FP1 = f_{p1}$. Since the rotor gear no. 1 turns in a counterclockwise (ccw) direction, the above change in $PH1$ must be positive.

The program accomplishes this task in the following manner:

1. The two possible transition angles $PH2PT1$ and $PH2PT2$ of pinion no. 2 are computed according to equation F-25 (app F).
2. Subroutine $TRANS1$, which is valid for meshes in which the input gear has ccw rotation, is called and the rotor transition angle $PH1T1$, which is associated with the pinion transition angle $PH2PT1$, is computed according to equations F-29 and F-30 (app F).
3. The rotor angle $PH1T1$ is made slightly larger to become $PHINEX$, and equation F-14 (app F) is used to find the associated pinion angle $P2NEX$. Since there are two such angles resulting from the computation, the subroutine must select that one which is closest to the pinion transition angle $PH2PT1$. Subsequently, the associated value of g_{11} , in the form of $G11$, is determined according to equation F-18 (app F).
4. After control is returned to the main program, the value of $G11$ is compared to that of the transition magnitude $FP1$. Assuming that $G11$ is smaller than $FP1$, the transition angles $PH1T1$ and $PH2PT1$ govern.
5. If that is not the case, steps 2 and 3 are repeated for the second transition angle of the pinion, i.e., $PH2PT2$. This results in the determination of $G12$.
6. Again, control is returned to the main program and $G12$ is now tested against $FP1$. If it is smaller than $FP1$, the transition angles $PH1T2$ and $PH2PT2$ govern. If the test fails, the program is terminated with the message "SOMETHING IS WRONG WITH MESH 1".

Determination of Correct Sign for Forward Round-on-Flat regime of Mesh No. 1

The sign preceding the square root in equation F-14 (app F), for the forward round-on-flat contact mode of mesh no. 1, is determined with the help of the rotor gear transition angle PHI1T . Both possible pinion angles PH2PF1 and PH2PF2 are first determined. The sign used in the determination of the one which deviates least from the pinion transition angle PH2PT is then given to the signum function SIGN1F . This parameter is used throughout the program in conjunction with equation F-14 (app F).

Latest and Earliest Possible Values of PHI1 and PHI2P of Mesh No. 1

The latest and earliest values of the gear and pinion angles PHI1 AND PHI2P , respectively, are found by continuously evaluating the round-on-flat regime equation F-14 (app F) with SIGN1F , and simultaneously checking the contact condition for the subsequent set of clock teeth, as given by equation F-31 (app F). This loop is initiated at the transition angle PHI1T and it is terminated when the condition of equation F-31 (app F) is met. The latter furnished PHI1F the latest possible contact angle of the rotor gear, as well as PH2PFF , the latest possible contact angle of pinion 2. (These are the angles at which contact is transferred to the subsequent gear mesh.) To obtain the earliest possible (initial) contact angles PHI1I of the rotor and PH2PI of the pinion, the appropriate tooth spacing angles are added or subtracted, as needed, from the respective final contact angles. The initial rotor angle PHI1I is obtained by subtracting the gear tooth spacing angle DPHI1 from the final angle PHI1F . By adding the pinion tooth spacing angle DPHI1P to PH2PFF , the initial pinion contact angle PH2PI results.

Determination of Correct Sign for Forward Round-on-Round Regime of Mesh No. 1

The sign preceding the square root in equation F-1 (app F), for the round-on-round contact mode of mesh no. 1, is determined with the help of the initial rotor gear angle PHI1I . Both possible pinion contact angles PH2PR1 and PH2PR2 are first obtained. The sign used in the computation of that one which deviates least from the initial pinion contact angle PH2PI , is subsequently assigned to the signum function SIGN1R .

Reverse Kinematics of Mesh No. 1

Determination of Correct Sign for Reverse Round-on-Round Regime of Mesh No. 1. The sign preceding the square root in equation F-68 (app F), which allows the determination of the rotor gear angle for a given angle of the pinion during reverse round-on-round contact, is found with the help of the initial pinion angle PH2PI . Both possible rotor gear angles PHI1R1 and PHI1R2 are first computed. The sign used in the determination of that of the above angles, which deviates least from the associated initial rotor angle PHI1I is then assigned to the signum function RSGN1R .

Determination of Correct Sign for Reverse Round-on-Flat Regime of Mesh No. 1. The sign preceding the square root in equation F-95 (app F), which is used to determine the rotor gear angle for a given pinion angle during reverse round-on-flat contact, is found with the help of the final (latest) pinion contact angle PH2PFF. Both possible rotor gear angles PHI1F1 and PHI1F2 are first obtained. Subsequently, the sign used in the computation of that rotor gear angle which deviates least from the associated final rotor angle PHI1F is assigned to the signum function RSGN1F.

Preliminary Computations for Mesh No. 2

The general procedures for the preliminary computations for mesh no. 2 are identical to those that were followed for mesh no. 1. It must only be kept in mind that for mesh no. 2 the gear (i.e., gear 2) rotates clockwise, while the pinion (i.e., pinion 3, the escape wheel pinion) turns in a ccw direction.

Determination of Transition Angles

The transition angle $PHIST = \phi_{ST}$ (app F, eq F-59) is also established as that angle for which a small change in the direction of continued forward motion of the now applicable gear no. 2 angle $PHI2 = \phi_{2G}$ will cause the associated value of $G2 = g_2$ (app F, eq F-52) to become smaller than the flank transition value $FP2 = f_{p2}$. Since gear no. 2 turns in a clockwise direction, the above change in PHI2 must be negative. The program accomplishes this task in the following manner:

1. The two possible transition angles PHIST1 and PHIST2 of pinion no. 3 are computed according to equation F-59.
2. Subroutine TRANS2, which is valid for meshes in which the driving gear has CW rotation, is called and the gear no. 2 transition angle PHI2T1, which is associated with the pinion transition angle PHIST1, is computed according to equations F-63 and F-64.
3. The gear no. 2 angle PHI2T1 is made slightly smaller to become PHINEX, and equation F-48 (for round-on-flat contact) is used to find the associated escape wheel pinion angles PSNEX1 and PSNEX2. The subroutine must now select the one of the two which is closest to the pinion transition angle PHIST1. Subsequently, the associated value of $G21 = g_{21}$ is determined according to equation F-52.
4. After control is returned to the main program, the value of G21 is compared to that of the transition magnitude FP2. Assuming that G21 is smaller than FP2, the transition angles PHI2T1 and PHIST1 govern.

5. If this is not the case, steps 2 and 3 are repeated for PHIST2, the second possible transition angle of the escape wheel pinion. This results in the determination of PH12T2 and G22.

6. Again, control is returned to the main program and G22 is now compared with FP2. If it is smaller than FP2, the transition angles PH12T2 and PHIST2 govern. If the test is failed, the program is terminated with the message: "SOMETHING IS WRONG WITH MESH 2."

Determination of Correct Sign for Forward Round-on-Flat Regime of Mesh No. 2

The sign preceding the square root in equation F-48 (app F), for the forward round-on-flat contact mode of mesh no. 2, is determined with the help of the gear no. 2 transition angle PH12T. Both possible angles PHISF1 and PHISF2 of pinion 3 are first computed. The sign employed in the determination of the angle which deviates least from the pinion transition angle PHIST is then assigned to the signum function SIGN2F. This parameter is subsequently used whenever there is need for equation F-48 (app F).

Latest and Earliest Possible Values of PHI2 and PHIS of Mesh 2

The latest and earliest values of the gear and pinion angles PHI2 AND PHIS, respectively, are found by continuously evaluating the forward round-on-flat regime equation F-48 (app F) with SIGN2F and simultaneously checking the contact condition for the subsequent set of teeth, as given by equation F-65 (app F). This loop is initiated at the transition angle PH12T and it is terminated when the condition of equation F-65 (app F) is met. (Note that the increments of angle PHI2 are negative, since gear no. 2 advances in the clockwise direction.) The latter furnished PHI2F, the latest possible contact angle of the gear, as well as PHISFF, the latest possible contact angle of pinion no. 3. Again, these are the angles at which contact is transferred to the subsequent gear mesh. To obtain the earliest possible (initial) contact angles PHI2I of the gear no. 2 and PHISI of pinion no. 3, the appropriate tooth spacing angles are again added or subtracted, as needed, from the final contact angles. The initial angle PHI2I of gear no. 2 is obtained by adding the tooth spacing angle DPHI2 to the final angle PHI2F. (The gear rotates clockwise and the subsequent tooth centerline is at a larger angle with respect to the reference axis than the preceding one.) By subtracting the pinion tooth spacing angle DPHIS from the final angle PHISFF, the initial pinion no. 3 contact angle PHISI results. (The pinion rotates ccw and the subsequent tooth centerline is at a smaller angle with respect to the reference axis than the preceding one.)

Determination of Correct Sign for Forward Round-on-Round Regime of Mesh No. 2

The sign preceding the square root in equation F-34 (app F), for the forward round-on-round contact mode of mesh no. 2, is determined with the help of the initial angle PHI2I . Both possible pinion no. 3 angles PHISR1 and PHISR2 are first obtained. Subsequently, the sign used in the determination of the angle which deviates least from the initial pinion no. 3 angle PHISI is assigned to the signum function SIGN2R .

Reverse Kinematics of Mesh No. 2

Determination of Correct Sign for Reverse Round-on-Round Regime of Mesh No. 2. The sign preceding the square root in equation F-113 (app F), which allows the determination of the gear no. 2 angle for a given angle of pinion no. 3 during reverse round-on-round contact, is found with the help of the initial pinion angle PHISI . Both possible angles PHI2R1 and PHI2R2 of gear no. 2 are first computed. Subsequently, the sign used in the determination of that angle, which deviates least from the associated initial gear angle PHI1I , is assigned to the signum function RSGN2R .

Determination of Correct Sign for Reverse Round-on-Flat Regime of Mesh No. 2. The sign preceding the square root in equation F-131 (app F), which is used to determine the angle of gear no. 2 for a given angle of pinion no. 3 during reverse round-on-flat contact, is found with the help of PHISFF , the final contact angle of pinion no. 3. Both possible angles PHI2F1 and PHI2F2 of gear no. 2 are first obtained. Subsequently, the sign used in the computation of that gear angle which deviates least from the final gear no. 2 angle PHI2F , is assigned to the signum function RSGN2F .

Data for Runge-Kutta

The program made use of the existing fourth order Runge-Kutta routine RKGS for the solution of all differential equations¹.

The initial statements make it possible to start the mechanism simulation with both gear meshes at arbitrary positions between their earliest and latest contact angles. To this end, the proportionality factors J1 and J2 , which may be set from zero to unity, are introduced to obtain the pinion starting angles PHI2P and PHIS of meshes no. 1 and no. 2, respectively.

¹IBM System/360 Scientific Subroutine Package (360A-CM-OX3), Version III.

To devise an appropriate expression for mesh no. 1, consider that pinion no. 2 always turns clockwise as the rotor advances. Because of this fact, the pinion angle PH2PFF, which is associated with the latest possible mesh contact, is always more negative (minus five degrees is more negative than minus one degree) than PH1PI, the pinion angle associated with the earliest possible contact. Similarly, all possible starting angles of pinion no. 2 must either be equal to or more negative than PH2PI. With this reasoning, the difference between the latest and earliest possible contact angles of pinion no. 2, i.e.,

$$\text{DIFF1} = \text{PH2PFF} - \text{PH2PI} \quad (1)$$

will always be negative, regardless of the signs of the two angles. Further, together with J1, any arbitrary starting angle of pinion no. 2 will be correctly described by

$$\text{PH12P} = \text{J1} * \text{DIFF1} + \text{PH2PI} \quad (2)$$

The expression for the starting angle PHIS of mesh 2 is based on the fact that the escape wheel pinion no. 3 always turns in the ccw direction. Therefore, any pinion angle, associated with contact after the earliest contact angle PHISI, will be larger (more positive) than PHISI. With this reasoning, the difference between the latest and earliest possible contact angles, i.e.,

$$\text{DIFF2} = \text{PHISFF} - \text{PHISI} \quad (3)$$

will always be positive, regardless of the signs of the two angles. Then, together with J2, the arbitrary starting angle of pinion no. 3 will be correctly given by:

$$\text{PHIS} = \text{J2} * \text{DIFF2} + \text{PHISI} \quad (4)$$

The starting conditions for coupled motion are as follows:

1. The initial angle PHID of the escape wheel, i.e., the Runge-Kutta variable PHI(1), equals 139 degrees (read in as part of data).
2. The initial angular velocity of the escape wheel, i.e., the Runge-Kutta variable PHI(2), equals zero.
3. The verge angle $\text{ALPHA} = \alpha$ equals $\text{ALPHEN} = \alpha_{\text{en}}$, for entrance, in distinction from the exit verge angle $\text{ALPHEx} = \alpha_{\text{ex}}$ (ref 5).

Coupled Motion

With the four possible gear contact modes, the coefficients of the governing differential equations of coupled motion must change accordingly. The general form of this expression is given by

$$W_1 \ddot{\phi} + W_2 \dot{\phi}^2 + W_3 \dot{\phi} = W_4 + W_5(O_x \sin \gamma - O_y \cos \gamma) + W_6(K_x \sin \beta - K_y \cos \beta) \quad (5)$$

where $\phi(t)$ represents the escape wheel angle $\text{PHI}(1)$.

The applicable subscripts of the A_i 's which correspond to the W_i 's as well as the equation numbers of the associated differential equations for the four gear contact mode are given in table 2.

The difference between entrance and exit coupled motion is expressed by the value of the signum function s_7 . This becomes crucial for the computations of the factors A_{16} , A_{21} , A_{29} , A_{36} , and A_{51}^2 .

Table 2. Coefficients of equation 5 for the coupled motion differential equations of the four gear train contact modes

Gear train contact mode	RR	FF	RF	FR
Governing differential equation	D-949	D-974	D-997	D-1020
W_1	A_{105}	A_{120}	A_{134}	A_{148}
W_2	A_{106}	A_{121}	A_{135}	A_{149}
W_3	A_{107}	A_{122}	A_{136}	A_{150}
W_4	A_{108}	A_{123}	A_{137}	A_{151}
W_5	A_{109}	A_{124}	A_{138}	A_{152}
W_6	A_{110}	A_{125}	A_{139}	A_{153}

²The program uses the symbol $AA1$, etc., throughout. This should not be confused with the symbols AA_{16} to AA_{51} , which are first used in the combined exit coupled motion differential equation D-372 (app D).

To solve the applicable form of equation 5, the program calls on the Runge-Kutta subroutine FCT. The principal purpose of this subroutine is to present the relevant form of a second order differential equation in terms of two first order ones to RKGS. Subroutine OUTP is responsible for preparing the results of various computations for printing.

The individual forms of equation 5 are chosen with the help of the following control criteria shown in table 3.

Table 3. Control criteria

RR gear train contact mode

$\text{PHI2} > \text{PHI2T}$	Mesh no. 2
$\text{PHI1} < \text{PHI1T}$	Mesh no. 1

FF gear train contact mode

$\text{PHI1} < \text{PHI2T}$	Mesh no. 2
$\text{PHI1} > \text{PHI1T}$	Mesh no. 1

RF gear train contact mode

$\text{PHI2} > \text{PHI2T}$	Mesh no. 2
$\text{PHI1} > \text{PHI1T}$	Mesh no. 1

FR gear train contact mode

$\text{PHI2} < \text{PHI2T}$	Mesh no. 2
$\text{PHI1} < \text{PHI1T}$	Mesh no. 1

Before discussing the details of subroutine FCT and subroutine OUTP, it is necessary to point out the manner in which each step of the integration, relates to the increase in the escape wheel pinion angle PHI_S , as well as to the determination of cumulative escape wheel angle PHITOT . (Since the escape wheel angle varies between approximately 134 and 144 degrees during entrance coupled motion, and between approximately 209 and 216 degrees during exit coupled motion, PHITOT can only be obtained by continuously adding the increment in $\text{PHI}(1)$ due to each cycle of computation.) The procedure of obtaining the angle γ of the rotor center of mass will be shown in connection with the description of subroutine GKINEM. The verge center of mass angle β is given in FCT with the help of subroutine KINEM.

Subroutine OUTP starts with the definition of the increment DELPHI of the escape wheel angle PHI(1):

$$\text{DELPHI} = \text{PHID} - \text{PHIPR} \quad (6)$$

where

PHID = the current value of PHI(1), as obtained after each round of integration

PHIPR = the value of PHI(1) obtained in the previous integration, or from the initial condition of this angle

Once DELPHI is determined, the cumulative escape wheel angle PHITOT can be incremented by this amount. Since the incremental rotation of pinion no. 3 must be identical to that of the escape wheel, the increment DDPHIS of PHIS is equal to DELPHI, and the cumulative pinion angle is obtained by

$$\text{PHIS} = \text{PHIS} + \text{DDPHIS} \quad (7)$$

It is to be noted that, for computing all initial quantities, such as contact forces, at $T = 0$, as well as for setting up the various values for the first round of integration, both DELPHI and DDPHIS are zero, since PHI(1) and PHIPR have the same value of the starting escape wheel angle.

As a consequence of the first and all subsequent integrations, DELPHI will always be a positive quantity.

Subroutine FCT. The computations for all the parameters, associated with the various forms of the coupled motion differential equation are made in FCT in terms of the current values of the escape wheel variables PHI(1) and PHI(2), as well as the escape wheel pinion angle PHIS. To accomplish some of this, FCT calls on other subroutines as needed. The following outlines all computations in FCT in a sequential manner:

1. Subroutine KINEM is called to compute the current values of the escapement variables $\text{PSI} = \psi$, $G = g$, $\text{DPSI} = \dot{\psi}$ and $\text{VST} = V_{S/T}$. In addition, the moment arms $\text{AONE} = A_1'$ to $\text{DONE} = D_1'$ are obtained (ref 5). The above makes it possible to determine angle $\text{BETA} = \beta$ in FCT.

2. Subroutine AFIVE is called.

- a. Subroutine ACCEL is called for the determination of the absolute accelerations of the pivot points of the individual train components.

b. Subroutine GKINEM is called. It deals with the determination of the reverse kinematics of meshes no. 1 and 2, as defined in appendixes F-III and F-IV, respectively. Starting with mesh no. 2, which now has the angle $\text{PHIS} = \phi_s$, the angular velocity $\text{PHI}(2) = \dot{\phi}$ and the angular acceleration $\ddot{\phi}$ of the escape wheel pinion as the inputs, the following output related variables are determined:

Round-on-round contact

$\text{PHI2} = \phi_{2G}$	(eq F-104)
$\text{LAMDA2} = \lambda_2$	(eq F-38 and F-39)
DER2R	(eq F-109)
$\text{PHDOT2} = \dot{\phi}_{2G}$	(eq F-108)
$\text{VST2R} = V_{S2/T2R}$	(eq F-47)
$\text{X7, X8, X9, Y5, Y6}$ used to determine $\ddot{\phi}_{2G}$	(eq F-114 to F-118)

Round-on-flat contact

$\text{PHI2} = \phi_{2G}$	(eq F-122)
$\text{G2} = g_2$	(eq F-52)
DER2F	(eq F-127)
$\text{PHDOT2} = \dot{\phi}_{2G}$	(eq F-126)
$\text{VST2F} = V_{S2/T2F}$	(eq F-58)
$\text{X10, X11, X12, Y7, Y8}$ used to determine $\ddot{\phi}_{2G}$	(eq F-132 to F-136)

Subsequently, parallel values are determined for mesh no. 1. Now PHI2 and PHDOT2 , as well as $\ddot{\phi}_{2G}$, of pinion no. 2 are the inputs, while $\text{PHI1} = \phi_1$, $\text{PHDOT1} = \dot{\phi}_1$ and $\ddot{\phi}_1$ of gear 1 are the outputs. The incremental angle DDPHI1 and the total angle PHI1TOT , both of gear no. 1, are defined. This allows the determination of the angle $\text{GAM} = \gamma$.

- c. The signum functions S4 , S5 , and S7 are computed.
- d. Subroutine AWON is called for the computation of AA1 to AA23 .
- e. Subroutine CWON is called for computation of CC1 to CC20 .
- f. Subroutine ATWO is called for the computation of AA24 to AA42 .
- g. Subroutine CTWO is called for the computation of CC21 to CC36 .
- h. Subroutine ATHREE is called for the computation of AA43 to AA71 .

- i. Subroutine CTHREE is called for the computation of CC37 to CC56.
- j. Subroutine AFOUR is called for the computation of AA72 to AA93.
- k. Subroutine CFOUR is called for the computation of CC57 to CC72.
- l. The parameters AA94 to AA132 are computed.

3. Subroutine ASIX is called by FCT. ASIX calls sequentially on subroutines ACCEL, GKINEM, and again computes S4, S5, and S7. Subsequently, it calls also on AWON, CWON, ATWO, CTWO, ATHREE, CTHREE, AFOUR, and CFOUR. The above are necessary for the further computation of AA133 to AA177.

4. Control is returned to FCT, and depending on the gear contact mode, the appropriate differential equation is chosen in the manner of tables 2 and 3.

5. The applicable second order coupled motion differential equation is now presented in terms of the following two first order ones for subsequent numerical solutions:

$$DPHI(1) = PHI(2) \quad : (= \dot{\phi}) \quad (8)$$

$$DPHI(2) = 1/W1*(-W2*PHI(2)**2 - W3*PHI(2) + W4 \\ + W5*(OX*SG - OY*CG) + W6*(KX*SB - KY*CB)) \quad : (= \ddot{\phi}) \quad (9)$$

Note that because many of the CC and AA parameters are independent of gear tooth geometry and thus do not change with tooth contact mode, the extra identifiers R or F used in the subscripts of the various derivations have been omitted in Program AERCLOC.

Subroutine OUTP. Subroutine OUTP prepares the step by step solution values of PHI(1), PHI(2), PSI (verge angle), DPSI (verge angular velocity), G (contact length on verge), PHITOT, as well as all contact forces for printing. Further, it determines the maximum values of these contact forces during one arming cycle. Finally, it performs a test for continued coupled motion by making sure that G is larger than zero for entrance coupled motion and negative for exit coupled motion (ref 5). In addition the contact force P_n must not vanish.

This is accomplished in the following sequence:

- 1. PHITOT and PHIS are incremented.
- 2. Subroutine KINEM is called.

3. Subroutine AFIVE is called.
4. Subroutine ASIX is called.
5. The appropriate contact forces are computed.
6. Output is printed.
7. Tests for continued coupled motion are performed.

Free Motion

The differential equations of free motion, i.e., that of the verge, as given by equation D-1038 (app D) and those for the four gear contact modes of the escape wheel - gear train - rotor system are again solved by way of a Runge-Kutta routine.

To account for the gear contact modes, the latter takes the following general form:

$$Z_1\ddot{\phi} + Z_2\dot{\phi}^2 + Z_3\dot{\phi} + Z_4 = 0 \quad , \quad (10)$$

where $\phi(t)$ again represents the escape wheel angle.

The applicable subscripts of the A_i 's which correspond to Z_i 's as well as the equation numbers of the associated differential equations are given in table 4.

Table 4. Coefficient of equation 10 for the free motion differential equations of the escape wheel - gear train - rotor system

Gear train contact mode	RR	FF	RF	FR
Governing differential equation	D-1040	D-1048	D-1056	D-1064
Z_1	A_{162}	A_{166}	A_{170}	A_{174}
Z_2	A_{163}	A_{167}	A_{171}	A_{175}
Z_3	A_{164}	A_{168}	A_{172}	A_{176}
Z_4	A_{165}	A_{169}	A_{173}	A_{177}

The individual forms of equation 10 are again chosen with the help of the control criteria given earlier in table 2. To solve the applicable set of differential equations, i.e., equation D-1038 (app D) and equation 10, the program calls on the Runge-Kutta subroutine FCTF. This routine presents the relevant forms of the two second order differential equations in terms of four first order ones to RKGS. Subroutine OUTPF is responsible for preparing the results of the various computations for printing. The cumulative escape wheel angle PHITOT is computed in a manner similar to that described earlier for coupled motion.

Subroutine FCTF

The computations for all the parameters, associated both with the independently moving verge and the escape wheel - gear train - rotor system, are made in terms of the current values of the verge variables ψ and $\dot{\psi}$ as well as the escape wheel variables ϕ and $\dot{\phi}$. To accomplish this, FCTF, like FCT before, calls on other subroutines as needed.

The following outlines all computations in FCTF in a sequential manner:

1. Subroutine AFIVE is called.

- a. Subroutine ACCEL is called for the determination of the absolute accelerations of the pivot points of the individual train components.

- b. Subroutine GKINEM is called to evaluate, in the same manner as for coupled motion, all variables associated with the reverse kinematics of meshes 1 and 2. Thus, with the escape wheel position, velocity and acceleration known, the same type of kinematic values are determined for gear and pinion no. 2 as well as the rotor.

Subsequently, steps 2c and 2l, 3, and 4 of FCT are performed, as applicable. (While the control criteria of table 3 remain, the coefficients of table 4 are used for obtaining the appropriate expressions for equation 10.)

To obtain the magnitude of the variables ϕ and ψ , as well as their derivatives at identical times, the two independent second order differential equations are transformed into four simultaneous first order ones.³ (While actually only the two first order equations, associated with each of the two variables are coupled, the routine treats all four as if they were coupled and, therefore, produces solutions for identical time increments.)

³Note that whenever $I_{PR} \leq 0$, the simulation terminates.

These four expressions have the following form in FCTF:

$$DX(1) = X(2) : (= \dot{\phi}) \quad (11)$$

$$DX(3) = X(4) : (= \dot{\psi}) \quad (12)$$

$$DX(2) = 1/Z_1 * (-Z_2 * X(2)**2 - Z_3 * X(2) - Z_4) : (= \ddot{\phi}) \quad (13)$$

$$DX(4) = \frac{1}{I_{PR}} * [-A_{32} * X(4)**2 - A_{31} * X(4) - A_{119} + m_p * r_{cp} * (K_x * SB - K_y * CB)] : (= \ddot{\psi}) \quad (14)$$

The note at the end of subroutine FCT also holds for subroutine FCTF.

Subroutine OUTPF

Subroutine OUTPF prepares the step by step solution values of PHI(1), the escape wheel angle, PHI(2), the escape wheel velocity, PSI (verge angle), DPSI (verge velocity), and PHITOT, as well as the gear contact forces for printing. Further, it determines the maximum values of these contact forces. Finally, it performs a test for continued free motion by computing the normal and tangential distances F and GP, respectively, of the tip of the escape wheel from the working surface of the verge. The signs of these parameters are different for entrance and exit free motion (ref 5).

This is accomplished in the following sequence:

1. PHITOT and PHIS are incremented.
2. Subroutine AFIVE is called.
3. Subroutine ASIX is called.
4. The gear contact forces associated with free motion are computed.
5. Output is printed.
6. Tests for continued free motion are performed.

Impact

Subroutine IMPACT uses the pre-impact values $\dot{\phi}_i$ and $\dot{\psi}_i$ of the angular velocities and computes their post-impact values $\dot{\phi}_f$ and $\dot{\psi}_f$ according to equations D-1071 and D-1072, respectively.

The value of the total moment of inertia ISTOT of the combined escape wheel - gear train - rotor system, as referred to the escape wheel axis, depends on the gear train contact mode and is chosen with the help of the control criteria of table 3. (See also equations D-1073 to D-1076.)

Reversal of Gear Train Motion Due to Impact

If the impact torque on the escape wheel is sufficiently large, the motion of the gear train may be temporarily reversed; i.e., the escape wheel angular velocity $\dot{\phi}$ may become negative. This would cause the friction forces between the gear teeth and at the various gear pivots to be reversed in direction. (The normal forces between the gear teeth remain unaffected, and the normal bearing forces are obtained in the usual manner.) This change in the direction of the friction forces is expressed for both coupled and free motion by letting the coefficient of friction μ of all gear train components become negative (app E or ref 3). This is accomplished in subroutines AFIVE and ASIX by the following use of the signum function:

$$\text{MU} = \text{ABS}(\text{MU}) * \dot{\phi} / |\dot{\phi}| \quad (15)$$

(The coefficient of friction associated with the escapement interface and the pallet pivot is called μ_1 and is read into the programs as MU1.) Any motion reversal at these surfaces is accounted for by the signum functions s_4 and s_5 , respectively.

Termination of Computations

Computations are terminated whenever the geared motion of the rotor ends. This corresponds to $\phi = \text{PHICUTD}$. The duration of the subsequent unretarded motion of the rotor is assumed to be negligible.

COMPUTER SIMULATION OF EXAMPLE MECHANISM

The simulated mechanism is that of the S&A device of the M577 fuze. It has configuration 2 (fig. 2) and is attached to the underside of the mechanism plane as shown by figures D-1 (app D) and G-1 (app G).

The clock-type gear and pinion parameters were obtained with the help of the clock gear formulae given in references 1 and 2. (See subroutines GEAR and PINION, respectively, in program AERCLOC.)

Computer program AERCLOC was run with a basic spin velocity of 30,000 rpm to obtain maximum contact forces. It used the projectile kinematics derived in appendix B (ref 6), which expresses both precession and nutation as predetermined percentages of spin.

The following shows the input requirements of the program, explains the various output data, and discusses the manner in which the number-of-turns-to-arm is obtained for a given spin velocity.

Input Data

The first portion of the output repeats all input data, which represent the mechanism parameters of the M577 S&A. These are listed both as computer variables and a symbols, according to the various appendixes of this report as well as of references 1, 2, 5, and 6.

Escapement Parameters

$A = a = 0.226$ in. = distance between pivots O_p and O_s (fig. 2)

$B = b = 0.1685$ in. = escape wheel radius

$C = c = 0.132$ in. = pallet radius as defined by figure F-1 of appendix F, reference 5

$ALPHEN = \alpha_{en} = 44.0056$ deg = entrance working surface angle

$ALPHEX = \alpha_{ex} = 28.8277$ deg = exit working surface angle

$NT = 4$ = number of escape wheel teeth spanned by verge

$CONFIG = 2$ = configuration no. 2 (fuze body configuration no. 2 in ref 5, app B)

$EREST = e_r = 0$ = coefficient of restitution

$LAMBDA = \lambda = 91.9887$ deg = angle between entrance and exit pallet radii (ref 5, app F, fig. F-1)

$N = 22$ = number of escape wheel teeth

For details of the above nomenclature, see reference 5, appendixes C, E, and F.

Clock Gear and Pinion Parameters

$NG1 = 41$ = number of teeth of total pitch circle of rotor gear no. 1

$NG2 = 29$ = number of teeth of gear no. 2

NP2 = 6 = number of teeth of pinion no. 2

NP3 = 6 = number of teeth of escape wheel pinion

CAPRP1 = R_{p1} = 0.46585 in. = pitch radius of rotor gear no. 1

CAPRP2 = R_{p2} = 0.22835 in. = pitch radius of gear no. 2

RP2 = r_{p2} = 0.06815 in. = pitch radius of pinion no. 2

RP3 = r_{p3} = 0.04725 in. = pitch radius of escape wheel pinion

CAPRO1 = R_{o1} = 0.4956 in. = outside radius of rotor gear no. 1

CAPRO2 = R_{o2} = 0.2486 in. = outside radius of gear no. 2

RO2 = r_{o2} = 0.08575 in. = outside radius of pinion no. 2

RO3 = r_{o3} = 0.0595 in. = outside radius of escape wheel pinion

RHOG1 = ρ_{G1} = 0.044 in. = radius of circular arc on tooth of rotor gear no. 1

RHOG2 = ρ_{G2} = 0.030 in. = radius of circular arc on tooth of gear no. 2

RHOP1 = ρ_{p1} = 0.0176 in. = radius of circular arc on tooth of pinion no. 2

RHOP2 = ρ_{p2} = 0.0122 in. = radius of circular arc on tooth of escape wheel pinion

TCG1 = t_{CG1} = 0.035 in. = circular tooth thickness at pitch circle of rotor tooth of gear no. 1

TCG2 = t_{CG2} = 0.024 in. = circular tooth thickness at pitch circle of tooth of gear no. 2

R1 = $\mathfrak{R}_1$ = 0.22539 in. = distance of rotor pivot from spin axis

R2 = $\mathfrak{R}_2$ = 0.408 in. = distance of pivot of gear and pinion no. 2 from spin axis

$R3 = \mathfrak{R}_3 = 0.3685 \text{ in.} = \text{distance of pivot of escape wheel from spin axis}$

$R4 = \mathfrak{R}_4 = 0.3881 \text{ in.} = \text{distance of pivot of pallet from spin axis}$

$RHO1 = \rho_1 = 0.0465 \text{ in.} = \text{pivot radius of rotor}$

$RHO2 = \rho_2 = 0.0225 \text{ in.} = \text{pivot radius of gear and pinion no. 2}$

$RHO3 = \rho_3 = 0.0165 \text{ in.} = \text{pivot radius of escape wheel}$

$RHO1 = \rho_{F1} = 0.054 \text{ in.} = \text{friction thrust radius of rotor (for computation of friction thrust radius see p. 268 of ref. 10)}$

$RHO2 = \rho_{F2} = 0.027 \text{ in.} = \text{friction thrust radius of gear and pinion no. 2}$

$RHO3 = \rho_{F3} = 0.020 \text{ in.} = \text{friction thrust radius of escape wheel and pinion no. 3}$

$RHO1 = \rho_F = 0.018 \text{ in.} = \text{friction thrust radius of verge}$

Mass Parameters of Components

$M1 = m_1 = 0.3851 \times 10^{-4} \text{ lb-sec}^2/\text{in.} = \text{mass of rotor}$

$M2 = m_2 = 0.385 \times 10^{-5} \text{ lb-sec}^2/\text{in.} = \text{mass of gear and pinion no. 2}$

$M3 = m_3 = 0.2592 \times 10^{-5} \text{ lb-sec}^2/\text{in.} = \text{mass of escape wheel and pinion no. 3}$

$MP = m_p = 0.2982 \times 10^{-5} \text{ lb-sec}^2/\text{in.} = \text{mass of pallet}$

$IXX1 = I_{\xi\xi_1} = 0.1748 \times 10^{-5} \text{ in.-lb-sec}^2 = \text{moment of inertia of rotor with respect to an axis parallel to } \xi_1\text{-axis through center of mass (fig. A-3), but located in midplane between bearing plates (origin at pivot axis)}^4$

$IEE1 = I_{\eta\eta_1} = 0.2324 \times 10^{-5} \text{ in.-lb-sec}^2 = \text{moment of inertia of rotor with respect to an axis parallel to } \eta_1\text{-axis through center of mass, but located in midplane}^4$

$IZZ1 = I_{\zeta\zeta_1} = 0.3462 \times 10^{-5} \text{ in.-lb-sec}^2 = \text{moment of inertia of rotor with respect to pivot axis } (\zeta_1\text{-axis})^4$

$IXE1 = I_{\xi\eta_1} = -0.4256 \times 10^{-6} \text{ in.-lb-sec}^2 = \xi_1\text{-}\eta_1 \text{ product of inertia of rotor with respect to above axes}$

$IZX1 = I_{\zeta\xi_1} = -0.3446 \times 10^{-6} \text{ in.-lb-sec}^2 = \zeta_1\text{-}\xi_1 \text{ product of inertia of rotor with respect to above axes}$

$IEZ1 = I_{\eta\zeta_1} = -0.0402 \times 10^{-6} \text{ in.-lb-sec}^2 = \eta_1\text{-}\zeta_1 \text{ product of inertia of rotor with respect to above axes}$

$IX2 = I_{x_2} = 0.0426 \times 10^{-6} \text{ in.-lb-sec}^2 = \text{moment of inertia of gear and pinion no. 2 (about axis normal to pivot axis in midplane)}$

$IY2 = I_{y_2} = 0.0426 \times 10^{-6} \text{ in.-lb-sec}^2 = \text{moment of inertia of gear and pinion no. 2 (about axis normal to pivot axis and perpendicular to } x_2\text{-axis)}$

$IZ2 = I_{z_2} = 0.4031 \times 10^{-7} \text{ in.-lb-sec}^2 = \text{moment of inertia of gear and pinion no. 2 with respect to pivot axis}$

⁴The intersection of the various pivot axes and the aforementioned midplane furnishes the origins for all component moment equations. (See also the moment arms $L_u = L_L$ below.)

$IXS = I_{xs} = 0.3094 \times 10^{-7} \text{ in.-lb-sec}^2 = \text{moment of inertia of escape wheel and pinion no. 3 (about axis normal to pivot axis in midplane)}$

$IYS = I_{ys} = 0.3094 \times 10^{-7} \text{ in.-lb-sec}^2 = \text{moment of inertia of escape wheel and pinion no. 3 (about axis normal to pivot axis and perpendicular to } x_s\text{-axis)}$

$IZS = I_{zs} = 0.1639 \times 10^{-7} \text{ in.-lb-sec}^2 = \text{moment of inertia of escape wheel and pinion no. 3 with respect to pivot axis}$

$IXXP = I_{\xi\xi_p} = 0.6286 \times 10^{-7} \text{ in.-lb-sec}^2 = \text{moment in inertia of pallet with respect to an axis parallel to } \xi_p\text{-axis through center of mass (fig. A-2), but located in midplane, with origin at the pivot axis}$

$IEEP = I_{\eta\eta_p} = 0.4827 \times 10^{-7} \text{ in.-lb-sec}^2 = \text{moment of inertia of pallet with respect to an axis parallel to } \eta_p\text{-axis through center of mass, but located in midplane}$

$IZPP = I_{\xi\xi_p} = 0.7173 \times 10^{-7} \text{ in.-lb-sec}^2 = \text{moment of inertia of pallet with respect to above pivot axis } (\xi_p\text{-axis})$

$IXEP = I_{\xi\eta_p} = 0.2813 \times 10^{-7} \text{ in.-lb-sec}^2 = \text{product of inertia of pallet with respect to above axes}$

$IEZP = I_{\eta\zeta_p} = 0.0 = \text{product of inertia of pallet with respect to above axes}$

$IZXP = I_{\zeta\xi_p} = 0.0 = \text{product of inertia of pallet with respect to above axes}$

General Parameters

$RC1 = r_{c1} = 0.100 \text{ in.} = \text{distance from pivot axis of rotor to its center of mass}$

$RCP = r_{cp} = 0 = \text{distance from pivot axis of verge to its center of mass}$

$RHOP = \rho_p = 0.0140 \text{ in.} = \text{pallet pivot radius}$

$RPM = 30,000 = \text{spin rate}$

$\text{PH1RCD} = \phi_{1\text{RC}} = -113.12 \text{ deg} = \text{rotor angle in starting position (fig. 2)}$

$\text{PSICCD} = \psi_c = 0 \text{ deg} = \text{eccentricity angle of pallet}$

$\text{PHID} = 141 \text{ deg} = \text{escape wheel starting angle of initial entrance coupled motion}$

$\text{PHICUTD} = 1595 \text{ deg} = \text{cumulative escape wheel angle obtained from product of total engaged rotor rotation and gear ratio. The total rotor rotation for the M577 fuze is } 48.292 \text{ deg while the nominal gear ratio equals } 41 \times 29/36 = 33.03. \text{ Thus, } \text{PHICUTD} = 48.292 \times 33.03 = 1595 \text{ deg. (With 5.5 circular pitches, the rotor rotation becomes } 5.5 \times 360/41 = 48.292 \text{ deg. Recall that NG1 = 41.)}$

$\text{MU} = \mu = 0.10 = \text{coefficient of friction of gear train (pivots and tooth-to-tooth contacts) and escape wheel pivot (constant for a computer run)}$

$\text{MU1} = \mu_1 = 0.10 = \text{coefficient of friction of pallet-escape wheel interface and pallet pivot (constant for a computer run)}$

$\text{LU} = \text{LL} = \text{L}_u = \text{L}_l = 0.177 = \text{distance from midplane to bearing plate half thickness}$

$\text{J1} = \text{J}_1 = 0.95 = \text{initialization parameter for mesh no. 1. (The zero value corresponds to earliest possible contact of mesh (ref 2).)}$

$\text{J2} = \text{J}_2 = 0.95 = \text{initialization parameter for mesh no. 2}$

Projectile Kinematics and Parameters

The projectile kinematics are programmed in subroutine AERO according to the expressions given in appendix E of reference 6 with the following parameters:

$\text{KP} = \text{K}_p = 100$

$\text{THETIN} = 8 \text{ deg}$

$\text{TV} = \text{T}_{\text{var}} = 2 \text{ deg}$

$\text{KN} = \text{K}_n = 10$

To express the kinematics of the aeroballistic system such that it conforms to the applicable S&A coordinate system, which may be located above or below the mechanism plane, appendix G introduces the signum function s_b (eqs G-7 to G-12 and G-15).

Thus for the present case:

$$S_8 = s_8 = -1$$

The drag deceleration is given by:

$$DDZ = s_8(\ddot{Z})$$

where $\ddot{Z} = 386.4 \times 10$. (The latter represents a deceleration of 10g, but is given as an absolute value.)

Depending on whether the mechanism is located on top or below the mechanism plane, the coordinates R_x , R_y , and R_z of the geometric center C of the mechanism plane with respect to the projectile center of mass O_{PR} must also be expressed with the help of the signum function s_8 (figs. C-1 and D-1).

Thus generally

$$R_{xgen} = R_x$$

$$R_{ygen} = s_8 R_y$$

$$R_{zgen} = s_8 R_z$$

The specific value used are:

$$RX = R_x = 0.001 \text{ in.}$$

$$RY = R_y = 0.001 \text{ in.}$$

$$RZ = R_z = 20.0 \text{ in.}$$

Output Data

The data blocks following the input data represent the results of various computations.

Fuze Geometry and Contact Angles of Both Meshes

The angles $BETA1D = \beta_1$ to $BETA3D = \beta_3$ and $GAMMA2D = \gamma_2$ to $GAMMA4D = \gamma_4$ are printed for checking purposes. In addition, the following earliest possible, transition and latest possible contact angles are given for both meshes (app F):

Mesh No. 1

PHI1TD = Transition angle of rotor no. 1

PHI2PTD = Transition angle of pinion no. 2

PHI1ID = Earliest possible contact angle of rotor no. 1

PH2PID = Earliest possible contact angle of pinion no. 2

PHI1FD = Latest possible contact angle of rotor no. 1

PH2PFD = Latest possible contact angle of pinion no. 2

Mesh No. 2

PHI2TD = Transition angle of gear no. 2

PHISTD = Transition angle of pinion no. 3 (escape wheel)

PHI2ID = Earliest possible contact angle of gear no. 2

PHISID = Earliest possible contact angle of pinion no. 3

PHI2FD = Latest possible contact angle of gear no. 2

PHISFD = Latest possible contact angle of pinion no. 3

Coupled Motion

The first coupled motion output refers to the entrance side of the verge. For each time T of the coupled motion, the following variables are computed:

$PHI = \phi$ = instantaneous escape wheel angle (deg)

$PHIDOT = \dot{\phi}$ = escape wheel angular velocity (rad/sec)

$G = g$ = pallet - escape wheel contact position (in.) (ref 5, app C, eq C-15)

PSID = ψ = pallet angle (deg)

PSIDOT = $\dot{\psi}$ = pallet angular velocity (rad/sec)

PHITOT = ϕ_T = cumulative escape wheel angle (deg)

$F_{23} = F_{23}$ = normal contact force of gear no. 2 on pinion no. 3 (lb) for various mesh contact modes. The associated additional subscripts, such as RR, etc., are defined in table 1.

$F_{12} = F_{12}$ = normal contact force of gear no. 1 on pinion no. 2 (lb), for various mesh contact modes (table 1).

$P_N = P_n$ = normal contact force between escape wheel and pallet (lb), computed according to equations D-969, D-992, D-1015, and D-1037, depending on specific contact mode, which can be determined from the subscript of the contact forces F_{12} and F_{23} .

$P_{NPSI} = P_n$ = normal contact force between escape wheel and pallet (lb), computed according to equation D-967 (app D) (serves for checking and requires the computations of ψ and $\dot{\psi}$).

DDPHI = $\ddot{\phi}$ = escape wheel angular acceleration (rad/sec²), Runge-Kutta output

Free Motion

The first free motion on the exit side follows the coupled motion on the entrance side of the verge. For each time T of the free motion, the following variables are evaluated:

PHI = ϕ = instantaneous escape wheel angle (deg)

PHIDOT = $\dot{\phi}$ = escape wheel angular velocity (rad/sec)

PSI = ψ = pallet angle (deg)

PSIDOT = $\dot{\psi}$ = pallet angular velocity (rad/sec)

PHITOT = ϕ_T = cumulative escape wheel angle (deg)

$T_{12} = T_{12}$ = normal contact force of gear no. 1 on pinion no. 2 for free motion (lb) (additional subscripts according to table 1)

$T_{23} = T_{23}$ = normal contact force of gear no. 2 on escape wheel pinion for free motion (lb) (additional subscripts according to table 1)

$F = f$ = contact sensing parameter (ref 5, app E)

$GP = g'$ = second contact sensing parameter (ref 5, app E)

Impact

The first exit impact follows the first exit free motion. Just preceding the IMPACT label, the program prints the values of $VP = V_{TNI}$ and $VS = V_{SNI}$, which stand for the pre-impact velocity components, normal to the verge face of both the pallet and escape wheel contact points (ref 5, app D, eq D-13). Subsequent to the IMPACT label, the referred moment of inertia ISTOT is computed for the applicable pre-impact mode according to equations D-1073 to D-1076, as applicable. After that, one finds the following variables:

$PHI = \phi$ = instantaneous escape wheel angle (deg), same as before impact

$PHIDOT = \dot{\phi}_i$ = post-impact escape wheel angular velocity (rad/sec) (app D, eq D-1071)

$PSI = \psi$ = pallet angle (deg), same as before impact

$PSIDOT = \dot{\psi}_i$ = post-impact pallet angular velocity (rad/sec) (app D, eq D-1072)

$PHITOT = \phi_T$ = cumulative escape wheel angle (deg), same as before impact

$VP = V_{TNI}$ = post-impact normal velocity component of pallet at contact point (ref 5, app D, eq D-15)

$VS = V_{SNI}$ = post-impact normal velocity component of escape wheel tooth at contact point (ref 5, app D, eq D-13)

In the present program, the post-impact VP is equal to VS since the coefficient of restitution is zero.

Number of Turns-to-Arm and Maximum Contact Forces

The number of turns-to-arm at 30,000 rpm is obtained with the help of that time T_{1595} which corresponds to the escape wheel angle $\text{PHICUTD} = 1595$ deg. Thus, with $T_{1595} = 0.09308$ sec.

$$\text{number of turns-to-arm} = \frac{30000}{60} \times 0.09308 = 46.54 \text{ turns}$$

CONCLUSIONS

While it was not the purpose of this investigation to undertake a parametric study of the mechanism for which the program was written, the program was sufficiently tested to confirm that such a study is possible. It may include variations in masses and moments of inertia of all components; variations in the locations of the centers of mass of the verge and the rotor; variations of clock gear, escapement and fuze geometries as well as various friction and coefficient of restitution conditions. In addition, the aeroballistic data can also be varied. This makes it possible to determine the functioning limits of the mechanism under pathological projectile flight conditions.

The present work reports only on a single test run using the M577 fuze data with a system coefficient of friction of 0.1. This is assumed to be representative of actual test conditions since previous simulations of verge escapements showed that the range of actual experimental results (with spin only) may be reproduced with coefficients of friction between 0.1 and 0.2. A zero coefficient of restitution is used in the impact model (ref 4 and 5).

Previous high-speed motion picture observation of pin pallet escapements showed that the impacts were essentially inelastic and that therefore a zero coefficient restitution was justified.

The test run with a spin rate of 30,000 RPM also contained small precession and nutation velocities, chosen in the manner shown in appendix E.

Finally, it is to be noted that this work is the first where clock gear teeth were incorporated into the mathematical model of an S&A mechanism. To this end both forward and reverse kinematics of such gear trains had to be developed, as shown in appendix F.

REFERENCES

1. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.
2. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Efficiency," Technical Report ARLCD-TR-80024, ARRADCOM, Dover, NJ, November 1981.
3. Lowen, G. G. and Tepper, F. R., "Dynamics of the Pin Pallet Runaway Escapement," Technical Report ARLCD-TR-77062, ARRADCOM, Dover, NJ, June 1978.
4. Lowen, G. G. and Tepper, F. R., "Computer Simulations of Artillery S&A Mechanisms (Involute Gear Train and Pin Pallet Runaway Escapement)," Technical Report ARLCD-TR-81039, ARRADCOM, Dover, NJ, July 1982.
5. Lowen, G. G. and Tepper, F. R., "Computer Simulation of Artillery S&A Mechanisms (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-82013, ARRADCOM, Dover, NJ, November 1982.
6. Tepper, F. R. and Lowen, G. G., "Computer Simulation of Artillery Safing and Arming Mechanism in Aeroballistic Environment (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-83050, Dover, NJ, July 1984.
7. Lowen, G. G., "Development of Simulation Techniques for the M739 and M577 Fuzes," Contractor Report ARLCD-CR-84003, ARDC, Dover, NJ, April 1984.
8. Hartenberg, R. and Denavit, J., Kinematic Synthesis of Linkages, McGraw-Hill Book Co., New York, NY, 1964.
9. Goldstein, H., Classical Mechanics, Addison-Wesley Publishing Co., Inc., Reading, MA, 1959.
10. Shames, I. H., Engineering Mechanics, Statics, and Dynamics, third edition, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1980.

APPENDIX A
KINEMATICS OF AEROBALLISTIC SYSTEMS

ANGULAR VELOCITIES AND ACCELERATIONS IN TERMS OF PROJECTILE-FIXED COORDINATES

A projectile which experiences general aeroballistic motion, i.e., spin about an axis through its center of mass as well as precession and nutation of this spin axis, is shown in figure A-1. (Point O_{PR} represents the origin of the coordinate system in this figure and the spin axis coincides with the geometric one.)

The spin angle, spin velocity, and spin acceleration are expressed by the time dependent quantities ϕ_E , $\dot{\phi}_E$, and $\ddot{\phi}_E$. (The subscript E stands for the Euler angles, which are involved in this derivation.) Similarly, the kinematic quantities associated with the precession are ψ_E , $\dot{\psi}_E$, and $\ddot{\psi}_E$. The nutation variables are θ_E , $\dot{\theta}_E$, and $\ddot{\theta}_E$ (refs 1 and 2).

With spin, precession, and nutation angular velocity vectors, together with their associated angles (fig. A-1), orthogonal angular velocity components in terms of the projectile fixed x-y-z system may be obtained as follows:

Let

$$\bar{\omega}_{b/a} = \omega_x \bar{i} + \omega_y \bar{j} + \omega_z \bar{k} \quad (A-1)$$

where $\bar{\omega}_{b/a}$ represents the angular velocity of the projectile b with respect to the inertial frame a. Then

$$\omega_x = \dot{\theta}_E \cos \phi_E + \dot{\psi}_E \sin \theta_E \sin \phi_E \quad (A-2)$$

$$\omega_y = -\dot{\theta}_E \sin \phi_E + \dot{\psi}_E \sin \theta_E \cos \phi_E \quad (A-3)$$

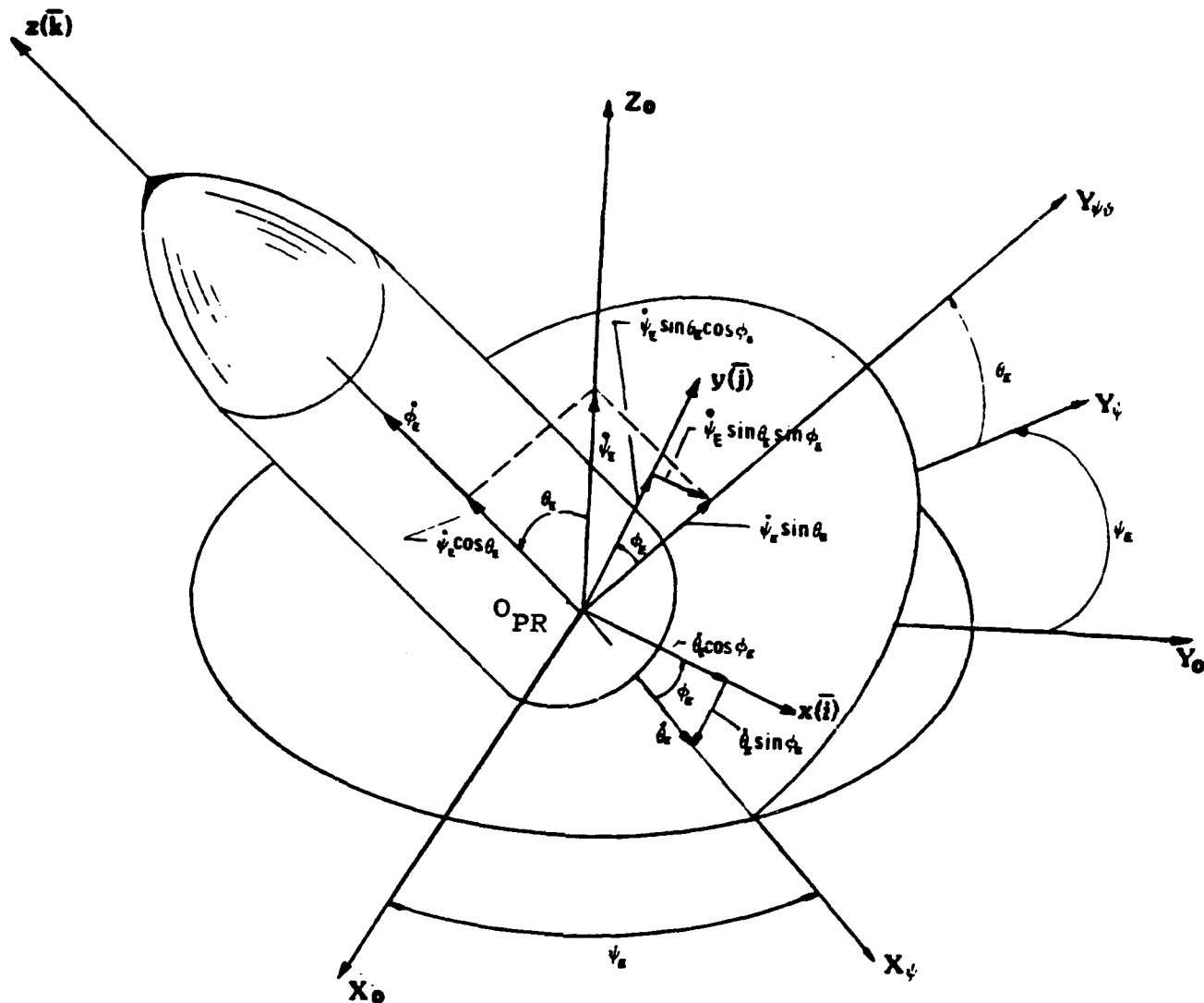
$$\omega_z = \dot{\phi}_E + \dot{\psi}_E \cos \theta_E \quad (A-4)$$

The absolute angular acceleration of the projectile, i.e.

$$\bar{\alpha}_{b/a} = \dot{\omega}_x \bar{i} + \dot{\omega}_y \bar{j} + \dot{\omega}_z \bar{k} \quad (A-5)$$

is obtained by differentiation of the body fixed quantities with respect to time. Thus

$$\begin{aligned} \dot{\omega}_x = & \ddot{\theta}_E \cos \phi_E - \dot{\theta}_E \dot{\phi}_E \sin \phi_E + \ddot{\psi}_E \sin \theta_E \sin \phi_E \\ & + \dot{\psi}_E \dot{\theta}_E \cos \theta_E \sin \phi_E + \dot{\psi}_E \dot{\phi}_E \sin \theta_E \cos \phi_E \end{aligned} \quad (A-6)$$



Note: This system is later described with capital letters X-Y-Z

Figure A-1. Projectile fixed x-y-z system

$$\begin{aligned}\dot{\omega}_y = & -\ddot{\theta}_E \sin \phi_E - \dot{\theta}_E \dot{\phi}_E \cos \phi_E + \ddot{\psi}_E \sin \theta_E \cos \phi_E \\ & + \dot{\psi}_E \dot{\theta}_E \cos \theta_E \cos \phi_E - \dot{\psi}_E \dot{\phi}_E \sin \theta_E \sin \phi_E\end{aligned}\quad (A-7)$$

$$\dot{\omega}_z = \ddot{\phi}_E + \ddot{\psi}_E \cos \theta_E - \dot{\psi}_E \dot{\theta}_E \sin \theta_E \quad (A-8)$$

Pallet-Fixed Coordinates

The relationship of the pallet-fixed $\xi_p - \eta_p - \zeta_p$ system with respect to the projectile fixed X-Y-Z and x'-y'-z' systems is shown in figure A-2 (ref 1).

The $\xi_p - \eta_p$ plane is parallel to the x'-y' and X-Y planes and contains the pallet center of mass C_p . The ζ_p -axis is parallel to the z and z' axes.

The pallet angles ψ and ψ_c are measured in the $\xi_p - \eta_p$ plane and are otherwise defined as in reference 1. Before determining the absolute angular velocity and acceleration of the pallet, a number of unit vectors should be defined. According to equations B-28 and B-29 of ref 2

$$\bar{i}' = -\cos \beta_3 \bar{i} - \sin \beta_3 \bar{j} \quad (A-9)$$

and

$$\bar{j}' = \sin \beta_3 \bar{i} - \cos \beta_3 \bar{j} \quad (A-10)$$

Further, when expressed in the primed system, pallet fixed unit vectors become

$$\bar{n}_{\xi_p} = \cos \beta \bar{i}' + \sin \beta \bar{j}' \quad (A-11)$$

$$\bar{n}_{\eta_p} = -\sin \beta \bar{i}' + \cos \beta \bar{j}' \quad (A-12)$$

where

$$\beta = \psi + \psi_c \quad (A-13)$$

If equations A-9 and A-10 are substituted into the above expressions, after some trigonometric simplifications, the following expressions are obtained for the pallet fixed unit vectors in terms of the X-Y-Z system

$$\bar{n}_{\xi_p} = -\cos \alpha \bar{i} - \sin \alpha \bar{j} \quad (A-14)$$

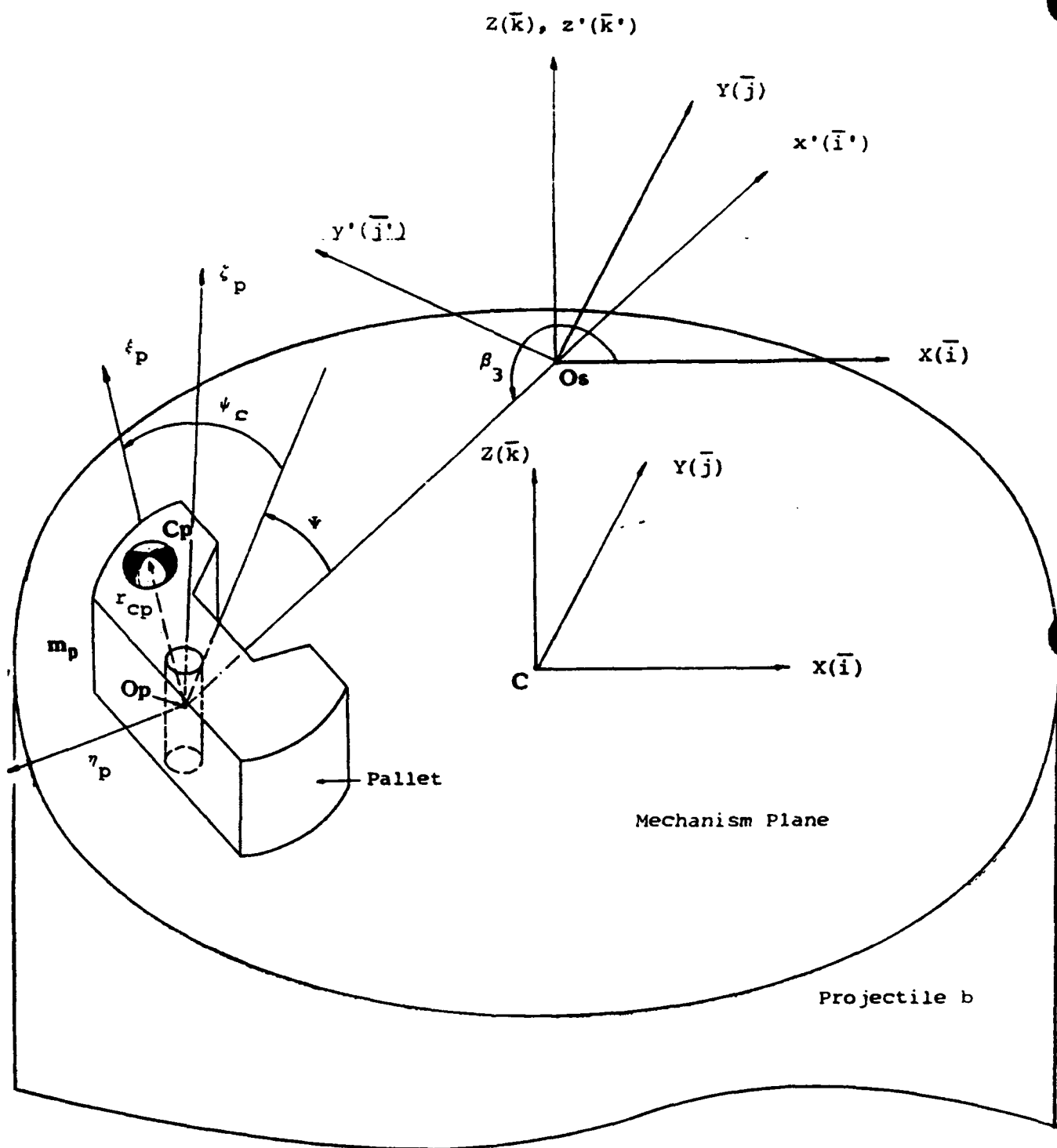


Figure A-2. Pallet-fixed ξ_p - η_p - ζ_p coordinate system

and

$$\bar{n}_{\eta_p} = \sin \alpha' \bar{i} - \cos \alpha' \bar{j} \quad (A-15)$$

where

$$\alpha' = \psi + \psi_c + \beta_3 \quad (A-16)$$

Because of the given parallel axes

$$\bar{n}_{\zeta_p} = \bar{k}' = \bar{k} \quad (A-17)$$

If the relative angular velocity of the pallet P with respect to the projectile b is given by

$$\bar{\omega}_{p/b} = \dot{\psi} \bar{n}_{\zeta_p} \quad (A-18)$$

then its absolute angular velocity $\bar{\omega}_{p/a}$ is given by

$$\bar{\omega}_{p/a} = \bar{\omega}_{p/b} + \bar{\omega}_{b/a} \quad (A-19)$$

To express equation A-16 in pallet-fixed terms, it is necessary to transform equation A-1 which gave $\bar{\omega}_{b/a}$. According to equations A-14 and A-15

$$\bar{i} = -\cos \alpha' \bar{n}_{\xi_p} + \sin \alpha' \bar{n}_{\eta_p} \quad (A-20)$$

and

$$\bar{j} = -\sin \alpha' \bar{n}_{\xi_p} - \cos \alpha' \bar{n}_{\eta_p} \quad (A-21)$$

Thus, one obtains in the pallet fixed system

$$\begin{aligned} \bar{\omega}_{b/a} = & \left[\omega_x \cos \alpha' + \omega_y \sin \alpha' \right] \bar{n}_{\xi_p} + \left[\omega_x \sin \alpha' - \omega_y \cos \alpha' \right] \bar{n}_{\eta_p} \\ & + \omega_z \bar{n}_{\zeta_p} \end{aligned} \quad (A-22)$$

Finally, the absolute angular velocity of the pallet $\bar{\omega}_{p/a}$ becomes with equations A-18 and A-19

$$\bar{\omega}_{p/a} = \omega_{\xi_p} \bar{n}_{\xi_p} + \omega_{\eta_p} \bar{n}_{\eta_p} + \omega_{\zeta_p} \bar{n}_{\zeta_p} \quad (A-23)$$

where

$$\omega_{\xi_p} = -(\omega_x \cos \alpha' + \omega_y \sin \alpha') \quad (\text{A-24})$$

$$\omega_{\eta_p} = \omega_x \sin \alpha' - \omega_y \cos \alpha' \quad (\text{A-25})$$

$$\omega_{\zeta_p} = \omega_z + \dot{\psi} \quad (\text{A-26})$$

The absolute angular acceleration $\ddot{\omega}_{p/a}$ of the pallet is obtained by the differentiation with respect to time of the measure numbers of equation A-23, i.e.,

$$\ddot{\omega}_{p/a} = \dot{\omega}_{\xi_p} \bar{n}_{\xi_p} + \dot{\omega}_{\eta_p} \bar{n}_{\eta_p} + \dot{\omega}_{\zeta_p} \bar{n}_{\zeta_p} \quad (\text{A-27})$$

where

$$\dot{\omega}_{\xi_p} = -(\dot{\omega}_x \cos \alpha' - \omega_x \dot{\psi} \sin \alpha' + \dot{\omega}_y \sin \alpha' + \omega_y \dot{\psi} \cos \alpha') \quad (\text{A-28})$$

$$\dot{\omega}_{\eta_p} = \dot{\omega}_x \sin \alpha' + \omega_x \dot{\psi} \cos \alpha' - \dot{\omega}_y \cos \alpha' + \omega_y \dot{\psi} \sin \alpha' \quad (\text{A-29})$$

$$\dot{\omega}_{\zeta_p} = \dot{\omega}_z + \dot{\psi} \quad (\text{A-30})$$

Rotor-Fixed Coordinates

The relationship between the rotor-fixed $\xi_1 - \eta_1 - \zeta_1$ system and the projectile fixed X-Y-Z system is shown in figure A-3 (see also ref 1). The $\xi_1 - \eta_1$ plane is parallel to the X-Y plane and contains the center of mass C_1 of the rotor (referred to as link 1 below). The ξ_1 -axis connects the point O_1 on the rotor pivot centerline and point C_1 .

The rotor angles ϕ_{1RC} and ϕ_{1R} are measured in the $\xi_1 - \eta_1$ plane. ϕ_{1RC} represents the initial position of the ξ_1 -axis, i.e. the ξ_{10} axis, with respect to the x-axis.

The unit vector associated with the rotor-fixed system are given by

$$\bar{n}_{\xi_1} = \cos (\phi_{1RC} + \phi_{1R}) \bar{i} + \sin (\phi_{1RC} + \phi_{1R}) \bar{j} \quad (\text{A-31})$$

$$\bar{n}_{\eta_1} = -\sin (\phi_{1RC} + \phi_{1R}) \bar{i} + \cos (\phi_{1RC} + \phi_{1R}) \bar{j} \quad (\text{A-32})$$

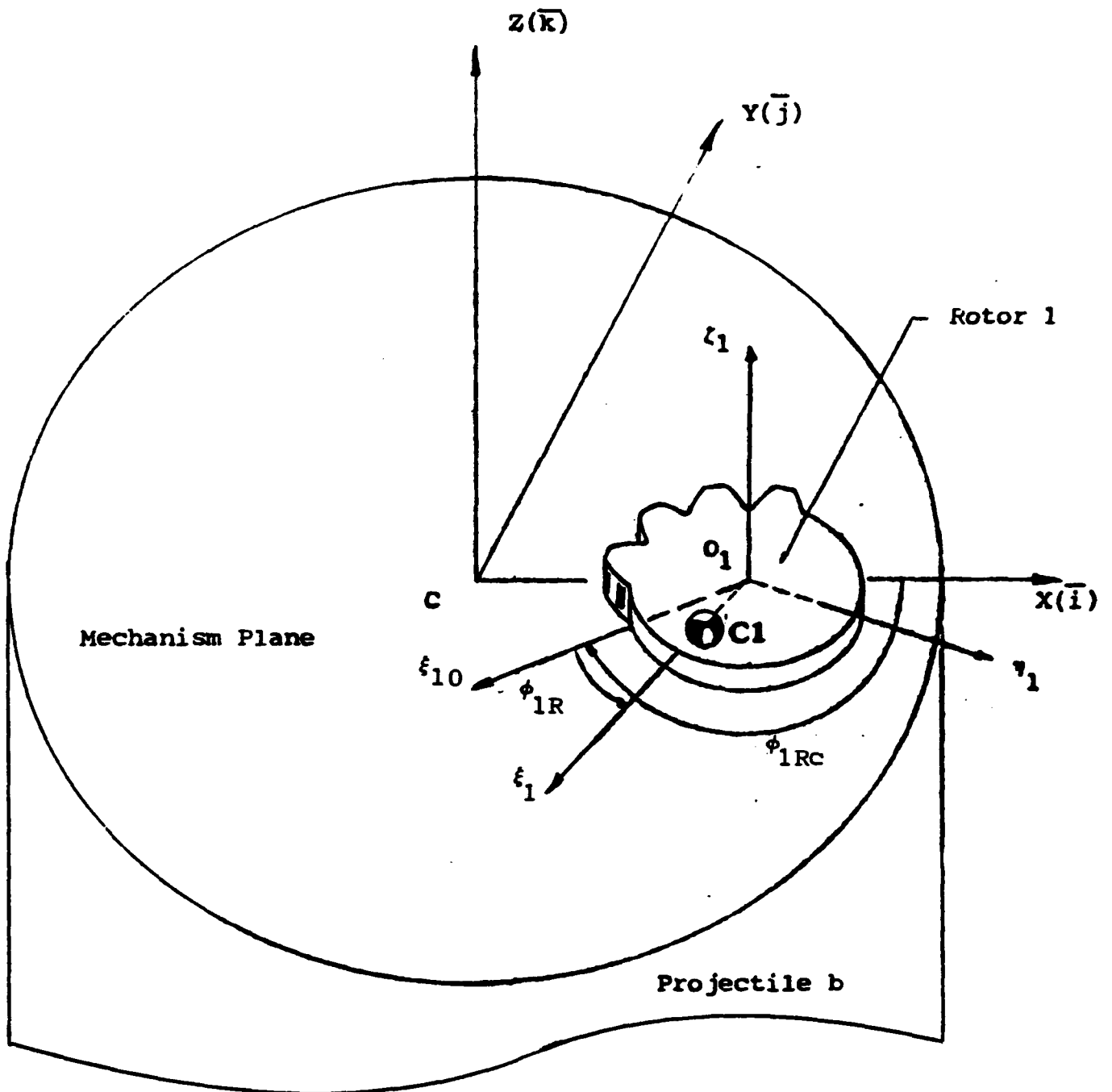


Figure A-3. Rotor-fixed ξ_1 - η_1 - ζ_1 coordinate system

and

$$\bar{n}_{\zeta_1} = \bar{k} \quad (A-33)$$

The effect of the gear train on the relationship between the angle ϕ_{1R} and the total escape wheel angle ϕ_T will presently be neglected. It is more complicated for clock gearing than for involute gearing (see ref 2, eq B123), and will be discussed in detail in Appendix F. Then with

$$\gamma = \phi_{1RC} + \phi_{1R} \quad (A-34)$$

The absolute angular velocity $\bar{\omega}_{b/a}$ of the projectile is expressed in terms of the rotor fixed coordinates with the help of equations A-1 and A-31 to A-33

$$\begin{aligned} \bar{\omega}_{b/a} &= \omega_x \bar{i} + \omega_y \bar{j} + \omega_z \bar{k} \\ &= \omega_x (\cos \gamma \bar{n}_{\xi_1} - \sin \gamma \bar{n}_{\eta_1}) + \omega_y (\sin \gamma \bar{n}_{\xi_1} + \cos \gamma \bar{n}_{\eta_1}) + \omega_z \bar{n}_{\zeta_1} \end{aligned}$$

or

$$\begin{aligned} \bar{\omega}_{b/a} &= [\omega_x \cos \gamma + \omega_y \sin \gamma] \bar{n}_{\xi_1} + [-\omega_x \sin \gamma + \omega_y \cos \gamma] \bar{n}_{\eta_1} \\ &\quad + \omega_z \bar{n}_{\zeta_1} \end{aligned} \quad (A-35)$$

To obtain the total angular velocity $\bar{\omega}_{1/a}$ of the rotor, its relative angular velocity $\bar{\omega}_{1/a} = \dot{\phi}_1 \bar{n}_{\zeta_1}$ must be added vectorially to equation A-35

$$\bar{\omega}_{1/a} = \bar{\omega}_{b/a} + \dot{\phi}_1 \bar{n}_{\zeta_1} \quad (A-36)$$

Then, with equation A-33

$$\bar{\omega}_{1/a} = \omega_{\xi_1} \bar{n}_{\xi_1} + \omega_{\eta_1} \bar{n}_{\eta_1} + \omega_{\zeta_1} \bar{n}_{\zeta_1} \quad (A-37)$$

where

$$\omega_{\xi_1} = \omega_x \cos \gamma + \omega_y \sin \gamma \quad (A-38)$$

$$\omega_{\eta_1} = -\omega_x \sin \gamma + \omega_y \cos \gamma \quad (A-39)$$

$$\omega_{\zeta_1} = \omega_z + \dot{\phi}_1 \quad (\text{A-40})$$

To obtain the absolute angular acceleration $\bar{\omega}_{1/a}$ of the rotor, differentiate the measure numbers of equation A-37 with respect to time. Therefore,

$$\bar{\omega}_{1/a} = \dot{\omega}_{\xi_1} \bar{n}_{\xi_1} + \dot{\omega}_{\eta_1} \bar{n}_{\eta_1} + \dot{\omega}_{\zeta_1} \bar{n}_{\zeta_1} \quad (\text{A-41})$$

where

$$\dot{\omega}_{\xi_1} = \dot{\omega}_x \cos \gamma - \omega_x \dot{\phi}_1 \sin \gamma + \dot{\omega}_y \sin \gamma + \omega_y \dot{\phi}_1 \cos \gamma \quad (\text{A-42})$$

$$\dot{\omega}_{\eta_1} = -\dot{\omega}_x \sin \gamma - \omega_x \dot{\phi}_1 \cos \gamma + \dot{\omega}_y \cos \gamma - \omega_y \dot{\phi}_1 \sin \gamma \quad (\text{A-43})$$

$$\dot{\omega}_{\zeta_1} = \dot{\omega}_z + \dot{\phi}_1 \quad (\text{A-44})$$

TWO EQUIVALENT METHODS FOR OBTAINING EXPRESSIONS FOR ABSOLUTE ANGULAR VELOCITIES AND ACCELERATIONS OF COMPONENTS, SUCH AS THE PALLET, IN TERMS OF PROJECTILE-FIXED COORDINATES

An example, ref 1 on pages 31-33 shows two equivalent methods for obtaining the absolute angular velocity and acceleration of the pallet in terms of the projectile-fixed $x'-y'z'$ system.

The first of these consists simply of the substitution of the unit vectors of eqs A-11 to A-13 into expressions A-23 and A-27, respectively.

The second method, which produces the identical results, interprets the relative angular velocity vector as a variable vector in the primed system. The absolute angular velocity of the pallet is obtained from

$$\bar{\omega}_{p/a_{x'y'z'}} = \dot{\psi} \bar{k}' + \bar{\omega}_{b/a_{x'y'z'}} \quad (\text{A-45})$$

The absolute angular acceleration results from the application of the appropriate carrier-fixed rule of differentiation

$$\bar{\omega}_{p/a_{x'y'z'}} = \dot{\psi} \bar{k}' + \bar{\omega}_{b/a_{x'y'z'}} \times \dot{\psi} \bar{k}' + \bar{\omega}_{b/a_{x'y'z'}} \quad (\text{A-46})$$

(See also eq B-9 in appendix B.)

REFERENCES

1. Tepper, F. R. and Lowen, G. G., "Computer Simulation of Artillery Safing and Arming Mechanism in Aeroballistic Environment (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-83050, ARDC, Dover, NJ, July 1984.
2. Lowen, G. G. and Tepper, F. R., "Computer Simulation of Artillery S&A Mechanisms (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-82013, ARRADCOM, Dover, NJ, November 1982.

APPENDIX B

**ANGULAR MOMENTUM AND ITS DERIVATIVES IN VARIOUS
COORDINATE SYSTEMS**

ANGULAR MOMENTUM EXPRESSION

The angular momentum vector $\bar{H}_0$, with respect to a point 0, has the general expression

$$\begin{aligned}\bar{H}_0 = & [I_{xx}\omega_x - I_{xy}\omega_y - I_{zx}\omega_z]\bar{i} + [-I_{xy}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z]\bar{j} \\ & + [-I_{zx}\omega_x - I_{yz}\omega_y + I_{zz}\omega_z]\bar{k}\end{aligned}\quad (B-1)$$

The above holds for all types of body-fixed and space-fixed coordinate systems. If principal axes are involved, the products of inertia vanish. Note that the angular velocity component must be absolute.

Derivative of Body-Fixed Angular Momentum Vector: Torque Equation

Body b in general motion is shown in figure B-1. It contains the body fixed X-Y-Z system and its angular momentum may be expressed with the help of equation B-1.

The time derivative of the angular momentum with respect to the inertial $X_0 - Y_0 - Z_0$ system is obtained from

$$\bar{H}_{0X_0Y_0Z_0} = \frac{d}{dt}(\bar{H}_0)_{XYZ} + \bar{\omega} \times \bar{H}_0 \quad (B-2)$$

where

$\frac{d}{dt}(\bar{H}_0)_{XYZ}$ = derivative of the measure numbers in equation B-1 and

$$\bar{\omega} \times \bar{H}_0 = (\omega_x\bar{i} + \omega_y\bar{j} + \omega_z\bar{k}) \times \bar{H}_0$$

It is to be recalled at this point, that the absolute angular acceleration of body b is given by

$$\bar{\dot{\omega}} = \dot{\omega}_x\bar{i} + \dot{\omega}_y\bar{j} + \dot{\omega}_z\bar{k} \quad (B-3)$$

Both $\bar{\omega}$ and $\bar{\dot{\omega}}$ are now expressed in terms of the body fixed coordinates.

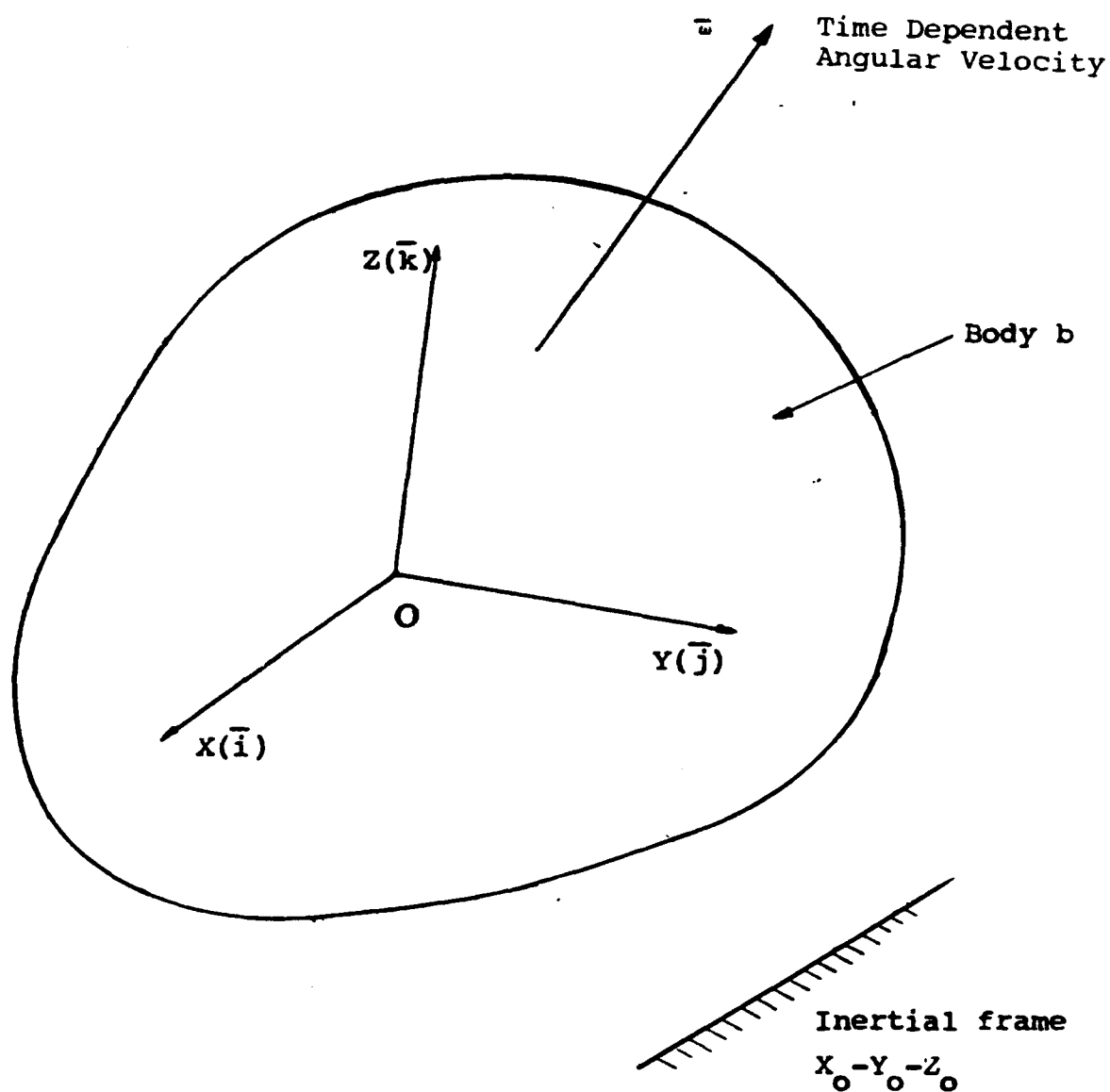


Figure B-1. Body b contains X-Y-Z system

Upon performing all operations of equation B-2, the torque equation with respect to point 0 results

$$\begin{aligned}
 \bar{M}_0 = \bar{H}_{0/X_0 Y_0 Z_0} = & [I_{xx} \dot{\omega}_x + \omega_y \omega_z (I_{zz} - I_{yy}) + I_{xy} (\omega_z \omega_x - \dot{\omega}_y) \\
 & - I_{zx} (\dot{\omega}_z + \omega_x \omega_y) - I_{yz} (\omega_y^2 - \omega_z^2)] \bar{i} \\
 & + [I_{yy} \dot{\omega}_y + \omega_x \omega_z (I_{xx} - I_{zz}) + I_{yz} (\omega_x \omega_y - \dot{\omega}_z) \\
 & - I_{xy} (\dot{\omega}_x + \omega_y \omega_z) - I_{zx} (\omega_z^2 - \omega_x^2)] \bar{j} \\
 & + [I_{zz} \dot{\omega}_z + \omega_x \omega_y (I_{yy} - I_{xx}) + I_{zx} (\omega_y \omega_z - \dot{\omega}_x) \\
 & - I_{yz} (\dot{\omega}_y + \omega_x \omega_z) - I_{xy} (\omega_x^2 - \omega_y^2)] \bar{k}
 \end{aligned} \tag{B-4}$$

When $I_{xy} = I_{yz} = I_{zx} = 0$, the above expression becomes the well known Euler torque equation.

Derivative of an Angular Momentum Vector Which is Described in Terms of the Body-Fixed System of a Carrier: Torque Equation

The carrier body b which has general rotational motion is shown in figure B-2. Its absolute angular velocity and acceleration are given in terms of the indicated body-fixed system, i.e.

$$\bar{\omega}_{b/a} = \omega_{b/ax} \bar{i} + \omega_{b/ay} \bar{j} + \omega_{b/az} \bar{k} \tag{B-5}$$

and

$$\dot{\bar{\omega}}_{b/a} = \dot{\omega}_{b/ax} \bar{i} + \dot{\omega}_{b/ay} \bar{j} + \dot{\omega}_{b/az} \bar{k} \tag{B-6}$$

respectively.

The symmetrical body c rotates about an axis parallel to the Z-axis with respect to body b with the relative angular velocity

$$\bar{\omega}_{c/b} = \omega_{c/b}(t) \bar{k} \tag{B-7}$$

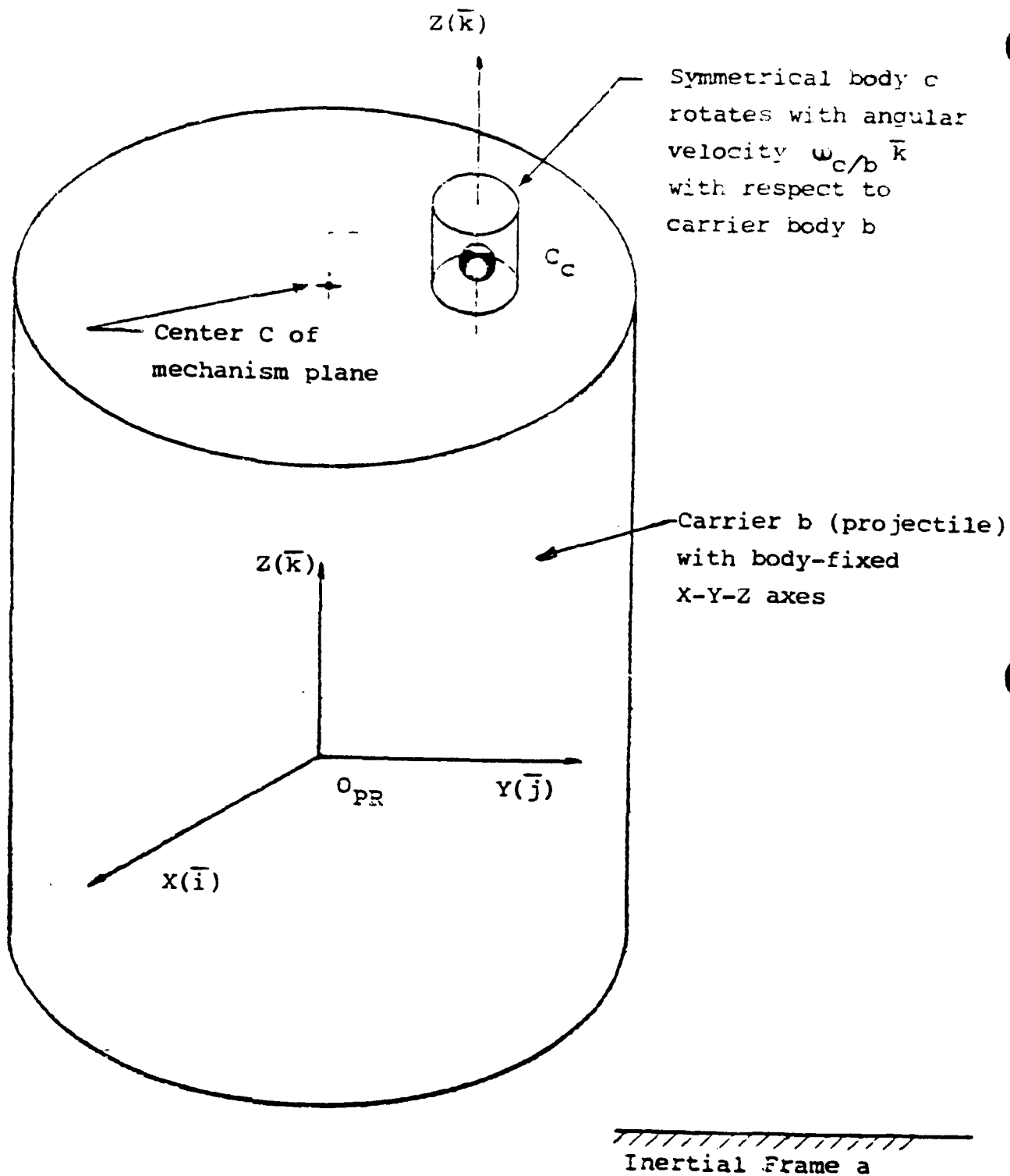


Figure B-2. Symmetrical body c has relative rotation about Z-axis with respect to carrier b

If the absolute angular velocity vector $\bar{\omega}_{c/a}$ of this body c is expressed in terms of the carrier-fixed X-Y-Z system, the following results

$$\bar{\omega}_{c/a} = \bar{\omega}_{c/b} + \bar{\omega}_{b/a} \quad (B-8)$$

(For comparison see equation A-45.)

To obtain the absolute angular velocity $\bar{\omega}_{c/a}$ in terms of the projectile-fixed system, interpret $\omega_{c/b}$ as a variable vector in the X-Y-Z system. Then,

$$\bar{\dot{\omega}}_{c/a_{x_o y_o z_o}} = \bar{\dot{\omega}}_{c/b} + \bar{\omega}_{b/a} \times \bar{\omega}_{c/b} + \bar{\dot{\omega}}_{b/a} \quad (B-9)$$

where

$\bar{\dot{\omega}}_{c/a} = \dot{\omega}_{c/b} \bar{k}$, the relative angular acceleration of component C with respect to projectile b

$\bar{\dot{\omega}}_{b/a}$ = given by equation B-6

Because body c is symmetrical, its products of inertia with respect to its center of mass C_c are zero. This symmetry also makes it possible to express its angular momentum with respect to point C_c in terms of the body-fixed system of the carrier b. (Regardless of the angle of body c with respect to body b, the moments of inertia I_{xx} and I_{yy} , expressed in terms of body b, remain invariant.) The angular momentum vector, with respect to point C_c , appropriately reduced, becomes according to equations B-1 and B-8

$$\bar{H}_{C_c} = I_{xx}\omega_{b/ax}\bar{i} + I_{yy}\omega_{b/ay}\bar{j} + I_{zz}(\omega_{b/az} + \omega_{c/b})\bar{k} \quad (B-10)$$

The vector $\bar{H}_{C_c}$ must be interpreted as a variable vector in the carrier-fixed coordinate system. Its time derivative with respect to the initial system is therefore obtained by the following operations

$$\bar{\dot{H}}_{C_{c_{x_o y_o z_o}}} = \frac{d}{dt}(\bar{H}_{C_c})_{XYZ} + \bar{\omega}_{b/a} \times \bar{H}_{C_c} \quad (B-11)$$

When applied to equation B-10, the following is obtained

$$\begin{aligned}
 \bar{H}_{C_{ox_0y_0z_0}} &= I_{xx} \dot{\omega}_{b/ax} \bar{i} + I_{yy} \dot{\omega}_{b/ay} \bar{j} + I_{zz} (\dot{\omega}_{b/az} + \dot{\omega}_{c/b}) \bar{k} \\
 &+ (\omega_{b/ax} \bar{i} + \omega_{b/ay} \bar{j} + \omega_{b/az} \bar{k}) \times [I_{xx} \omega_{b/ax} \bar{i} + I_{yy} \omega_{b/ay} \bar{j} \\
 &+ I_{zz} (\omega_{b/az} + \omega_{c/b}) \bar{k}]
 \end{aligned} \tag{B-12}$$

The above becomes the torque equation with respect to point C_c

$$\begin{aligned}
 \bar{H}_{C_{ox_0y_0z_0}} &= \bar{M}_{C_c} = [I_{xx} \dot{\omega}_{b/ax} + I_{zz} \omega_{b/ay} (\omega_{b/az} + \omega_{c/b}) - I_{yy} \omega_{b/ay} \omega_{b/az}] \bar{i} \\
 &+ [I_{yy} \dot{\omega}_{b/ay} + I_{xx} \omega_{b/ax} \omega_{b/az} - I_{zz} \omega_{b/ax} (\omega_{b/az} + \omega_{c/b})] \bar{j} \\
 &+ I_{zz} (\dot{\omega}_{b/az} + \dot{\omega}_{c/b}) \bar{k}
 \end{aligned} \tag{B-13}$$

APPENDIX C

ABSOLUTE ACCELERATION OF GEOMETRIC CENTER C
OF THE S&A PLANE

The relationship between the center of mass C_{PR} of the projectile and the center C of the plane, where the S&A mechanism is located¹, is shown in figure C-1. The origin O_{PR} of the projectile-fixed $X_p-Y_p-Z_p$ coordinate system lies on the geometric axis of the projectile. (The subscript P is now introduced in order to distinguish this system from the parallel X-Y-Z one, which is fixed both to the mechanism plane and the projectile.)

The geometric axis is assumed to be parallel to the spin axis of the projectile. The center of mass of the projectile, about which all rotation takes place, lies in the X_p-Y_p plane. Note that the figure shows the S&A mechanism to be in configuration 2, as seen from the tip of the projectile. The position vector from the center of mass to point C is given by

$$\bar{R} = R_x \bar{i} + R_y \bar{j} + R_z \bar{k} \quad (C-1)$$

It is assumed that the deceleration of the center of mass due to drag is only in the Z-direction and that it is given by

$$\bar{A}_{C_{PR}/\text{ground}} = \ddot{Z} \bar{k} \quad (C-2)$$

The absolute acceleration $\bar{A}_{C/\text{ground}}$ of point C, may then be obtained from

$$\bar{A}_{C/\text{ground}} = \bar{A}_{C_{PR}/\text{ground}} + \bar{\omega} \times (\bar{\omega} \times \bar{R}) + \dot{\bar{\omega}} \times \bar{R} \quad (C-3)$$

where $\bar{\omega}$ and $\dot{\bar{\omega}}$ are obtained from equations A-1 and A-5, respectively. (For clarity they were designated as $\bar{\omega}_{b/a}$ and $\dot{\bar{\omega}}_{b/a}$ in appendix A.)

When the operations of equation C-3 are carried out and equation C-2 is substituted, the following is obtained

$$\bar{A}_{C/\text{ground}} = G_x \bar{i} + G_y \bar{j} + G_z \bar{k} \quad (C-4)$$

where

$$G_x = (\omega_y R_y + \omega_z R_z) \omega_x - (\omega_y^2 + \omega_z^2) R_x + (\dot{\omega}_y R_z - \dot{\omega}_z R_y) \quad (C-5)$$

$$G_y = (\omega_x R_x + \omega_z R_z) \omega_y - (\omega_x^2 + \omega_z^2) R_y + (\dot{\omega}_z R_x - \dot{\omega}_x R_z) \quad (C-6)$$

$$G_z = (\omega_x R_x + \omega_y R_y) \omega_z - (\omega_x^2 + \omega_y^2) R_z + (\dot{\omega}_x R_y - \dot{\omega}_y R_x) + \ddot{Z} \quad (C-7)$$

¹Note that in figure C-1 the S&A mechanism is located on the topside of the mechanism plane.

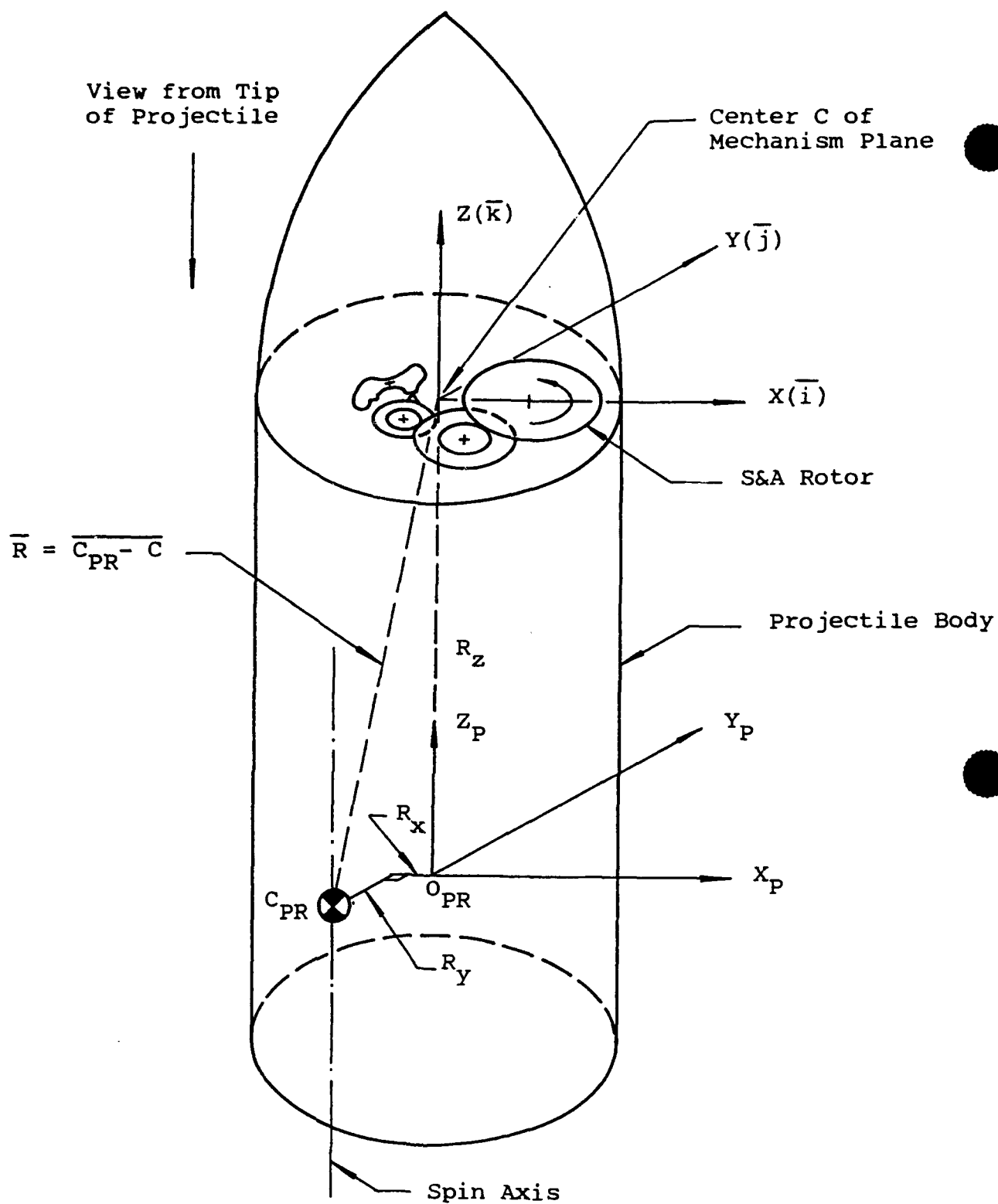


Figure C-1. Relationship between center of mass C_{PR} of projectile and center **C** of mechanism plane. S&A is in configuration 2 as seen from the tip of the projectile. (S&A is located on upper side of the mechanism plane).

APPENDIX D

DYNAMICS OF ROTOR-DRIVEN S&A MECHANISM WITH A TWO-PASS CLOCK GEAR TRAIN AND A VERGE RUNAWAY ESCAPEMENT OPERATING IN AN AEROBALLISTIC ENVIRONMENT

FUZE BODY CONFIGURATIONS AND THEIR RELATIONSHIPS TO PROJECTILE GEOMETRY

All the following expressions of the present simulation are directly applicable to the two fuze body configurations of references 1 and 2, as long as the involved S&A mechanisms appear in these configurations, with the rotor turning counterclockwise (ccw), when seen from the tip of the projectile toward its bottom (fig. C-1).

The S&A mechanism of the M577 fuze is located in its projectile so that its configuration 2, with the rotor turning ccw, becomes discernible only when an observer looks at it from the bottom of the projectile towards its tip.¹ As shown in figure D-1, this construction places the Y_P and Z_P axes of the projectile-fixed system, which is used to express the kinematics of the projectile, in opposite directions to the corresponding axes of the mechanism plane-fixed X-Y-Z system.

To be able to apply all the following simulation expressions to this situation, i.e., to be able to work in the mechanism plane system as shown in appendix G, it is necessary to reverse the signs of the Y and Z component values of the projectile angular velocity (eq. A-1) and angular acceleration (eq. A-5). Similarly, the signs of the Y and Z components of vector R (eq. C-1) and of the drag deceleration (eq. C-2) must be reversed.

All work concerning fuze body angles, as given in reference 3, is applicable regardless of the position of the S&A in the projectile as long as the fuze body has configuration 1 or 2.

DYNAMICS OF ESCAPEMENT IN COUPLED MOTION

Absolute Acceleration of Pallet Pivot O_p

The position of the pallet pivot O_p with respect to the geometric center C of the mechanism plane is shown in figure D-2. In addition, the relationship of the projectile-fixed $x'-y'-z'$ system to the mechanism plane-fixed X-Y-Z system is indicated.

¹In figure D-1 the S&A mechanism is located on the underside of the mechanism plane.

View from Bottom
of Projectile

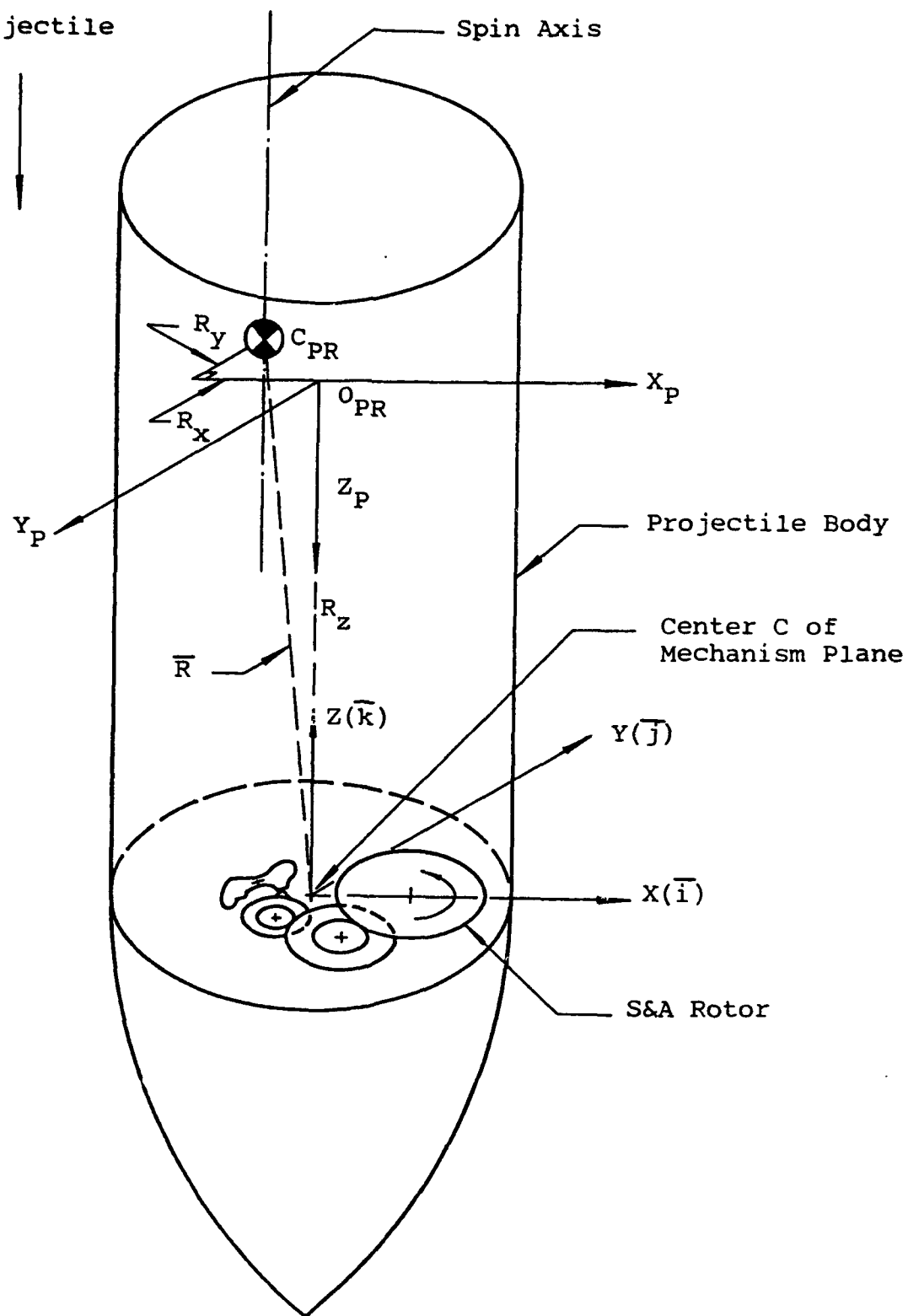


Figure D-1. Relationship between X_P - Y_P - Z_P system and mechanism plane fixed X - Y - Z system in M577 S&A. Configuration 2 is seen from bottom of projectile. (S&A is located on the underside of the mechanism plane.)

The absolute acceleration of point O_p is given by

$$\bar{A}_{O_p/\text{ground}} = \bar{A}_{O_p/C} + \bar{A}_{C/\text{ground}} \quad (\text{D-1})$$

where, $\bar{A}_{C/\text{ground}}$ is given by equation C-4 of appendix C and

$$\bar{A}_{O_p/C} = \bar{\omega} \times (\bar{\omega} \times \bar{\mathcal{R}}_4) + \bar{\dot{\omega}} \times \bar{\mathcal{R}}_4$$

In the above, $\bar{\omega}$ and $\bar{\dot{\omega}}$ are obtained from equations (A-1) and (A-5) respectively, and

$$\bar{\mathcal{R}}_4 = \mathcal{R}_4 \bar{n}_4 \quad (\text{D-3})$$

where, in the primed coordinate system (see ref 3 for configuration angles)

$$\bar{n}_4 = \cos \gamma_p' \bar{i}' + \sin \gamma_p' \bar{j}' \quad (\text{D-4})$$

After transformation into the X-Y-Z system with the help of equations (A-9) and (A-10) and some trigonometric rearrangement, the following is obtained

$$\bar{n}_4 = -\cos(\gamma_p' + \beta_3) \bar{i} - \sin(\gamma_p' + \beta_3) \bar{j} \quad (\text{D-5})$$

Equation D-3 may now be written as

$$\bar{\mathcal{R}}_4 = \mathcal{R}_{4x} \bar{i} + \mathcal{R}_{4y} \bar{j} = -\mathcal{R}_4 \cos(\gamma_p' + \beta_3) \bar{i} - \mathcal{R}_4 \sin(\gamma_p' + \beta_3) \bar{j} \quad (\text{D-6})$$

With the above, equation D-2 is now evaluated

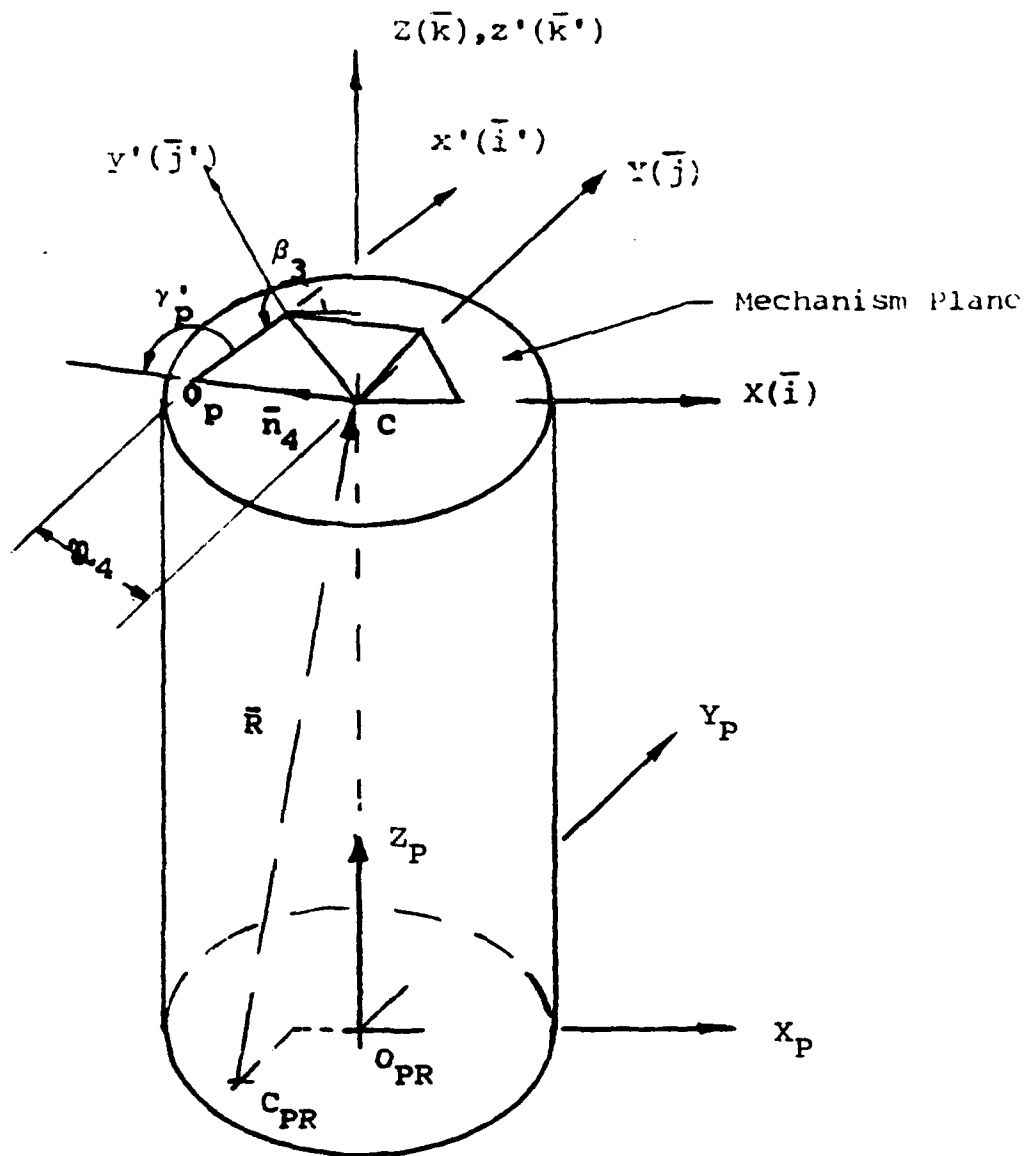
$$\bar{A}_{O_p/C} = H_x \bar{i} + H_y \bar{j} + H_z \bar{k} \quad (\text{D-7})$$

where

$$H_x = [\mathcal{R}_{4y} \omega_x \omega_y - \mathcal{R}_{4x} (\omega_y^2 + \omega_z^2) - \mathcal{R}_{4y} \dot{\omega}_z] \quad (\text{D-8})$$

$$H_y = [\mathcal{R}_{4x} \omega_x \omega_y - \mathcal{R}_{4y} (\omega_x^2 + \omega_z^2) - \mathcal{R}_{4x} \dot{\omega}_z] \quad (\text{D-9})$$

$$H_z = [(\mathcal{R}_{4x} \omega_x + \mathcal{R}_{4y} \omega_y) \omega_z + (\mathcal{R}_{4y} \dot{\omega}_x - \mathcal{R}_{4x} \dot{\omega}_y)] \quad (\text{D-10})$$



C_{PR} = Projectile Center of Mass

C = Geometric Center of Mechanism Plane

Figure D-2. Relationship between mechanism plane-fixed $x'-y'-z'$ and $X-Y-Z$ systems (the mechanism plane is part of projectile)

The acceleration $\bar{A}_{O_p/\text{ground}}$ is evaluated according to equation D-1 with the help of equations C-4 and D-7, i.e.,

$$\bar{A}_{O_p/\text{ground}} = (G_x + H_x)\bar{i} + (G_y + H_y)\bar{j} + (G_z + H_z)\bar{k} \quad (\text{D-11})$$

For later computational convenience, the above expression is transformed into the $x'-y'-z'$ system

$$\bar{A}_{O_p/\text{ground}} = K_x\bar{i}' + K_y\bar{j}' + K_z\bar{k}' \quad (\text{D-12})$$

where

$$K_x = (G_x + H_x) \cos \beta_3 - (G_y + H_y) \sin \beta_3 \quad (\text{D-13})$$

$$K_y = (G_x + H_x) \sin \beta_3 - (G_y + H_y) \cos \beta_3 \quad (\text{D-14})$$

$$K_z = G_z + H_z \quad (\text{D-15})$$

Acceleration of Pallet Center of Mass C_p with Respect to Pallet Pivot O_p

When the relative acceleration of the pallet center or mass with respect to the pallet pivot is formulated in terms of the pallet-fixed $\xi_p - \eta_p - \zeta_p$ coordinate system, the following is obtained (fig. D-3):

$$\bar{A}_{C_p/O_p} = \bar{\omega}_{p/a} \times (\bar{\omega}_{p/a} \times r_{cp} \bar{n}_{\xi_p}) + \bar{\omega}_{p/a} \times r_{cp} \bar{n}_{\xi_p} \quad (\text{D-16})$$

where

$$\bar{\omega}_{p/a} = \omega_{\xi_p} \bar{n}_{\xi_p} + \omega_{\eta_p} \bar{n}_{\eta_p} + \omega_{\zeta_p} \bar{n}_{\zeta_p} \quad (\text{see eq. A-23})$$

$$\dot{\bar{\omega}}_{p/a} = \dot{\omega}_{\xi_p} \bar{n}_{\xi_p} + \dot{\omega}_{\eta_p} \bar{n}_{\eta_p} + \dot{\omega}_{\zeta_p} \bar{n}_{\zeta_p} \quad (\text{see eq. A-27})$$

$$r_{cp} = O_p - C_p$$

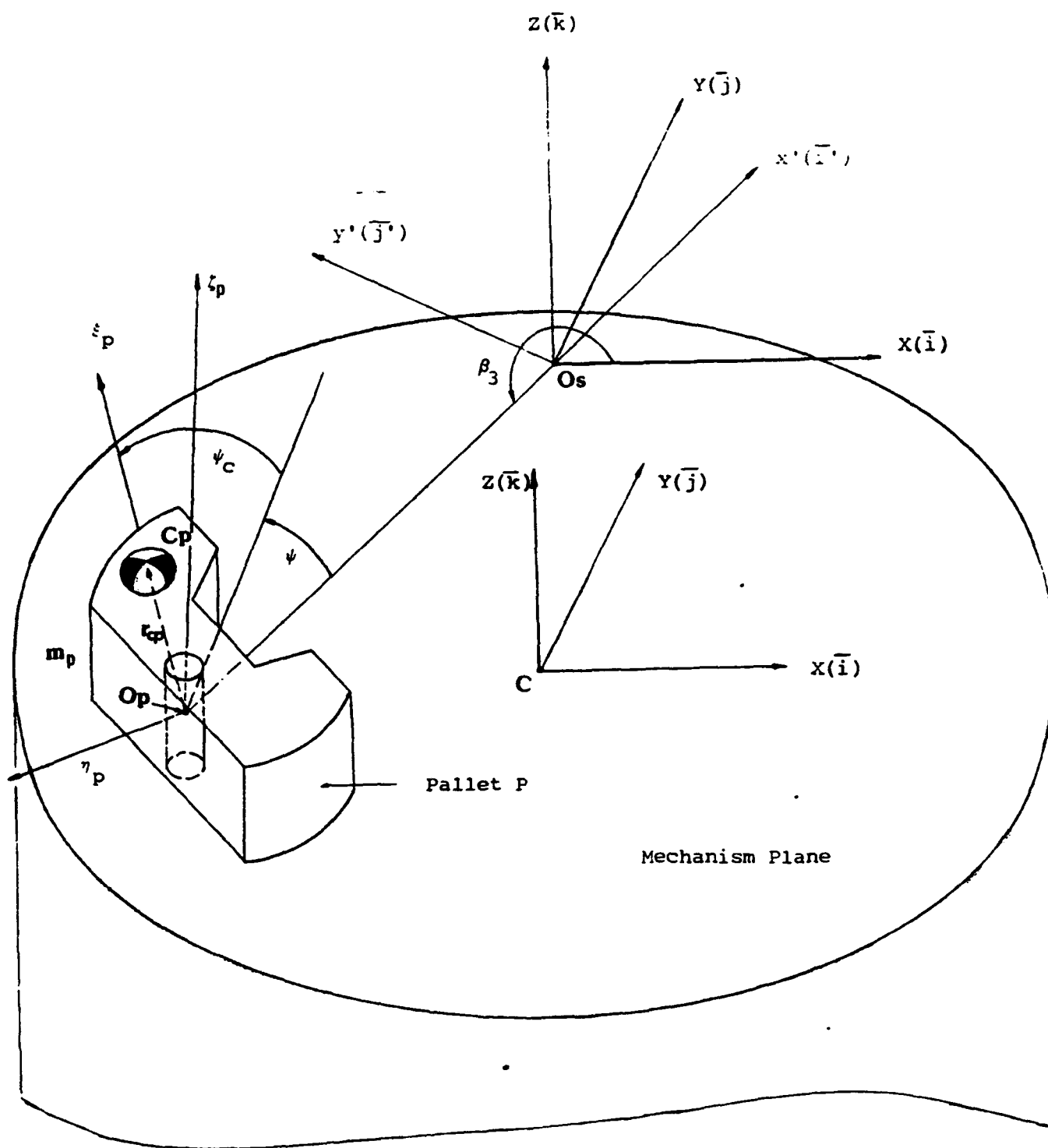


Figure D-3. Pallet center of mass C_p and pallet pivot O_p

Appropriate substitution and evaluation of equation D-16 furnishes

$$\begin{aligned}\bar{A}_{C_p/O_p} = r_{C_p} \{ & [-(\omega_x \sin \alpha' - \omega_y \cos \alpha')^2 - (\omega_z + \dot{\psi})^2] \bar{n}_{\xi_p} + [\sin \alpha' \cos \alpha' (\omega_y^2 - \omega_x^2) \\ & + \omega_x \omega_y (\cos^2 \alpha' - \sin^2 \alpha') + \dot{\omega}_z + \dot{\psi}] \bar{n}_{\eta_p} + [-\sin \alpha' (\dot{\omega}_x + 2\omega_y \dot{\psi} + \omega_y \omega_z) \\ & + \cos \alpha' (\dot{\omega}_y - 2\omega_x \dot{\psi} - \omega_x \omega_z)] \bar{n}_{\zeta_p} \} \end{aligned} \quad (D-17)$$

The above expression is now transformed into the $x'-y'-z'$ system (again for later computational convenience) with the help of equations A-11, A-12, and A-14

$$\bar{A}_{C_p/O_p} = T_x \bar{i}' + T_y \bar{j}' + T_z \bar{k}' \quad (D-18a)$$

where

$$\begin{aligned}T_x = r_{cp} [& -\omega_x^2 \sin \beta_3 \sin \alpha' - \omega_y^2 \cos \beta_3 \cos \alpha' + \omega_x \omega_y \sin (\alpha' + \beta_3) \\ & - (\omega_z + \dot{\psi})^2 \cos \beta - (\dot{\omega}_z + \dot{\psi}) \sin \beta] \end{aligned} \quad (D-18b)$$

$$\begin{aligned}T_y = r_{cp} [& -\omega_x^2 \cos \beta_3 \sin \alpha' + \omega_y^2 \sin \beta_3 \cos \alpha' + \omega_x \omega_y \cos (\alpha' + \beta_3) \\ & - (\omega_z + \dot{\psi})^2 \sin \beta + (\dot{\omega}_z + \dot{\psi}) \cos \beta] \end{aligned} \quad (D-18c)$$

$$T_z = r_{cp} [-\sin \alpha' (\dot{\omega}_x + 2\omega_y \dot{\psi} + \omega_y \omega_z) + \cos \alpha' (\dot{\omega}_y - 2\omega_x \dot{\psi} - \omega_x \omega_z)] \quad (D-18d)$$

Absolute Acceleration of Pallet Center of Mass C_p

The total acceleration of the pallet center of mass is given by

$$\bar{A}_{C_p/\text{ground}} = \bar{A}_{C_p/O_p} + \bar{A}_{O_p/\text{ground}} \quad (D-19)$$

Substitution of equations D-12 and D-18a into the above yields the following expression

$$\begin{aligned} \bar{A}_{C_p/\text{ground}} = & \{r_{cp}[-\omega_x^2 \sin\beta_3 \sin\alpha' - \omega_y^2 \cos\beta_3 \cos\alpha' + \omega_x \omega_y \sin(\alpha' + \beta_3) - (\omega_z + \dot{\psi})^2 \cos\beta \\ & - (\dot{\omega}_z + \dot{\psi}) \sin\beta] + K_x\} \bar{i}' + \{r_{cp}[-\omega_x^2 \cos\beta_3 \sin\alpha' + \omega_y^2 \sin\beta_3 \cos\alpha' - \omega_x \omega_y \\ & \cos(\alpha' + \beta_3) - (\omega_z + \dot{\psi})^2 \sin\beta + (\dot{\omega}_z + \dot{\psi}) \cos\beta] + K_y\} \bar{j}' + \{r_{cp}[-(\dot{\omega}_x + \omega_x \omega_z) \\ & \sin\alpha' + (\dot{\omega}_y - \omega_x \omega_z) \cos\alpha' - 2\dot{\psi}(\omega_x \cos\alpha' + \omega_y \sin\alpha')] + K_z\} \bar{k}' \end{aligned} \quad (D-20)$$

Signum Functions

Before deriving the equations of motion of the pallet and the escape wheel, it is necessary to introduce two signum functions which will be used to determine the directions of the friction forces at the pallet-escape wheel interface and at the pallet pivots, respectively (ref 1).

The relationship between the contact point S on the escape wheel and the coincident point T on the pallet is shown in figure D-4a. The signum function s_4 makes use of the relative velocity V_{ST} ; i.e., (see ref 1)

$$s_4 = \frac{V_{ST}}{|V_{ST}|} \quad (D-21)$$

The signum function s_5 , which is associated with pallet rotation, is defined by

$$s_5 = \frac{\dot{\psi}}{|\dot{\psi}|} \quad (D-22)$$

Pallet and Escape Wheel in Entrance Coupled Motion

A free body diagram of the pallet with the normal force P_n and the friction force μP_n acting on its entrance working surface is shown in figure D-4a. The normal and friction forces acting on the upper and lower pivots of the pallet are shown in figure D-4b. For verge nomenclature see reference 1.

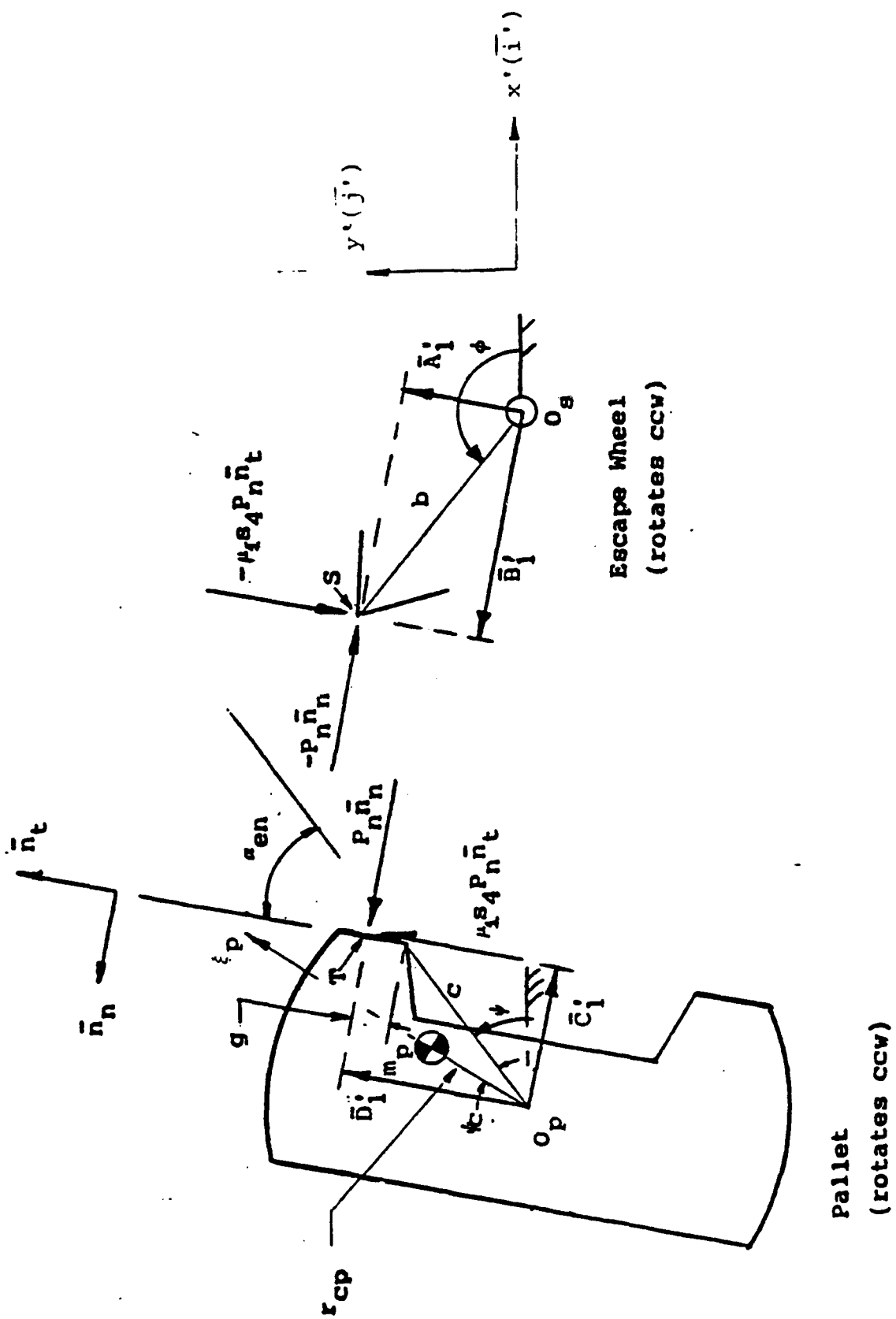


Figure D-4a. Top view free body diagram of pallet in entrance coupled motion

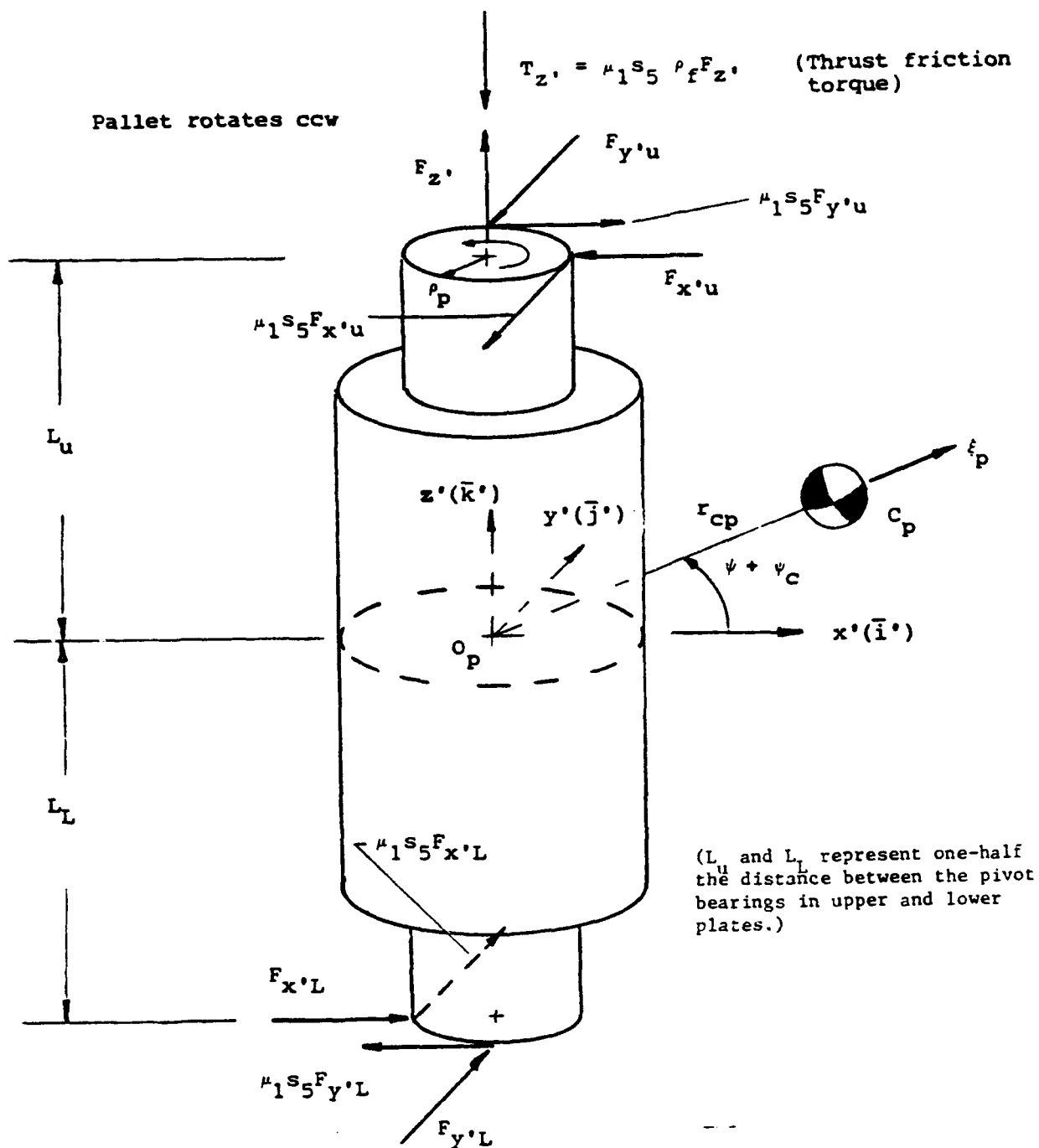


Figure D-4b. Pallet in entrance coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots.

Force Equations for Pallet

The force equations for the pallet in entrance coupled motion are obtained from Newton's law according to

$$\Sigma \vec{F} = m_p \vec{A}_{C_p/\text{ground}} \quad (\text{D-23})$$

where the acceleration $\vec{A}_{C_p/\text{ground}}$ of the pallet center of mass is given by equation D-20. The sum of the forces is obtained with the help of the figures mentioned. (For escape-ment forces, see equation B-43 of reference 1.) Equation D-23 becomes

$$\begin{aligned} P_n \bar{n}_n + \mu_1 s_4 P_n \bar{n}_t + F_z' \bar{k}' - F_{x'u} \bar{i}' - F_{y'u} \bar{j}' - \mu_1 s_5 F_{x'u} \bar{j}' + s_5 \mu_1 F_{y'u} \bar{i}' + F_{x'L} \bar{i}' + F_{y'L} \bar{j}' \\ + \mu_1 s_5 F_{x'L} \bar{j}' - \mu_1 s_5 F_{y'L} \bar{i}' = m_p \{ [r_{cp} [-\omega_x^2 \cos \beta_3 \sin \alpha' - \omega_y^2 \cos \beta_3 \cos \alpha' \\ + \omega_x \omega_y \sin(\alpha' + \beta_3) - (\omega_z + \psi)^2 \cos \beta - (\dot{\omega}_z + \dot{\psi}) \sin \beta] + K_x \} \bar{i}' \\ + \{ r_{cp} [-\omega_x^2 \cos \beta_3 \sin \alpha' + \omega_y^2 \sin \beta_3 \cos \alpha' - \omega_x \omega_y \cos(\alpha' + \beta_3) \\ - (\omega_z + \psi)^2 \sin \beta + (\dot{\omega}_z + \dot{\psi}) \cos \beta] + K_y \} \bar{j}' + \{ r_{cp} [\dot{\omega}_x + \omega_y \omega_z] \sin \alpha' \\ + (\dot{\omega}_y - \omega_x \omega_z) \cos \alpha' - 2\dot{\psi} (\omega_x \cos \alpha' + \omega_y \sin \alpha') \} + K_z \} \bar{k}' \end{aligned} \quad (\text{D-24})$$

where $F_{x'u}$ and $F_{y'u}$ are the normal force components acting on the upper pivot, $F_{x'L}$ and $F_{y'L}$ act on the lower pivot, and F_z' represents a thrust force exerted on the pivot shaft.

Note that, as in reference 1, the force and moment equations of the pallet are given in the $x'-y'-z'$ system for computation convenience.

The unit vectors $\bar{n}_t$ and $\bar{n}_n$ are expressed according to equations C-5 and C-6 of reference 1 in the primed system as follows

$$\bar{n}_t = \cos(\psi + \alpha) \bar{i}' + \sin(\psi + \alpha) \bar{j}' \quad (\text{D-25})$$

$$\bar{n}_n = -\sin(\psi + \alpha) \bar{i}' + \cos(\psi + \alpha) \bar{j}' \quad (\text{D-26})$$

The angle α is associated with the pallet and is different for entrance and exit contact.

Substitution of equations D-25 and D-26 into equation D-24 furnishes the following component expressions

x' - component of force equation

$$\begin{aligned}
 & -P_n \sin(\psi + \alpha) + \mu_1 s_4 P_n \cos(\psi + \alpha) - F_{x'u} + \mu_1 s_5 F_{y'u} + F_{x'L} - \mu_1 s_5 F_{y'L} \\
 & = m_p \{ r_{cp} [-\omega_x^2 \sin \beta_3 \sin \alpha' - \omega_y^2 \cos \beta_3 \cos \alpha' + \omega_x \omega_y \sin(\alpha' + \beta_3) \\
 & \quad - (\omega_z + \dot{\psi})^2 \cos \beta - (\dot{\omega}_z + \ddot{\psi}) \sin \beta] + K_x \}
 \end{aligned} \tag{D-27}$$

y' - component of force equation

$$\begin{aligned}
 & P_n \cos(\psi + \alpha) + \mu_1 s_4 P_n \sin(\psi + \alpha) - F_{y'u} - \mu_1 s_5 F_{x'u} + F_{y'L} + \mu_1 s_5 F_{x'L} \\
 & = m_p \{ r_{cp} [-\omega_x^2 \cos \beta_3 \sin \alpha' + \omega_y^2 \sin \beta_3 \cos \alpha' - \omega_x \omega_y \\
 & \quad \cos(\alpha' + \beta_3) - (\omega_z + \dot{\psi})^2 \sin \beta + (\dot{\omega}_z + \ddot{\psi}) \cos \beta] + K_y \}
 \end{aligned} \tag{D-28}$$

z' - component of force equation

$$\begin{aligned}
 F_{z'} & = m_p \{ r_{cp} [-(\dot{\omega}_x + \omega_y \omega_z) \sin \alpha' + (\dot{\omega}_y - \omega_x \omega_z) \cos \alpha' - 2\dot{\psi}(\omega_x \cos \alpha' \\
 & \quad + \omega_y \sin \alpha')] + K_z \}
 \end{aligned} \tag{D-29}$$

Moment Equation for the Pallet

The moment equation for the pallet must be written with respect to the accelerated pivot point O_p

$$\overline{M}_{O_p} = -\overline{A}_{O_p/\text{ground}} \times m_p r_{cp} (\cos \beta \ddot{\gamma}' + \sin \beta \ddot{\gamma}') + \overline{H}_{O_p x' y' z'} \tag{D-30}$$

where $\overline{M}_{O_p}$ is the sum of external moments about point O_p . It is assumed that O_p lies in the plane of the center of mass of the verge (normal to the verge pivot axis). It is also

assumed that the forces $\vec{P}_n$ and $\mu_1 s_4 \vec{P}_n$ lie in this plane. $\vec{A}_{O_p/\text{ground}}$ is the absolute acceleration of point O_p according to equation D-12. $\vec{H}_{O_p, x'y'z'}$ is the rate of change of the angular momentum of the verge with respect to point O_p . This expression is obtained by adapting equation B-4 to the parameters of the pallet and transforming the result into the $x'y'z'$ system.

Determination of $\vec{M}_{O_p}$

The moments due to the verge contact force $\vec{P}_n$ and the associated friction force $\mu_1 s_4 \vec{P}_n$ are taken from equation B-48 of reference 1. The moments due to the pivot forces, both normal and frictional, are obtained with the help of the figure D-4b. The symbols ρ_p and ρ_f stand for the pallet pivot radius and the pallet thrust friction radius, respectively.² Therefore,

$$\begin{aligned} \vec{M}_{O_p} = & D_1' \vec{P}_n \vec{k}' - \mu_1 s_4 C_1' \vec{P}_n \vec{k}' - \mu_1 s_5 \rho_f F_z' \vec{k}' \\ & + (L_u \vec{k}' + \rho_p \vec{j}') \times (-F_y' \vec{j}' + \mu_1 s_5 F_{y'u}' \vec{i}') \\ & + (L_u \vec{k}' + \rho_p \vec{i}') \times (-F_x' \vec{i}' - \mu_1 s_5 F_{x'u}' \vec{j}') \\ & + (-L_L \vec{k}' - \rho_p \vec{j}') \times (F_y' \vec{j}' - \mu_1 s_5 F_{y'L}' \vec{i}') \\ & + (-L_L \vec{k}' - \rho_p \vec{i}') \times (F_x' \vec{i}' + \mu_1 s_5 F_{x'L}' \vec{j}') \end{aligned} \quad (D-31)$$

The above becomes

$$\begin{aligned} \vec{M}_{O_p} = & [L_u F_{y'u}' + L_u \mu_1 s_5 F_{x'u}' + L_L F_{y'L}' + L_L \mu_1 s_5 F_{x'L}'] \vec{j}' \\ & + [L_u \mu_1 s_5 F_{y'u}' - L_u F_{x'u}' + L_L \mu_1 s_5 F_{y'L}' - L_L F_{x'L}'] \vec{i}' \\ & + [P_n (D_1' - \mu s_4 C_1') - \mu_1 \rho_f s_5 F_z' - \rho_p \mu_1 s_5 F_{y'u}' - \rho_p \mu_1 s_5 F_{x'u}' \\ & - \rho_p \mu_1 s_5 F_{y'L}' - \rho_p \mu_1 s_5 F_{x'L}'] \vec{k}' \end{aligned} \quad (D-32)$$

² Reference 3 for determination of thrust friction radius, p 268.

Determination of $\bar{A}_{O_p/ground} \underline{x m_p r_{cp}} (\cos \beta_i' + \sin \beta_j')$

With the help of equation D-12, for the above cross-product the following is obtained

$$\begin{aligned} &-(K_x \bar{i}' + K_y \bar{j}' + K_z \bar{k}') \underline{x m_p r_{cp}} (\cos \beta_i' + \sin \beta_j') \\ &= m_p r_{cp} K_z \sin \beta_i' - m_p r_{cp} K_z \cos \beta_j' - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \bar{k}' \end{aligned} \quad (D-33)$$

Determination of $\bar{H}_{O_p x' y' z'}$

As stated earlier, equation B-4 must first be adapted to the pallet-fixed coordinate system with pallet related nomenclature. This leads to

$$\begin{aligned} \bar{H}_{O_p} = & [I_{\xi \xi_p} \dot{\omega}_\xi + \omega_\eta \omega_\zeta (I_{\zeta \zeta_p} - I_{\eta \eta_p}) + I_{\xi \eta_p} (\omega_\zeta \omega_\xi - \dot{\omega}_\eta) \\ & + I_{\zeta \xi_p} (\dot{\omega}_\zeta + \omega_\xi \dot{\omega}_\eta) + I_{\eta \zeta_p} (\omega_\eta^2 - \omega_\zeta^2)] \bar{n}_{\xi_p} \\ & + [I_{\eta \eta_p} \dot{\omega}_\eta + \omega_\xi \omega_\zeta (I_{\xi \xi_p} - I_{\zeta \zeta_p}) + I_{\eta \zeta_p} (\omega_\xi \omega_\eta - \dot{\omega}_\zeta) \\ & - I_{\xi \eta_p} (\dot{\omega}_\xi + \omega_\eta \omega_\zeta) - I_{\zeta \xi_p} (\omega_\zeta^2 - \omega_\xi^2)] \bar{n}_{\eta_p} \\ & + [I_{\zeta \zeta_p} \dot{\omega}_\zeta + \omega_\xi \omega_\eta (I_{\eta \eta_p} - I_{\xi \xi_p}) + I_{\zeta \xi_p} (\omega_\eta \omega_\zeta - \dot{\omega}_\xi) \\ & - I_{\eta \zeta_p} (\dot{\omega}_\eta + \omega_\xi \omega_\zeta) - I_{\xi \eta_p} (\omega_\xi^2 - \omega_\eta^2)] \bar{n}_{\zeta_p} \end{aligned} \quad (D-34)$$

The angular velocities and accelerations of the pallet are now expressed according to equations A-24 to A-26 and equations A-28 to A-30, respectively. Subsequently, the unit vectors $\bar{n}_\xi$, $\bar{n}_\eta$, and $\bar{n}_\zeta$ are substituted according to equations A-11, A-12, and A-17.

These operations result in the following component expressions for

$$\bar{H}_{O_p x' y' z'}$$

$$\bar{H}_{O_p x'} = A_1 + A_2 \dot{\psi} + A_3 \dot{\psi}^2 + A_4 \ddot{\psi} \quad (D-35)$$

$$\bar{H}_{O_p y'} = A_5 + A_6 \dot{\psi} + A_7 \dot{\psi}^2 + A_8 \ddot{\psi} \quad (D-36)$$

$$\bar{H}_{O_p z'} = A_9 + A_{10} \ddot{\psi} \quad (D-37)$$

where

$$\begin{aligned} A_1 = & \cos\beta \{ -I_{\xi\xi_p} (\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha') + (I_{\zeta\zeta_p} - I_{\eta\eta_p}) \omega_z (\omega_x \sin\alpha' \\ & - \omega_y \cos\alpha') - I_{\xi\eta_p} [\omega_z (\omega_x \cos\alpha' + \omega_y \sin\alpha') + (\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha') \\ & + I_{\zeta\xi_p} [(\omega_x \cos\alpha' + \omega_y \sin\alpha') (\omega_x \sin\alpha' - \omega_y \cos\alpha') - \dot{\omega}_z] \\ & - I_{\eta\zeta_p} [(\omega_x \sin\alpha' - \omega_y \cos\alpha')^2 - \omega_z^2] \} - \sin\beta \{ I_{\eta\eta_p} (\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha') \\ & - (I_{\xi\xi_p} - I_{\zeta\zeta_p}) \omega_z (\omega_x \cos\alpha' + \omega_y \sin\alpha') - I_{\eta\zeta_p} [(\omega_x \cos\alpha' + \omega_y \sin\alpha') \\ & (\omega_x \sin\alpha' - \omega_y \cos\alpha') + \dot{\omega}_z] + I_{\xi\eta_p} [(\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha') - \omega_z (\omega_x \sin\alpha' \\ & - \omega_y \cos\alpha')] - I_{\zeta\xi_p} [\omega_z^2 - (\omega_x \cos\alpha' + \omega_y \sin\alpha')^2] \} \end{aligned} \quad (D-38)$$

$$\begin{aligned} A_2 = & (\omega_x \sin\alpha' - \omega_y \cos\alpha') [(I_{\xi\xi_p} + I_{\zeta\zeta_p} - I_{\eta\eta_p}) \cos\beta + 2 I_{\xi\eta_p} \sin\beta] \\ & - (\omega_x \cos\alpha' + \omega_y \sin\alpha') [2 I_{\xi\eta_p} \cos\beta + (I_{\eta\eta_p} - I_{\xi\xi_p} + I_{\zeta\zeta_p}) \sin\beta] \\ & + 2 \omega_z (I_{\eta\zeta_p} \cos\beta + I_{\zeta\xi_p} \sin\beta) \end{aligned} \quad (D-39)$$

$$A_3 = I_{\eta\zeta_p} \cos\beta + I_{\zeta\xi_p} \sin\beta \quad (D-40)$$

$$A_4 = I_{\eta\zeta_p} \sin\beta - I_{\zeta\xi_p} \cos\beta \quad (D-41)$$

$$\begin{aligned} A_5 = & \sin\beta \{ -I_{\xi\xi_p} (\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha') + (I_{\zeta\zeta_p} - I_{\eta\eta_p}) \omega_z (\omega_x \sin\alpha' \\ & - \omega_y \cos\alpha') + I_{\xi\eta_p} [-\omega_z (\omega_x \cos\alpha' + \omega_y \sin\alpha') - (\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha')] \\ & - I_{\zeta\xi_p} [-(\omega_x \cos\alpha' + \omega_y \sin\alpha')(\omega_x \sin\alpha' - \omega_y \cos\alpha') + \dot{\omega}_z] \\ & - I_{\eta\zeta_p} [(\omega_x \sin\alpha' - \omega_y \cos\alpha')^2 - \omega_z^2] \} + \cos\beta \{ I_{\eta\eta_p} (\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha') \\ & - (I_{\xi\xi_p} - I_{\zeta\zeta_p}) \omega_z (\omega_x \cos\alpha' + \omega_y \sin\alpha') + I_{\eta\zeta_p} [-(\omega_x \cos\alpha' + \omega_y \sin\alpha') \\ & (\omega_x \sin\alpha' - \omega_y \cos\alpha') - \dot{\omega}_z] - I_{\xi\eta_p} [-(\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha') + \omega_z (\omega_x \sin\alpha' \\ & - \omega_y \cos\alpha')] - I_{\zeta\xi_p} [\omega_z^2 - (\omega_x \cos\alpha' + \omega_y \sin\alpha')^2] \} \end{aligned} \quad (D-42)$$

$$\begin{aligned} A_6 = & (\omega_x \sin\alpha' - \omega_y \cos\alpha') [(I_{\xi\xi_p} + I_{\zeta\zeta_p} - I_{\eta\eta_p}) \sin\beta - 2 I_{\xi\eta_p} \cos\beta] + (\omega_x \cos\alpha' \\ & + \omega_y \sin\alpha') \left[(I_{\eta\eta_p} - I_{\xi\xi_p} + I_{\zeta\zeta_p}) \cos\beta - 2 I_{\xi\eta_p} \sin\beta \right] + 2 \omega_z (I_{\eta\zeta_p} - I_{\zeta\xi_p}) \end{aligned} \quad (D-43)$$

$$A_7 = I_{\eta\zeta_p} \sin\beta - I_{\zeta\xi_p} \cos\beta \quad (D-44)$$

$$A_8 = - (I_{\zeta\xi_p} \sin\beta + I_{\eta\zeta_p} \cos\beta) \quad (D-45)$$

$$\begin{aligned}
A_9 = & I_{\zeta\zeta_p} \dot{\omega}_z - (I_{\eta\eta_p} - I_{\xi\xi_p})[(\omega_x \cos\alpha' + \omega_y \sin\alpha')(\omega_x \sin\alpha' - \omega_y \cos\alpha')] \\
& + I_{\xi\xi_p} [\omega_z (\omega_x \sin\alpha' - \omega_y \sin\alpha') + (\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha')] \\
& - I_{\eta\zeta_p} [(\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha') - \omega_z (\omega_x \cos\alpha' + \omega_y \sin\alpha')] \\
& - I_{\xi\eta_p} [(\omega_x \cos\alpha' + \omega_y \sin\alpha')^2 - (\omega_x \sin\alpha' - \omega_y \cos\alpha')^2]
\end{aligned} \tag{D-46}$$

$$A_{10} = I_{\zeta\zeta_p} \tag{D-47}$$

Simplification of Force and Moment Equations

In order to be able to solve for the upper and lower pivot forces, both the force and moment component equations are now rewritten in an appropriate simplified form.

x'-Component of the Force Equation

Equation D-27 becomes

$$-F_{x'u} + A_{11}F_{y'u} + F_{x'L} - A_{11}F_{y'L} = A_{12} + A_{13}\dot{\psi} + A_{14}\dot{\psi}^2 + A_{15}\ddot{\psi} + P_n A_{16} \tag{D-48}$$

where

$$A_{11} = \mu_1 S_5 \tag{D-49}$$

$$\begin{aligned}
A_{12} = & m_p r_{cp} [-\omega_x^2 \sin\beta_3 \sin\alpha' - \omega_y^2 \cos\beta_3 \cos\alpha' + \omega_x \omega_y \sin(\alpha' + \beta_3) \\
& - \omega_z^2 \cos\beta - \dot{\omega}_z \sin\beta] + m_p K_x
\end{aligned} \tag{D-50}$$

$$A_{13} = -2\omega_z m_p r_{cp} \cos\beta \tag{D-51}$$

$$A_{14} = -m_p r_{cp} \cos \beta \quad (D-52)$$

$$A_{15} = -m_p r_{cp} \sin \beta \quad (D-53)$$

$$A_{16} = -[\mu_1 s_4 \cos(\psi + \alpha) - \sin(\psi + \alpha)] \quad (D-54)$$

y'-Component of the Force Equation

Equation D-28 becomes

$$-A_{11} F'_{xu} - F'_{yu} + A_{11} F'_{xL} + F'_{yL} = A_{17} + A_{18} \dot{\psi} + A_{19} \dot{\psi}^2 + A_{20} \ddot{\psi} + A_{21} P_n \quad (D-55)$$

where

$$A_{17} = m_p r_{cp} [-\omega_x^2 \cos \beta_3 \sin \alpha' + \omega_y^2 \sin \beta_3 \cos \alpha' - \omega_x \omega_y \cos(\alpha' + \beta_3) - \omega_z^2 \sin \beta + \ddot{\omega}_z \cos \beta] + m_p K_y \quad (D-56)$$

$$A_{18} = -2\omega_z m_p r_{cp} \sin \beta \quad (D-57)$$

$$A_{19} = -m_p r_{cp} \sin \beta \quad (D-58)$$

$$A_{20} = m_p r_{cp} \cos \beta \quad (D-59)$$

$$A_{21} = -[\cos(\psi + \alpha) + \mu_1 s_4 \sin(\psi + \alpha)] \quad (D-60)$$

z'-Component of the Force Equation

Equation D-29 is rewritten to read

$$\tilde{F}'_z = A_{22} + A_{23} \dot{\psi} \quad (D-61)$$

The tilde is now used to indicate the conservative nature of this force, when the terms A_{22} and A_{23} are made absolute.

Thus

$$A_{22} = |m_p r_{cp} [-\dot{\omega}_x + \omega_y \omega_z] \sin \alpha' + (\dot{\omega}_y - \omega_x \omega_z) \cos \alpha' + m_p K_d| \quad (D-62)$$

and

$$A_{23} = |-2m_p r_{cp} (\omega_x \cos \alpha' + \omega_y \sin \alpha')| \quad (D-63)$$

The absolute values in the above expressions will be useful later in equation D-123.

x'-Component of Moment Equation

The x'-component of equation D-30 is obtained with the help of the x'-components of equations D-32 and D-33, as well as equation D-35. Therefore,

$$\begin{aligned} L_u A_{11} F_{x'u} + L_u F_{y'u} + L_L A_{11} F_{x'L} + L_L F_{y'L} &= m_p r_{cp} K_z \sin \beta \\ + A_1 + \dot{\psi} A_2 + \dot{\psi}^2 A_3 + \ddot{\psi} A_4 \end{aligned} \quad (D-64)$$

y'-Component of Moment Equation

The y'-component of equation D-30 is obtained with the help of the y'-components of equations D-32 and D-33, as well as equation D-36

$$\begin{aligned} -L_u F_{x'u} + L_u A_{11} F_{y'u} + L_L F_{x'L} + L_L A_{11} F_{y'L} &= -m_p r_{cp} K_z \cos \beta \\ + A_5 + A_6 \dot{\psi} + A_7 \dot{\psi}^2 + A_8 \ddot{\psi} \end{aligned} \quad (D-65)$$

z'-Component of Moment Equation

The z'-component of equation D-30 is composed of the z'-components of equations D-32 and D-33, as well as equation D-37

$$\begin{aligned} P_n (D_1' - \mu_1 S_4 C_1') - \rho_f A_{11} F_{z'} - \rho_p A_{11} F_{y'u} - \rho_p A_{11} F_{x'u} - \rho_p A_{11} F_{y'L} - \rho_p A_{11} F_{x'L} \\ = -m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) + A_9 + A_{10} \ddot{\psi} \end{aligned} \quad (D-66)$$

Solution for the Pallet Pivot Forces. The forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$ are obtained from the simultaneous solution of equations D-48, D-55, D-64, and D-65. The force $F_{z'}$ is given by equation D-61. These five forces are eventually substituted into equation D-66, and the resulting expression is solved for the contact force P_n .

The simultaneous set of equations becomes

$$\begin{bmatrix} -1 & A_{11} & 1 & -A_{11} \\ -A_{11} & -1 & A_{11} & 1 \\ L_u A_{11} & L_u & L_L A_{11} & L_L \\ -L_u & L_u A_{11} & -L_L & L_L A_{11} \end{bmatrix} \begin{bmatrix} F_{x'u} \\ F_{y'u} \\ F_{x'L} \\ F_{y'L} \end{bmatrix} = \begin{bmatrix} B_{p1} \\ B_{p2} \\ B_{p3} \\ B_{p4} \end{bmatrix} \quad (D-67)$$

where

$$B_{p1} = A_{12} + A_{13}\dot{\psi} + A_{14}\dot{\psi}^2 + A_{15}\ddot{\psi} + P_n A_{16} \quad (D-68)$$

$$B_{p2} = A_{17} + A_{18}\dot{\psi} + A_{19}\dot{\psi}^2 + A_{20}\ddot{\psi} + P_n A_{21} \quad (D-69)$$

$$B_{p3} = m_p r_{cp} K_z \sin\beta + A_1 + A_2\dot{\psi} + A_3\dot{\psi}^2 + A_4\ddot{\psi} \quad (D-70)$$

$$B_{p4} = -m_p r_{cp} K_z \cos\beta + A_5 + A_6\dot{\psi} + A_7\dot{\psi}^2 + A_8\ddot{\psi} \quad (D-71)$$

Cramer's rule will now be used to determine the four pivot forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$. To this end, the coefficient determinant D must be found first.

Evaluation of the Coefficient Determinant D

The coefficient determinant of equation D-67 is given by

$$D = \begin{vmatrix} -1 & A_{11} & 1 & -A_{11} \\ -A_{11} & -1 & A_{11} & 1 \\ L_u A_{11} & L_u & L_L A_{11} & L_L \\ -L_u & L_u A_{11} & -L_L & L_L A_{11} \end{vmatrix} \quad (D-72)$$

Evaluation of the above furnishes

$$D = [(L_u + L_L)(1 + A_{11}^2)]^2 \quad (D-73)$$

Since, according to equation D-49

$$A_{11} = \mu_1 s_5 \quad (D-74)$$

and s_5^2 is always equal to unity (eq D-22), the coefficient determinant becomes

$$D = [(L_u + L_L)(1 + \mu_1^2)]^2 \quad (D-75)$$

Evaluation of Pivot Force $\tilde{F}_{x'u}$

The pivot force $F_{x'u}$ is obtained from

$$F_{x'u} = \frac{D_{F_{x'u}}}{D} \quad (D-76)$$

where

$$D_{F_{x'u}} = \begin{vmatrix} B_{p1} & A_{11} & 1 & -A_{11} \\ B_{p2} & -1 & A_{11} & 1 \\ B_{p3} & L_u & L_L A_{11} & L_L \\ B_{p4} & L_u A_{11} & -L_L & L_L A_{11} \end{vmatrix} \quad (D-77)$$

Evaluation of $D_{F_{x'u}}$ furnishes

$$D_{F_{x'u}} = (L_u + L_L)(1 + A_{11}^2)(-L_L B_{p1} - A_{11} L_L B_{p2} + A_{11} B_{p3} - B_{p4}) \quad (D-78)$$

After substitution of

$$A_{11}^2 = \mu_1^2 \quad (D-79)$$

the following is obtained

$$D_{F_{x'u}} = (L_u + L_L)(1 + \mu_1^2)(-L_L B_{p1} - A_{11} L_L B_{p2} + A_{11} B_{p3} - B_{p4}) \quad (D-80)$$

Subsequently, equations D-49 and D-68 to D-71 are substituted into the above and the coefficients of similar terms are collected and made absolute. The latter is done to get conservative pivot and friction forces. This leads to

$$D_{F_{x'u}} = (L_u + L_L)(1 + \mu_1^2)(C_1 + C_2 \dot{\psi} + C_3 \dot{\psi}^2 + C_4 \ddot{\psi} + C_5 P_n) \quad (D-81)$$

where

$$C_1 = |-L_L A_{12} + \mu_1 s_5 (A_1 - L_L A_{17}) - A_5 + m_p r_{cp} K_z (\mu_1 s_5 \sin \beta + \cos \beta)| \quad (D-82)$$

$$C_2 = |-L_L A_{13} + \mu_1 s_5 (A_2 - L_L A_{18}) - A_6| \quad (D-83)$$

$$C_3 = |-L_L A_{14} + \mu_1 s_5 (A_3 - L_L A_{19}) - A_7| \quad (D-84)$$

$$C_4 = |-L_L A_{15} + \mu_1 s_5 (A_4 - L_L A_{20}) - A_8| \quad (D-85)$$

$$C_5 = |-L_L A_{16} + \mu_1 s_5 L_L A_{21}| \quad (D-86)$$

Finally, substitution of equations D-75 and D-81 into equation D-76 gives the now titled pivot force

$$\tilde{F}_{x'u} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} (C_1 + C_2 \dot{\psi} + C_3 \dot{\psi}^2 + C_4 \ddot{\psi} + C_5 P_n) \quad (D-87)$$

Evaluation of Pivot Force $\tilde{F}_{y'u}$

The pivot force $\tilde{F}_{y'u}$ is obtained with Cramer's rule, i.e.,

$$\tilde{F}_{y'u} = \frac{D_{F_{y'u}}}{D} \quad (D-88a)$$

where

$$D_{F_{y'u}} = \begin{vmatrix} -1 & B_{p1} & 1 & -A_{11} \\ -A_{11} & B_{p2} & A_{11} & 1 \\ L_u A_{11} & B_{p3} & L_L A_{11} & L_L \\ -L_u & B_{p4} & L_L & L_L A_{11} \end{vmatrix} \quad (D-88b)$$

Evaluation of $D_{F_{y'u}}$ furnishes

$$D_{F_{y'u}} = (L_u + L_L)(1 + A_{11}^2)(A_{11}L_L B_{p1} - L_L B_{p2} + B_{p3} + A_{11}B_{p4}) \quad (D-89)$$

and again, with $A_{11} = s_5 \mu_1$

$$D_{F_{y'u}} = (L_u + L_L)(1 + \mu_1^2)(\mu_1 s_5 L_L B_{p1} - L_L B_{p2} + B_{p3} + \mu_1 s_5 B_{p4}) \quad (D-90)$$

Appropriate substitution into equation D-88a and proceeding in a manner parallel to that followed in the determination of $\tilde{F}_{x'u}$, the following is obtained for $\tilde{F}_{y'u}$

$$\tilde{F}_{y'u} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} (C_6 + C_7 \dot{\psi} + C_8 \dot{\psi}^2 + C_9 \ddot{\psi} + C_{10} P_n) \quad (D-91)$$

where

$$C_6 = |A_1 - L_L A_{17} + \mu_1 s_5 (L_L A_{12} + A_5) + m_p r_{cp} K_z (\sin \beta - \mu_1 s_5 \cos \beta)| \quad (D-92)$$

$$C_7 = |A_2 - L_L A_{18} + \mu_1 s_5 (A_6 + L_L A_{13})| \quad (D-93)$$

$$C_8 = |A_3 - L_L A_{19} + \mu_1 s_5 (A_7 + L_L A_{14})| \quad (D-94)$$

$$C_9 = |A_4 - L_L A_{20} + \mu_1 s_5 (L_L A_{15} - A_8)| \quad (D-95)$$

$$C_{10} = |\mu_1 s_5 L_L A_{16} - L_L A_{21}| \quad (D-96)$$

Evaluation of Pivot Force $F_{x'L}$

The pivot force $F_{x'L}$ is obtained from

$$F_{x'L} = \frac{D_{F_{x'L}}}{D} \quad (D-97)$$

where

$$D_{F_{x'L}} = \begin{vmatrix} -1 & A_{11} & B_{p1} & -A_{11} \\ -A_{11} & -1 & B_{p2} & 1 \\ L_u A_{11} & L_u & B_{p3} & L_L \\ -L_u & L_u A_{11} & B_{p4} & L_L A_{11} \end{vmatrix} \quad (D-98)$$

Evaluation of $D_{F_{x'L}}$ furnishes

$$D_{F_{x'L}} = (L_u + L_L)(1 + A_{11}^2)(L_u B_{p1} + L_u A_{11} B_{p2} + A_{11} B_{p3} - B_{p4}) \quad (D-99)$$

and again, with $A_{11} = s_5 \mu_1$

$$D_{F_{x'L}} = (L_u + L_L)(1 + \mu_1^2)(L_u B_{p1} + \mu_1 s_5 L_u B_{p2} + \mu_1 s_5 B_{p3} - B_{p4}) \quad (D-100)$$

Proceeding as before to obtain $\tilde{F}_{x'L}$, the following is found

$$\tilde{F}_{x'L} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} (C_{11} + C_{12}\dot{\psi} + C_{13}\dot{\psi}^2 + C_{14}\ddot{\psi} + C_{15}P_n) \quad (D-101)$$

where

$$C_{11} = |L_u A_{12} - A_5 + \mu_1 s_5 (L_u A_{17} + A_1) + m_p r_{cp} K_z (\mu_1 s_5 \sin \beta + \cos \beta)| \quad (D-102)$$

$$C_{12} = |L_u A_{13} - A_6 + \mu_1 s_5 (L_u A_{18} + A_2)| \quad (D-103)$$

$$C_{13} = |L_u A_{14} - A_7 + \mu_1 s_5 (L_u A_{19} + A_3)| \quad (D-104)$$

$$C_{14} = |L_u A_{15} - A_8 + \mu_1 s_5 (L_u A_{20} + A_4)| \quad (D-105)$$

$$C_{15} = |L_u A_{16} + \mu_1 s_5 L_u A_{21}| \quad (D-106)$$

Evaluation of Pivot Force $\tilde{F}_{y'L}$

The pivot force $F_{y'L}$ is obtained from

$$F_{y'L} = \frac{D_{F_{y'L}}}{D} \quad (D-107)$$

where

$$D_{F_{y'L}} = \begin{vmatrix} -1 & A_{11} & 1 & B_{p1} \\ -A_{11} & -1 & A_{11} & B_{p2} \\ L_u A_{11} & L_u & L_L A_{11} & B_{p3} \\ -L_u & L_u A_{11} & -L_L & B_{p4} \end{vmatrix} \quad (D-108)$$

Evaluation of $D_{F_{y'L}}$ furnishes

$$D_{F_{y'L}} = (L_u + L_L)(1 + A_{11}^2)(-L_u A_{11} B_{p1} + L_u B_{p2} + B_{p3} + A_{11} B_{p4}) \quad (D-109)$$

and again, with $A_{11} = s_5 \mu_1$

$$D_{F_{y'L}} = (L_u + L_L)(1 + \mu_1^2)(-\mu_1 s_5 L_u B_{p1} + L_u B_{p2} + B_{p3} + \mu_1 s_5 B_{p4}) \quad (D-110)$$

$F_{y'L}$ is found from equation D-107 in a manner shown earlier

$$\tilde{F}_{y'L} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} (C_{16} + C_{17}\dot{\psi} + C_{18}\dot{\psi}^2 + C_{19}\ddot{\psi} + C_{20}P_n) \quad (D-111)$$

where

$$C_{16} = |L_u A_{17} + A_1 + \mu_1 s_5 (A_5 - L_u A_{12}) + m_p r_{cp} K_z (\sin\beta - \mu_1 s_5 \cos\beta)| \quad (D-112)$$

$$C_{17} = |L_u A_{18} + A_2 + \mu_1 s_5 (A_6 - L_u A_{13})| \quad (D-113)$$

$$C_{18} = |L_u A_{19} + A_3 + \mu_1 s_5 (A_7 - L_u A_{14})| \quad (D-114)$$

$$C_{19} = |L_u A_{20} + A_4 + \mu_1 s_5 (A_8 - L_u A_{15})| \quad (D-115)$$

$$C_{20} = |L_u A_{21} - \mu_1 s_5 L_u A_{16}| \quad (D-116)$$

Determination of Contact Force P_n in Terms of Pallet Parameters

Substitution of Conservative (Tilded) Pivot Forces into the z' -Moment Equation. Rather than substitute the forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, $F_{y'L}$, and $F_{z'L}$ into the z' -moment equation D-66, the associated tilded, conservative expressions, as given by equations D-61, D-87, D-91, D-101, and D-111 are used. To simplify matters, let the sum of $\tilde{F}_{x'u}$, $\tilde{F}_{y'u}$, $\tilde{F}_{x'L}$, and $\tilde{F}_{y'L}$ be first determined

$$\tilde{F}_{x'u} + \tilde{F}_{y'u} + \tilde{F}_{x'L} + \tilde{F}_{y'L} = A_{24} + A_{25}\dot{\psi} + A_{26}\dot{\psi}^2 + A_{27}\ddot{\psi} + A_{28}P_n \quad (D-117)$$

where

$$A_{24} = \frac{C_1 + C_6 + C_{11} + C_{16}}{L_T(1 + \mu_1^2)} \quad (D-118)$$

$$A_{25} = \frac{C_2 + C_7 + C_{12} + C_{17}}{L_T(1 + \mu_1^2)} \quad (D-119)$$

$$A_{26} = \frac{C_3 + C_8 + C_{13} + C_{18}}{L_T(1 + \mu_1^2)} \quad (D-120)$$

$$A_{27} = \frac{C_4 + C_9 + C_{14} + C_{19}}{L_T(1 + \mu_1^2)} \quad (D-121)$$

$$A_{28} = \frac{C_5 + C_{10} + C_{15} + C_{20}}{L_T(1 + \mu_1^2)} \quad (D-122a)$$

and

$$L_T = L_u + L_L \quad (D-122b)$$

Substitution of the above, as well as equation D-61 into equation D-66, and letting $A_{11} = \mu_1 s_5$ according to equation D-49 leads to the following provisional z' -moment expression

$$\begin{aligned} P_n (D'_1 - \mu_1 s_4 C'_1) - \rho_f \mu_1 s_5 (A_{22} \pm A_{23} \dot{\psi}) - \rho_p \mu_1 s_5 (A_{24} \pm \dot{\psi} A_{25} \pm \dot{\psi}^2 A_{26} \\ \pm \ddot{\psi} A_{27} + P_n A_{28}) = -m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) + A_9 + A_{10} \ddot{\psi} \end{aligned} \quad (D-123)$$

To make sure that all friction moments act in a direction opposite to the instantaneous rotation of the pallet, the signs of those friction terms which depend on ψ , $\dot{\psi}$, or $\ddot{\psi}$ have been left undecided for the moment. They will be resolved below.

Before these decisions are made, let equation D-123 be written as follows

$$\begin{aligned} P_n (D'_1 - C'_1 \mu_1 s_4 - \rho_p \mu_1 s_5 A_{28}) - \mu_1 s_5 (\rho_f A_{22} + \rho_p A_{24}) \pm \mu_1 s_5 \\ (\rho_f A_{23} + \rho_p A_{25}) \dot{\psi} \pm \rho_p \mu_1 s_5 A_{26} \dot{\psi}^2 \pm \rho_p \mu_1 s_5 A_{27} \ddot{\psi} \\ = A_{10} \ddot{\psi} + A_9 - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \end{aligned} \quad (D-124)$$

With s_5 positive for positive rotation of the verge and vice versa and with all other parameters positive at all times, the following moment components of equation D-124 must have negative signs during positive rotation

$$-P_n \rho_p \mu_1 s_5 A_{28} \quad (D-125)$$

$$-\mu_1 s_5 (\rho_f A_{22} + \rho_p A_{24}) \quad (D-126)$$

$$-\rho_p \mu_1 s_5 A_{26} \dot{\psi}^2 \quad (D-127)$$

The sign of the term containing $\dot{\psi}$ must be negative for a positive $\dot{\psi}$ and vice versa. Therefore, the sign of $\dot{\psi}$ can be used to control the sign of this term, and the signum operator s_5 has been omitted. This term becomes

$$-\mu_1 (\rho_f A_{23} + \rho_p A_{25}) \dot{\psi} \quad (D-128)$$

The choice of sign for the term containing the pallet angular acceleration is discussed in detail in appendix F of reference 4. This work leads to the computational rules of equations D-134 and D-135 below. These rules deal with the sign in the effective moment of inertia I_{PR} . (Note that the signum function s_5 has been omitted in these expressions.)

With the above considerations, equation D-124 becomes

$$P_n A_{29} - A_{30} - A_{31} \dot{\psi} - A_{32} \dot{\psi}^2 = I_{PR} \ddot{\psi} + A_9 - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \quad (D-129)$$

where

$$A_{29} = D'_1 - C'_1 \mu_1 s_4 - \rho_p \mu_1 s_5 A_{28} \quad (D-130)$$

$$A_{30} = \mu_1 s_5 (\rho_f A_{22} + \rho_p A_{24}) \quad (D-131)$$

$$A_{31} = \mu_1 (\rho_f A_{23} + \rho_p A_{25}) \quad (D-132)$$

$$A_{32} = \mu_1 s_5 \rho_p A_{26} \quad (D-133)$$

$$I_{PR} = I_{\zeta \zeta_p} + A_{333}, \text{ when } \dot{\psi} \text{ and } \ddot{\psi} \text{ have identical signs} \quad (D-134)$$

$$I_{PR} = I_{\zeta_{sp}} - A_{333}, \text{ when } \dot{\psi} \text{ and } \ddot{\psi} \text{ have opposite signs}^3 \quad (D-135)$$

$$A_{333} = \mu_1 \rho_p A_{27} \quad (D-136)$$

Equation D-129 is now rewritten to find an expression for the contact force P_n

$$P_n = \frac{I_{PR} \ddot{\psi} + A_9 + A_{30} + A_{31} \dot{\psi} + A_{32} \dot{\psi}^2 - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta)}{A_{29}} \quad (D-137)$$

The above expression is now changed to reflect the escape wheel angular velocity and angular acceleration $\dot{\phi}$ and $\ddot{\phi}$, respectively, so that it may later be equated to an expression for the escape wheel. Equations C-19 and C-26 of appendix C of reference 1 show the following relationships

$$\dot{\psi} = \dot{\phi} U \quad (D-138)$$

and

$$\ddot{\psi} = U \ddot{\phi} + V \dot{\phi}^2 \quad (D-139)$$

U and V may also be obtained from reference 1. This leads to

$$P_n = \frac{1}{A_{29}} [I_{PR} U \ddot{\phi} + (A_{32} U^2 + I_{PR} V) \dot{\phi}^2 + A_{31} U \dot{\phi} + A_9 + A_{30} - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta)] \quad (D-140)$$

Force Equations for Escape Wheel and Pinion No. 3 with Mesh 2 in Round-on-Round-Contact (see reference 1, for clock tooth force analysis background)

The action of the contact forces $\bar{P}_n$ and $\bar{F}_{23}$, together with their associated friction forces are shown in figure D-5a. A separate free body diagram of the pivot shaft of the escape wheel is shown in figure D-5b.

³ $I_p - A_{333}$ must not become negative. If this occurs I_{PR} must be set equal to zero.

All forces must now be expressed in terms of the mechanism plane-fixed X - Y - Z system. This makes it necessary to transform the unit vectors $\bar{n}_t$ and $\bar{n}_n$ from the X' - Y' system into the X-Y one. (See eqs B-16 and B-17, as well as eqs B-79 to B-82 of reference 1.)

Since

$$\bar{i}' = -\cos\beta_3 \bar{i} - \sin\beta_3 \bar{j} \quad (D-141)$$

and

$$\bar{j}' = \sin\beta_3 \bar{i} - \cos\beta_3 \bar{j} \quad (D-142)$$

the previous unit vectors become

$$\bar{n}_t = -\cos(\psi + \alpha + \beta_3) \bar{i} - \sin(\psi + \alpha + \beta_3) \bar{j} \quad (D-143)$$

$$\bar{n}_n = \sin(\psi + \alpha + \beta_3) \bar{i} - \cos(\psi + \alpha + \beta_3) \bar{j} \quad (D-144)$$

Further, the round-on-round contact force F_{23} has the direction of the unit $\bar{n}_{\lambda 2}$ vector so that

$$\bar{F}_{23} = F_{23} \bar{n}_{\lambda 2} \quad (D-145a)$$

where, according to equation G-48 of reference 5

$$\bar{n}_{\lambda 2} = \cos\lambda_2 \bar{i} + \sin\lambda_2 \bar{j} \quad (D-145b)$$

The associated friction force is given by

$$\bar{F}_{f23} = \mu s_{2R} F_{23} \bar{n}_{N\lambda 2} \quad (D-146)$$

where, according to eq G-49 of ref 5

$$\bar{n}_{N\lambda 2} = -\sin\lambda_2 \bar{i} + \cos\lambda_2 \bar{j} \quad (D-147)$$

The signum function s_{2R} is defined with the help of eq F-47 of appendix F

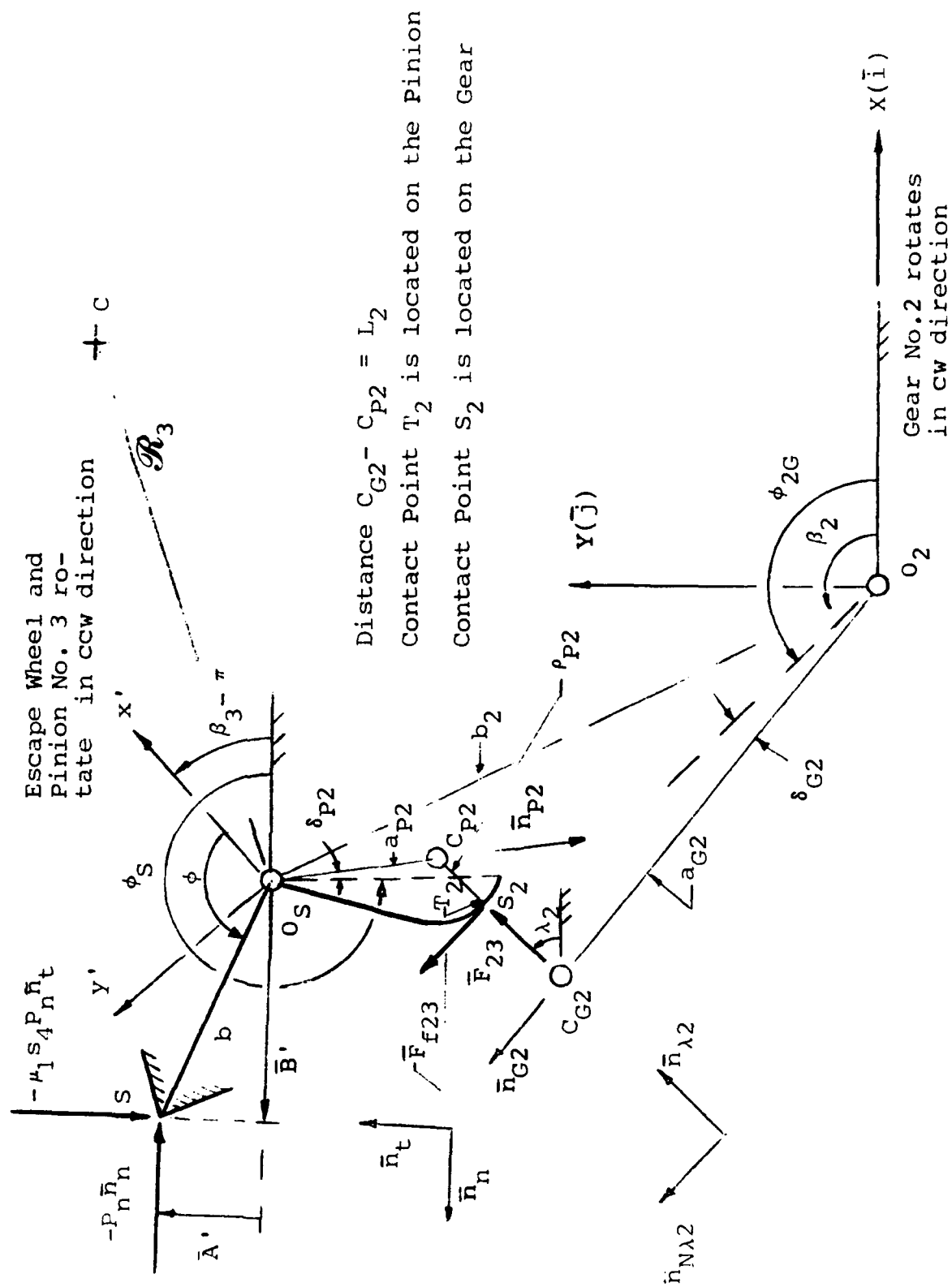


Figure D-5a. Top view of escape wheel and pinion no. 3 in entrance coupled motion. Round-on-round contact of mesh no. 2

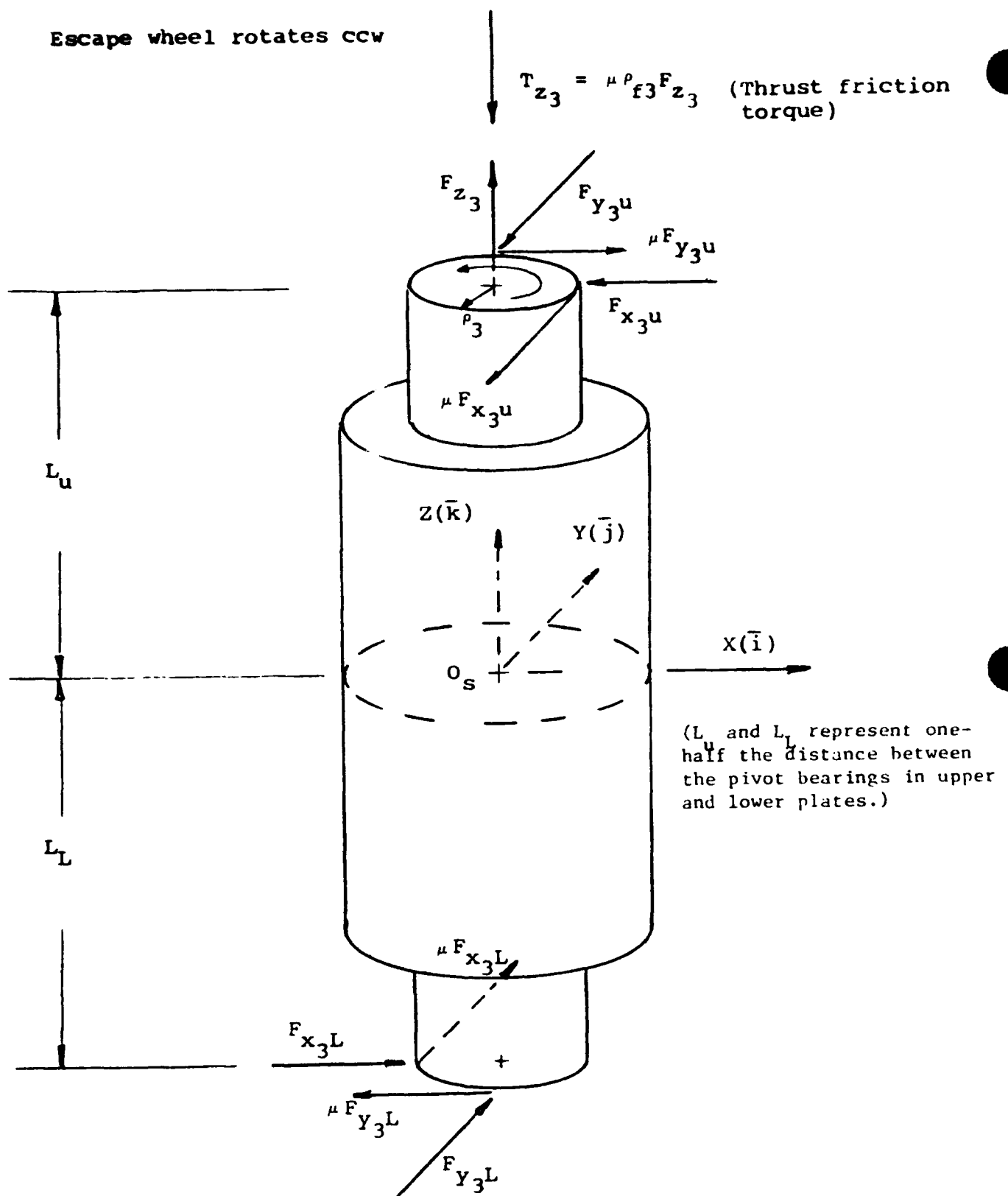


Figure D-5b. Escape wheel and pinion no. 3 in entrance coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots. (Not influenced by type of mesh contact.)

$$S_{2R} = \frac{V_{S_2/T_{2R}}}{|V_{S_2/T_{2R}}|} \quad (D-148)$$

The force equations for the escape wheel in coupled motion are generally obtained from Newton's law

$$\Sigma \bar{F} = m_3 \bar{A}_{O_3/\text{ground}} \quad (D-149)$$

where

$\Sigma \bar{F}$ = sum of pivot forces as well as contact forces P_n and F_{23} and their associated friction forces

m_3 = mass of escape wheel and pinion no. 3

$\bar{A}_{O_3/\text{ground}}$ = acceleration of escape wheel center of mass, which lies on axis of rotation, with respect to ground. Therefore

$$\bar{A}_{O_3/\text{ground}} = \bar{A}_{O_3/C} + \bar{A}_{C/\text{ground}} \quad (D-150)$$

In the above, $\bar{A}_{C/\text{ground}}$, the acceleration of the fuze geometric center C with respect to the ground is given in terms of the X-Y-Z system by equation C-4 of appendix C. The acceleration of the escape wheel center of mass with respect to the above point C, i.e., $\bar{A}_{O_3/C}$, becomes

$$\bar{A}_{O_3/C} = \bar{\omega}_x \times (\bar{\omega}_x \times \mathfrak{R}_3 \bar{n}_3) + \bar{\dot{\omega}} \times \mathfrak{R}_3 \bar{n}_3 \quad (D-151)$$

where

$$\bar{n}_3 = \cos \gamma_3 \bar{i} + \sin \gamma_3 \bar{j} \quad (D-152)$$

Substitution of

$$\bar{\omega} = \omega_x \bar{i} + \omega_y \bar{j} + \omega_z \bar{k} \quad (D-153)$$

according to equation A-1 and

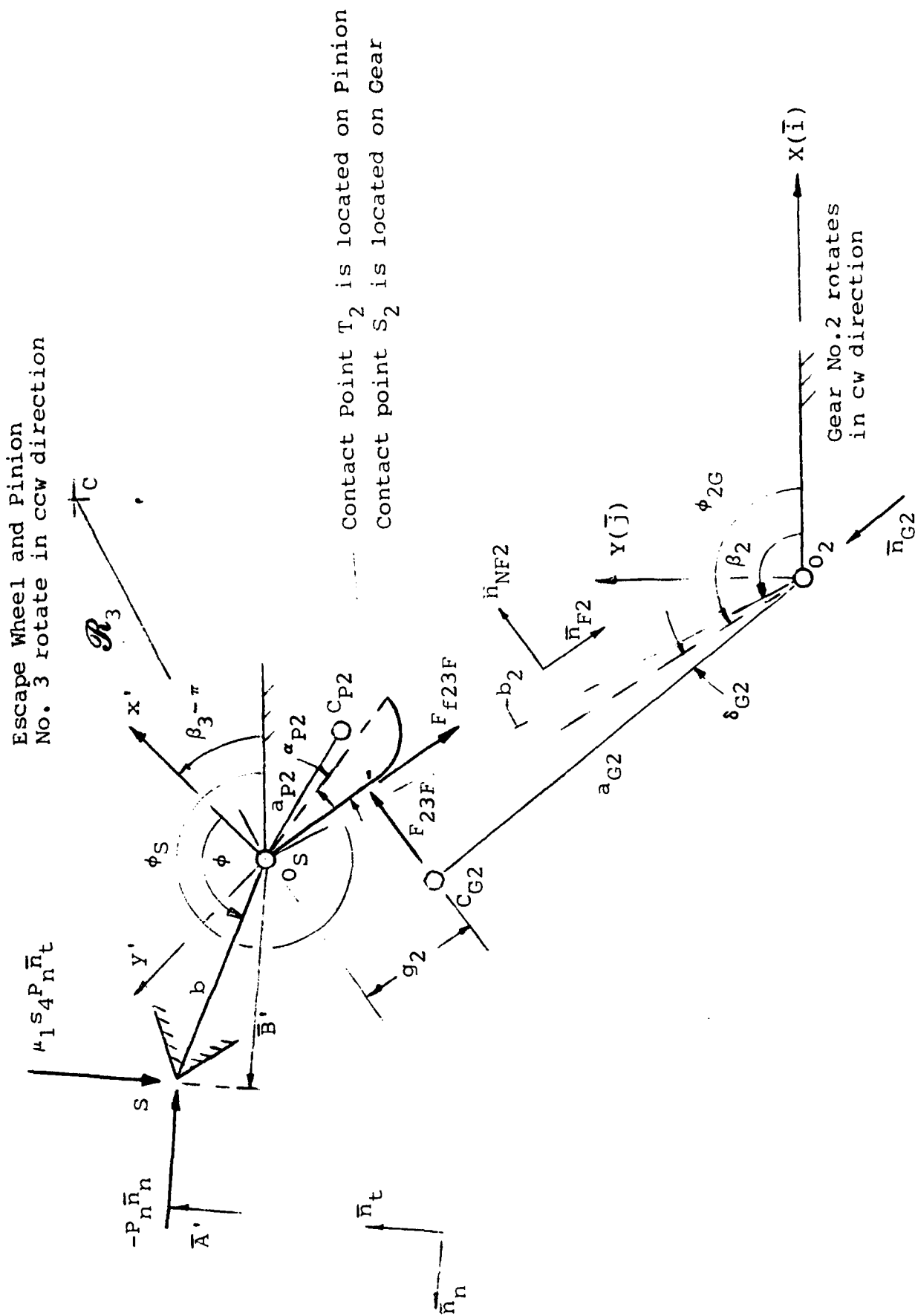


Figure D-6a. Top view of escape wheel and pinion no. 3 in entrance coupled motion. Round-on-flat contact of mesh no. 2

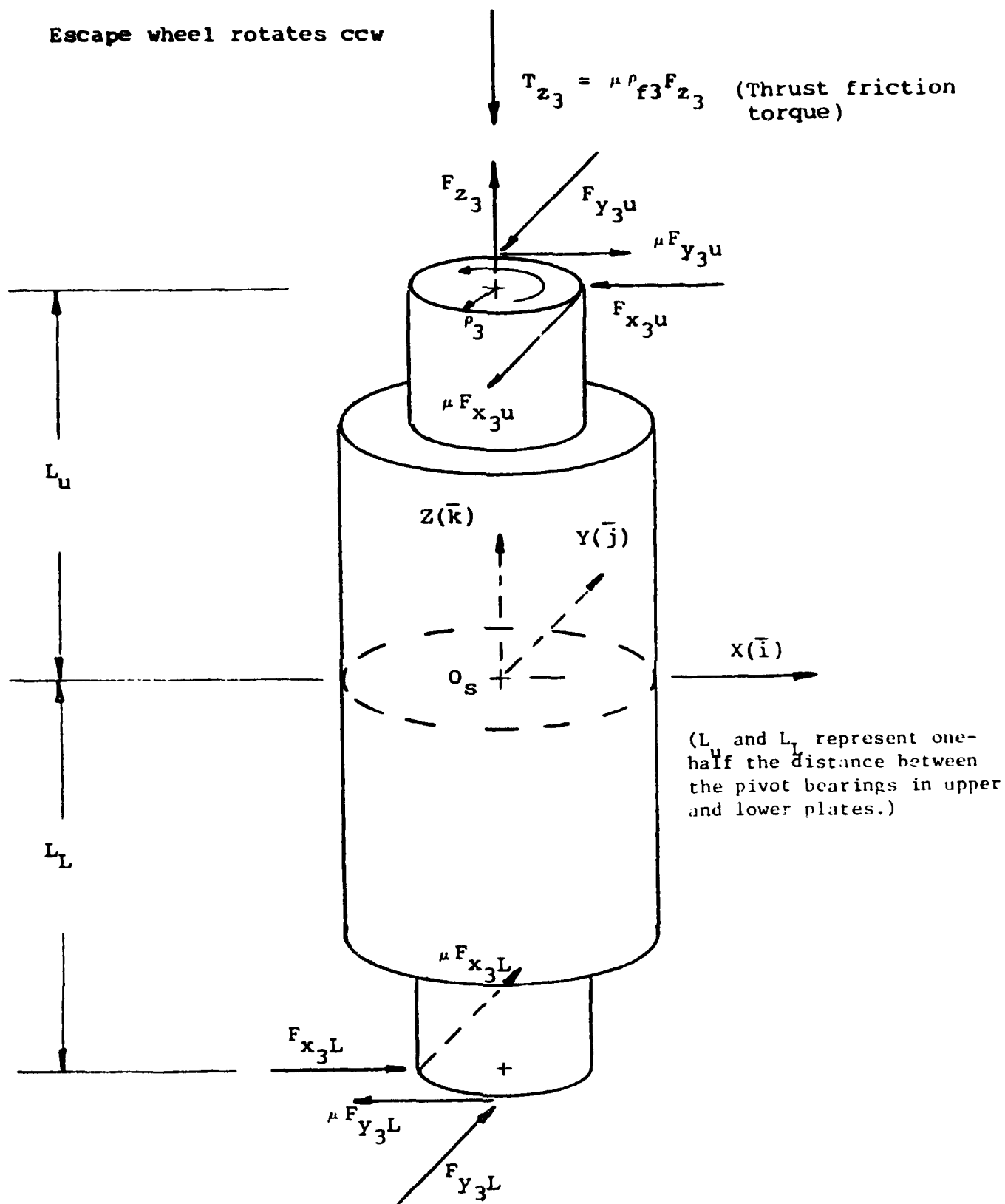


Figure D-6b. Escape wheel and pinion no. 3 in entrance coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots. (Same as figure D-5b. Not influenced by type of mesh contact.)

$$\bar{\omega} = \dot{\omega}_x \bar{i} + \dot{\omega}_y \bar{j} + \dot{\omega}_z \bar{k} \quad (D-154)$$

according to equation A-5, with

$$\mathcal{R}_{3x} = \mathcal{R}_3 \cos \gamma_3 \quad (D-155)$$

and

$$\mathcal{R}_{3y} = \mathcal{R}_3 \sin \gamma_3 \quad (D-156)$$

results in

$$\bar{A}_{O/C} = J_x \bar{i} + J_y \bar{j} + J_z \bar{k} \quad (D-157)$$

where

$$J_x = \omega_x \omega_y \mathcal{R}_{3y} - (\omega_y^2 + \omega_z^2) \mathcal{R}_{3x} - \dot{\omega}_z \mathcal{R}_{3y} \quad (D-158)$$

$$J_y = \omega_x \omega_y \mathcal{R}_{3x} - (\omega_x^2 + \omega_z^2) \mathcal{R}_{3y} + \dot{\omega}_z \mathcal{R}_{3x} \quad (D-159)$$

$$J_z = (\omega_x \mathcal{R}_{3x} + \omega_y \mathcal{R}_{3y}) \omega_z + \dot{\omega}_x \mathcal{R}_{3y} - \dot{\omega}_y \mathcal{R}_{3x} \quad (D-160)$$

Equation D-157 is now substituted together with equation C-3 into D-150

$$\bar{A}_{O/\text{ground}} = N_x \bar{i} + N_y \bar{j} + N_z \bar{k} \quad (D-161)$$

where

$$N_x = G_x + J_x \quad (D-162)$$

$$N_y = G_y + J_y \quad (D-163)$$

$$N_z = G_z + J_z \quad (D-164)$$

The vectorial force equation is now obtained with the help of figures D-5a and D-5b, and equation D-149

$$\begin{aligned}
& -P_n \bar{n} - \mu_1 s_4 P_n \bar{n}_t + F_{23} \bar{n}_{\lambda 2} + \mu s_{2R} F_{23} \bar{n}_{N\lambda 2} + F_{23} \bar{k} - F_{x3u} \bar{i} - F_{y3u} \bar{j} - \mu F_{x3u} \bar{j} \\
& + \mu F_{y3u} \bar{i} + F_{x3L} \bar{i} + F_{y3L} \bar{j} + \mu F_{x3L} \bar{j} - \mu F_{y3L} \bar{i} = (N_x \bar{i} + N_y \bar{j} + N_z \bar{k}) m_3 \quad (D-165)
\end{aligned}$$

Substitution of the appropriate unit vectors, according to equations D-143 and D-146

$$\begin{aligned}
& -P_n [\sin(\psi + \alpha + \beta_3) \bar{i} - \cos(\psi + \alpha + \beta_3) \bar{j}] - \mu_1 s_4 P_n [-\cos(\psi + \alpha + \beta_3) \bar{i} \\
& - \sin(\psi + \alpha + \beta_3) \bar{j}] + F_{23} [\cos \lambda_2 \bar{i} + \sin \lambda_2 \bar{j}] + \mu s_{2R} F_{23} [-\sin \lambda_2 \bar{i} + \cos \lambda_2 \bar{j}] \\
& + F_{23} \bar{k} - F_{x3u} \bar{i} - F_{y3u} \bar{j} - \mu F_{x3u} \bar{j} + F_{y3u} \bar{i} + F_{x3L} \bar{i} + F_{y3L} \bar{j} + \mu F_{x3L} \bar{j} - \mu F_{y3L} \bar{i} \\
& = (N_x \bar{i} + N_y \bar{j} + N_z \bar{k}) m_3
\end{aligned}$$

This leads to the following force component expressions

$$\begin{aligned}
& -P_n \sin(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \cos(\psi + \alpha + \beta_3) + F_{23} \cos \lambda_2 \\
& - \mu s_{2R} F_{23} \sin \lambda_2 - F_{x3u} + \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \quad (D-166)
\end{aligned}$$

as well as

$$\begin{aligned}
& P_n \cos(\psi + \alpha + \beta_3) + P_n \mu_1 s_4 \sin(\psi + \alpha + \beta_3) + F_{23} \sin \lambda_2 \\
& + \mu s_{2R} F_{23} \cos \lambda_2 - F_{y3u} - \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \quad (D-167)
\end{aligned}$$

and

$$F_{23} = N_z m_3 \quad (D-168)$$

Moment Equations for Escape Wheel and Pinion No. 3 with Mesh in Round-on Round Contact

Since the escape wheel and pinion no. 3 represents a symmetrical body, its moment equation may be expressed in terms of the projectile-fixed X-Y-Z system according to equation B-13 of appendix B. Adaptation of this expression to the escape wheel system furnishes

$$\begin{aligned}\bar{M}_{O_s} = & \left[I_{xs} \dot{\omega}_x + I_{zs} \omega_y (\omega_z + \dot{\phi}) - I_{ys} \omega_y \omega_z \right] \bar{i} + \left[I_{ys} \dot{\omega}_y + I_{xs} \omega_x \omega_z \right. \\ & \left. - I_{zs} \omega_x (\omega_z + \dot{\phi}) \right] \bar{j} + I_{zs} (\dot{\omega}_z + \ddot{\phi}) \bar{k}\end{aligned}\quad (D-169)$$

The moment sum $\bar{M}_{O_s}$ about point O_s is now found with the help of the free body diagrams of figures D-5a and D-5b (also refs 1 and 2).

$$\begin{aligned}M_{O_s} = & -P_n (A'_1 - B'_1 \mu_1 s_4) \bar{k} - \mu \rho_{f3} F_{z3} \bar{k} + (a_{p2} \bar{n}_{p2} - \rho_{p2} \bar{n}_{\lambda 2}) \\ & \times (F_{23} \bar{n}_{\lambda 2} + \mu s_{2R} F_{23} \bar{n}_{N\lambda 2}) + (L_u \bar{k} + \rho_3 \bar{j}) \times (-F_{y3u} \bar{j} + \mu F_{y3u} \bar{i}) \\ & + (L_u \bar{k} + \rho_3 \bar{j}) \times (-F_{x3u} \bar{i} - \mu F_{x3u} \bar{j}) + (-L_L \bar{k} - \rho_3 \bar{j}) \times (F_{y3L} \bar{j} - \mu F_{y3L} \bar{i}) \\ & + (-L_L \bar{k} - \rho_3 \bar{j}) \times (F_{x3L} \bar{i} + \mu F_{x3L} \bar{j})\end{aligned}\quad (D-170)$$

The term $-\mu \rho_{f3} F_{z3}$ represents the thrust friction moment due to force F_{z3} (eq D-168). The term ρ_{f3} stands for the thrust friction radius of the escape wheel pivot. Further, the unit (vector $\bar{n}_{p2}$) is given by equation G-50 of reference 5. The subscript s is now used with the angle ϕ .

Then, with equation D-145 and D-147 and

$$\bar{n}_{p2} = \cos(\phi_s + \delta_{p2}) \bar{i} + \sin(\phi_s + \delta_{p2}) \bar{j}\quad (D-171)$$

equation D-170 becomes

$$\begin{aligned}M_{O_s} = & -P_n (A'_1 - B'_1 \mu_1 s_4) \bar{k} - \mu \rho_{f3} F_{z3} \bar{k} + a_{p2} F_{23} (\bar{n}_{p2} \times \bar{n}_{\lambda 2}) \\ & + a_{p2} \mu s_{2R} F_{23} (\bar{n}_{p2} \times \bar{n}_{N\lambda 2}) - \rho_{p2} \mu s_{2R} F_{23} (\bar{n}_{\lambda 2} \times \bar{n}_{N\lambda 2}) + (L_u \bar{k} + \rho_3 \bar{j}) \\ & \times (-F_{y3u} \bar{j} + \mu F_{y3u} \bar{i}) + (L_u \bar{k} + \rho_3 \bar{j}) \times (-F_{x3u} \bar{i} - \mu F_{x3u} \bar{j}) + (-L_L \bar{k} - \rho_3 \bar{j}) \\ & \times (F_{y3L} \bar{j} - \mu F_{y3L} \bar{i}) + (-L_L \bar{k} - \rho_3 \bar{j}) \times (F_{x3L} \bar{i} + \mu F_{x3L} \bar{j})\end{aligned}$$

with

$$\begin{aligned}
 \bar{n}_{p2} \times \bar{n}_{\lambda 2} &= [\cos(\phi_s + \delta_{p2}) \bar{i} + \sin(\phi_s + \delta_{p2}) \bar{j}] \times [\cos\lambda_2 \bar{i} + \sin\lambda_2 \bar{j}] \\
 &= [\cos(\phi_s + \delta_{p2}) \sin\lambda_2 - \sin(\phi_s + \delta_{p2}) \cos\lambda_2] \bar{k} = \sin(\lambda_2 - \phi_s - \delta_{p2}) \bar{k} \\
 \bar{n}_{p2} \times \bar{n}_{N\lambda 2} &= [\cos(\phi_s + \delta_{p2}) \bar{i} + \sin(\phi_s + \delta_{p2}) \bar{j}] \times [-\sin\lambda_2 \bar{i} + \cos\lambda_2 \bar{j}] \\
 &= \cos(\phi_s + \delta_{p2}) \cos\lambda_2 + \sin(\phi_s + \delta_{p2}) \sin\lambda_2 = \cos(\lambda_2 - \phi_s - \delta_{p2}) \bar{k} \\
 \bar{n}_{\lambda 2} \times \bar{n}_{N\lambda 2} &= \bar{k}
 \end{aligned}$$

Substitution furnishes

$$\begin{aligned}
 \bar{M}_{O_s} &= -P_n (A'_1 - B'_1 \mu_1 s_4) \bar{k} - \mu \rho_{f3} F_{z3} \bar{k} + a_{p2} F_{23} \sin(\lambda_2 - \phi_s - \delta_{p2}) \bar{k} \\
 &+ a_{p2} \mu s_{2R} F_{23} \cos(\lambda_2 - \phi_s - \delta_{p2}) \bar{k} - \rho_{p2} \mu s_{2R} F_{23} \bar{k} - \rho_3 \mu F_{y3u} \bar{k} - \rho_3 \mu F_{x3u} \bar{k} \\
 &- \rho_3 \mu F_{y3L} \bar{k} - \rho_3 \mu F_{x3L} \bar{k} + [L_u F_{y3u} + L_u \mu F_{x3u} + L_L F_{y3L} + L_L \mu F_{x3L}] \bar{i} \\
 &+ [L_u \mu F_{y3u} - L_u F_{x3u} + L_L \mu F_{y3L} - L_L F_{x3L}] \bar{j}
 \end{aligned}$$

or

$$\begin{aligned}
 \bar{M}_{O_s} &= [L_u F_{y3u} + L_u \mu F_{x3u} + L_L F_{y3L} + L_L \mu F_{x3L}] \bar{i} + [L_u \mu F_{y3u} - L_u F_{x3u} \\
 &+ L_L \mu F_{y3L} - L_L F_{x3L}] \bar{j} + [-P_n (A'_1 - B'_1 \mu_1 s_4) + a_{p2} F_{23} \sin(\lambda_2 - \phi_s - \delta_{p2}) \\
 &+ \mu s_{2R} \cos(\lambda_2 - \phi_s - \delta_{p2})] - \mu s_{2R} \rho_{p2} F_{23} - \mu \rho_{f3} F_{z3} - \rho_3 \mu F_{y3u} - \rho_3 \mu F_{x3u} \\
 &- \rho_3 \mu F_{y3L} - \rho_3 \mu F_{x3L}] \bar{k}
 \end{aligned}$$

(D-172)

Substitution of equation 72 into equation D-169 leads to the following moment component expressions

$$\begin{aligned} & L_u \mu F_{x3u} + L_u F_{y3u} + L_L \mu F_{x3L} + L_L F_{y3L} \\ & = I_{xs} \dot{\omega}_x + I_{zs} \omega_y (\omega_z + \dot{\phi}) - I_{ys} \omega_y \omega_z \end{aligned} \quad (D-173)$$

$$\begin{aligned} & - L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} \\ & = I_{ys} \dot{\omega}_y + I_{xs} \omega_x \omega_z - I_{zs} \omega_x (\omega_s + \ddot{\phi}) \end{aligned} \quad (D-174)$$

$$\begin{aligned} & - P_n (A'_1 - B'_1 \mu_1 s_4) + a_{p2} F_{23} [\sin (\lambda_2 - \phi_s - \delta_{p2}) + \mu s_{2r} \cos (\lambda_2 - \phi_s - \delta_{p2})] \\ & - \mu s_{2r} \rho_{p2} F_{23} - \mu \rho_{t3} F_{z3} - \mu \rho_3 [F_{x3u} + F_{y3u} + F_{x3L} + F_{y3L}] \\ & = I_{zs} (\dot{\omega}_z + \ddot{\phi}) \end{aligned} \quad (D-175)$$

Simplification of Force and Moment Equations and Determination of Escape Wheel Pivot Forces

To solve for the pivot forces F_{x3u} , F_{y3u} , F_{x3L} , and F_{y3L} , the X and Y components of the force and moment equations must be rewritten in an appropriate form.

X-Component of Force Equation

Equation D-166 becomes

$$F_{x3u} = -\mu F_{y3u} - F_{x3L} + \mu F_{y3L} = P_n A_{33R} + F_{23} A_{34R} + A_{35R} \quad (D-176)$$

where

$$A_{33R} = \mu_1 s_4 \cos (\psi + \alpha + \beta_3) - \sin (\psi + \alpha + \beta_3) \quad (D-177)$$

$$A_{34R} = \cos \lambda_2 - \mu s_{2R} \sin \lambda_2 \quad (D-178)$$

$$A_{35R} = -N_x m_3 \quad (D-179)$$

Y-Component of Force Equation

Equation D-167 becomes

$$\mu F_{x3u} + F_{y3u} - \mu F_{x3L} - F_{y3L} = P_n A_{36R} + F_{23} A_{37R} + A_{38R} \quad (D-180)$$

where

$$A_{36R} = \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 \sin(\psi + \alpha + \beta_3) \quad (D-181)$$

$$A_{37R} = \sin \lambda_2 + \mu s_{2R} \cos \lambda_2 \quad (D-182)$$

$$A_{38R} = -N_y m_3 \quad (D-183)$$

Z-Component of Force Equation

Equation D-168 cannot be further simplified.

X-Component of Moment Equation

Equation D-173 becomes

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L} = A_{39R} + A_{40R} \dot{\phi} \quad (D-184)$$

where

$$A_{39R} = I_{xs} \dot{\omega}_x + \omega_y \omega_z (I_{zs} - I_{ys}) \quad (D-185)$$

$$A_{40R} = I_{zs} \omega_y \quad (D-186)$$

Y-Component of Moment Equation

Equation D-174 becomes

$$-L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} = A_{41R} + A_{42R} \dot{\phi} \quad (D-187)$$

where

$$A_{41R} = I_{ys} \dot{\omega}_y + \omega_x \omega_z (I_{xs} - I_{zs}) \quad (D-188)$$

$$A_{42R} = -I_{zs} \omega_x \quad (D-189)$$

Z-Component of Moment Equation

For present purposes equation D-175 remains as it is.

Solution of Escape Wheel Pivot Forces. To derive expressions for the escape wheel pivot forces, equations D-176, D-180, D-184, and D-187 must be solved simultaneously. To obtain the same general form as in equation D-67, equations D-186 and D-180 are multiplied by (-1). The resulting form may then use the solution to equation D-167. Note that A_{11} in equation D-67 is now replaced by μ . Then

$$\begin{bmatrix} -1 & \mu & 1 & -\mu \\ -\mu & -1 & \mu & 1 \\ \mu L_u & L_u & \mu L_L & L_L \\ -L_u & \mu L_u & -L_L & \mu L_L \end{bmatrix} \begin{bmatrix} F_{x3u} \\ F_{y3u} \\ F_{x3L} \\ F_{y3L} \end{bmatrix} = \begin{bmatrix} B_{s1r} \\ B_{s2r} \\ B_{s3r} \\ B_{s4r} \end{bmatrix} \quad (D-190)$$

where now

$$B_{s1r} = -[P_n A_{33R} + F_{23} A_{34R} + A_{35R}] \quad (D-191)$$

$$B_{s2r} = [P_n A_{36R} + F_{23} A_{37R} + A_{38R}] \quad (D-192)$$

$$B_{s3r} = A_{39R} + A_{40R} \dot{\phi} \quad (D-193)$$

$$B_{s4r} = A_{41R} + A_{42R} \dot{\phi} \quad (D-194)$$

Evaluation of the Coefficient Determinant D

The solution for the coefficient determinant D of equation D-190 is identical to equation D-72. With A_{11} now equal to μ , the following parallel to equation D-75 is obtained

$$D = [(L_u + L_L) (1 + \mu^2)]^2 \quad (D-195)$$

Evaluation of Pivot Force $\tilde{F}_{x3u}$

The pivot force F_{x3u} is obtained from

$$F_{x3u} = \frac{D_{F_{x3u}}}{D} \quad (D-196)$$

where

$$D_{F_{x3u}} = \begin{vmatrix} B_{x1r} & \mu & 1 & -\mu \\ B_{s2r} & -1 & \mu & 1 \\ B_{s3r} & L_u & \mu L_L & L_L \\ B_{s4r} & \mu L_u & -L_L & \mu L_L \end{vmatrix} \quad (D-197)$$

If μ is substituted for A_{11} in equation D-77, the identical form as above is obtained and the solution of equation D-80 can be adapted

$$D_{F_{x3u}} = (1 + \mu^2)(L_u + L_L)[-L_L B_{s1r} - \mu L_L B_{s2r} + \mu B_{s3r} - B_{s4r}] \quad (D-198)$$

Now equations D-191 to D-194 are substituted into the above expression and the coefficients of similar terms are collected. In order to get conservative pivot and pivot friction forces, the latter terms are made absolute. Finally, the tilded force $\tilde{F}_{x3u}$ is obtained from the appropriate change of equation D-196

$$\tilde{F}_{x3u} = \frac{\tilde{D}_{F_{x3u}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{21R} + C_{22R}P_n + C_{23R}F_{23} + C_{24R}\dot{\phi}] \quad (D-199)$$

where

$$C_{21R} = |L_L A_{35R} - A_{41R} + \mu(L_L A_{38R} + A_{39R})| \quad (D-200)$$

$$C_{22R} = |L_L(A_{33R} + \mu A_{36R})| \quad (D-201)$$

$$C_{23R} = |L_L(A_{34R} + \mu A_{37R})| \quad (D-202)$$

$$C_{24R} = |\mu A_{40R} - A_{42R}| \quad (D-203)$$

Evaluation of Pivot Force $\tilde{F}_{y3u}$

The pivot force F_{y3u} is obtained from

$$F_{y3u} = \frac{D_{Dy3u}}{D} \quad (D-204)$$

where

$$D_{F_{y3u}} = \begin{vmatrix} -1 & B_{s1r} & 1 & -\mu \\ -\mu & B_{s2r} & \mu & 1 \\ \mu L_u & B_{s3r} & \mu L_L & L_L \\ -L_u & B_{s4r} & -L_L & \mu L_L \end{vmatrix} \quad (D-205)$$

Since the form of the above is the same as that of the determinant of equation D-89, equation D-90, which represents the solution of the latter, may be adapted as follows

$$D_{F_{x3u}} = (1 + \mu^2)(L_u + L_L)[-L_L B_{s1r} - \mu L_L B_{s2r} + \mu B_{s3r} - B_{s4r}] \quad (D-206)$$

Again, substitute the B_{s1r} terms of equations D-191 to D-194, collect the coefficients of similar terms, and make the result absolute. The tilded pivot force $\tilde{F}_{y3u}$ then becomes parallel to equation D-199

$$\tilde{F}_{y3u} = \frac{\tilde{D}_{F_{y3u}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{25R} + C_{26R}P_n + C_{27R}F_{23} + C_{28R}\phi] \quad (D-207)$$

where

$$C_{25R} = |L_L A_{38R} + A_{39R} + \mu(A_{41R} - L_L A_{35R})| \quad (D-208)$$

$$C_{26R} = |L_L(A_{36R} - \mu A_{33R})| \quad (D-209)$$

$$C_{27R} = |L_L(A_{37R} - \mu A_{34R})| \quad (D-210)$$

$$C_{28R} = |A_{40R} + \mu A_{42R}| \quad (D-211)$$

Evaluation of Pivot Force $\tilde{F}_{x3L}$

The pivot force F_{x3L} is obtained from

$$F_{x3L} = \frac{D_{F_{x3L}}}{D} \quad (D-212)$$

where

$$D_{F_{x3L}} = \begin{vmatrix} -1 & \mu & B_{s1r} & -\mu \\ -\mu & -1 & B_{s2r} & 1 \\ \mu L_u & L_u & B_{s3r} & L_L \\ -L_u & \mu L_u & B_{s4r} & \mu L_L \end{vmatrix} \quad (D-213)$$

Since the form of the above is the same as that of equation D-98, equation D-100 may be adapted

$$D_{F_{x3L}} = (L_u + L_L)(1 + \mu^2)[L_u B_{s1r} + \mu L_u B_{s2r} + \mu B_{s3r} - B_{s4r}] \quad (D-214)$$

Again, the B_{s1r} terms are substituted according to equations D-191 to D-194 and the requisite work obtains the tilded determinant $\tilde{D}_{F_{x3L}}$. Then

$$\tilde{F}_{x3L} = \frac{\tilde{D}_{F_{x3L}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{29R} + C_{30R}P_n + C_{31R}F_{23} + C_{32R}\phi] \quad (D-215)$$

where

$$C_{29R} = |\mu(A_{39R} - L_u A_{38R}) - L_u A_{35R} - A_{41R}| \quad (D-216)$$

$$C_{30R} = |L_u(A_{33R} + \mu A_{36R})| \quad (D-217)$$

$$C_{31R} = |L_u(A_{34R} + \mu A_{37R})| \quad (D-218)$$

$$C_{32R} = |\mu A_{40R} - A_{42R}| \quad (D-219)$$

Evaluation of Pivot Force $\tilde{F}_{y3L}$

The pivot force F_{y3L} is obtained from

$$F_{y3L} = \frac{D_{F_{y3L}}}{D} \quad (D-220)$$

where

$$D_{Fy3L} = \begin{vmatrix} -1 & \mu & 1 & B_{s1r} \\ -\mu & -1 & \mu & B_{s2r} \\ \mu L_u & L_u & \mu L_L & B_{s3r} \\ -L_u & \mu L_u & -L_L & B_{s4r} \end{vmatrix} \quad (D-221)$$

Since the form of the above is the same as that of the determinant of equation D-108, equation D-110 may be adapted to the present situation, therefore

$$D_{Fy3L} = (L_u + L_L)(1 + \mu^2)[- \mu L_u B_{s1r} + L_u B_{s2r} + B_{s3r} + \mu B_{s4r}] \quad (D-222)$$

The B_{s1r} terms are now substituted according to equations D-191 to D-194, terms are collected and the tilded pivot force is defined

$$\tilde{F}_{y3L} = \frac{\tilde{D}_{Fy3L}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{33R} + C_{34R}P_n + C_{35R}F_{23} + C_{36R}\phi] \quad (D-223)$$

where

$$C_{33R} = |\mu(A_{41R} + L_u A_{35R}) + A_{39R} - L_u A_{38R}| \quad (D-224)$$

$$C_{34R} = |L_u(\mu A_{33R} - A_{36R})| \quad (D-225)$$

$$C_{35R} = |L_u(\mu A_{34R} - A_{37R})| \quad (D-226)$$

$$C_{36R} = |A_{40R} - \mu A_{42R}| \quad (D-227)$$

Determination of Contact Force P_n in Terms of Escape Wheel Parameters (Round-on-Round Contact)

Substitution of Conservative (Tilded) Pivot Forces into the z-Component of the Moment Equation. Again, let the sum of the tilded pivot forces be first determined. Subsequently, this expression is substituted into the moment equation D-175. Then

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L} = A_{43R} + A_{44R}P_n + A_{45R}F_{23} + A_{46R}\dot{\phi} \quad (D-228)$$

where

$$L_T = L_U + L_L \quad (D-229)$$

$$A_{43R} = \frac{C_{21R} + C_{25R} + C_{29R} + C_{33R}}{L_T(1 + \mu^2)} \quad (D-230)$$

$$A_{44R} = \frac{C_{22R} + C_{26R} + C_{30R} + C_{34R}}{L_T(1 + \mu^2)} \quad (D-231)$$

$$A_{45R} = \frac{C_{23R} + C_{27R} + C_{31R} + C_{35R}}{L_T(1 + \mu^2)} \quad (D-232)$$

$$A_{46R} = \frac{C_{24R} + C_{28R} + C_{32R} + C_{36R}}{L_T(1 + \mu^2)} \quad (D-233)$$

Equation D-228 is now substituted into equation D175. Further, F_{z3} of equation D-168 is made conservative, i.e.

$$\tilde{F}_{z3} = A_{47} = |N_z m_3| \quad (D-234)$$

Equation D-175 then becomes

$$\begin{aligned} & -P_n(A_1' - B_1\mu_1s_4) + F_{23}a_{p2}(\sin(\lambda_2 - \phi_s - \delta_{p2}) + \mu s_{2R}\cos(\lambda_2 - \phi_s - \delta_{p2})) \\ & \mu s_{2R}p_{p2}F_{23} - \mu p_{13}A_{47} - \mu p_3[A_{43R} + A_{44R}P_n + A_{45R}F_{23} + A_{46R}\dot{\phi}] \\ & = I_{zs}\dot{\omega}_z + I_{zs}\ddot{\phi} \end{aligned} \quad (D-235)$$

The above expression must now be solved for P_n . Before this is possible consider the sign of the friction moment component

$$-\mu \rho_3 A_{46R} \dot{\phi} \quad (D-236)$$

Since a reversal of gear train motion after impact will again be expressed by letting μ become negative, as described originally in appendix E of reference 4, equation D-236 is modified to read

$$-\mu \rho_3 A_{46R} \frac{\dot{\phi}^2}{|\dot{\phi}|} \quad (D-237)$$

In this way, the sign of μ alone decides the direction of this friction torque component. P_n is then obtained from equation D-235

$$\begin{aligned} P_n \left[-A_1' + B_1' \mu_1 S_4 - \mu \rho_3 A_{44R} \right] + F_{23} \left[a_{P2} \left(\sin(\lambda_2 - \phi_s - \delta_{P2}) \right. \right. \\ \left. \left. + \mu S_{2R} \cos(\lambda_2 - \phi_s - \delta_{P2}) \right) - \mu S_{2R} \rho_{P2} - \mu \rho_3 A_{45R} \right] - \mu \rho_3 A_{46R} \frac{\dot{\phi}^2}{|\dot{\phi}|} \\ - \mu \left[\rho_3 A_{47} + \rho_3 A_{43R} \right] = I_{zs} \ddot{\phi} + I_{zs} \dot{\omega}_z \end{aligned} \quad (D-238)$$

Then

$$P_n = \frac{I_{zs} \ddot{\phi} + A_{48R} \dot{\phi}^2 + F_{23} A_{49R} + A_{50R}}{A_{51R}} \quad (D-239)$$

where

$$A_{48R} = \frac{\mu \rho_3 A_{46R}}{|\dot{\phi}|} \quad (D-240)$$

$$\begin{aligned} A_{49R} = \mu \left(S_{2R} \rho_{P2} + \rho_3 A_{45R} \right) - a_{P2} \left[\sin(\lambda_2 - \phi_s - \delta_{P2}) \right. \\ \left. + \mu S_{2R} \cos(\lambda_2 - \phi_s - \delta_{P2}) \right] \end{aligned} \quad (D-241)$$

$$A_{50R} = I_{zs}\dot{\omega}_z + \mu [\rho_{13}A_{47} + \rho_3A_{43R}] \quad (D-242)$$

$$A_{51R} = B_1'\mu_1S_4 - A_1' - \mu\rho_3A_{44R} \quad (D-243)$$

Combined Entrance Coupled Motion Differential Equation with Mesh 2 in Round-on-Round Contact

Equations D-140 and D-239 are now set equal to each other. This furnishes the following combined coupled motion differential equation for the escapement under entrance conditions and with mesh 2 in round-on-round contact.

$$\begin{aligned} & [A_{51R}I_{PR}U - A_{29}I_{zs}] \ddot{\phi} + [A_{51R}(A_{32}U^2 + I_{PR}V) - A_{29}A_{48R}] \dot{\phi}^2 \\ & + A_{51R}A_{31}U\dot{\phi} = F_{23}A_{29}A_{49R} + A_{29}A_{50R} - A_{51R}(A_9 + A_{30}) \\ & + A_{51R}m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) \end{aligned} \quad (D-244)$$

Force Equations for Escape Wheel and Pinion No. 3 with Mesh 2 in Round-on-Flat Contact (see reference 5 for clock tooth force analysis background)

The action of the contact forces $\bar{P}_n$ and $\bar{F}_{23F}$, together with their associated friction forces, on escape wheel and pinion no. 3, when mesh no. 2 is in round-on-flat contact is shown in figure D-6a. Figure D-6b is identical to figure D-5b, which showed a free body diagram of the escape wheel pivot shaft. As for the round-on-round contact, equations (D-141) to (D-144) for the unit vectors $\bar{i}'$, $\bar{j}'$, $\bar{n}_t$, and $\bar{n}_n$ are applicable.

The round-on-flat contact force $\bar{F}_{23F}$ has the direction of the unit vector $\bar{n}_{NF2}$, so that

$$\bar{F}_{23F} = F_{23F}\bar{n}_{NF2} \quad (D-245a)$$

where

$$\bar{n}_{NF2} = -\sin(\phi_s - \alpha_{P2})\bar{i} + \cos(\phi_s - \alpha_{P2})\bar{j} \quad (D-245b)$$

(eq G-65, ref 5).

The associated friction force is given by

$$\bar{F}_{f23F} = \mu S_2 F_{23F} \bar{n}_{NF2} \quad (D-246)$$

where, according to equation G-64 of reference 5

$$\bar{n}_{F2} = \cos(\phi_s - \alpha_{P2}) \bar{i} + \sin(\phi_s - \alpha_{P2}) \bar{j} \quad (D-247)$$

The signum function s_{2F} is defined with the help of equation F-58 of appendix F

$$S_{2F} = \frac{V_{S_2/T_{2F}}}{|V_{S_2/T_{2F}}|} \quad (D-248)$$

The force equation for the escapewheel is again based on equations D-149 and D-161. With the help of figures D-6a and D-6b the following vectorial expression may be written

$$\begin{aligned} & -P_n \bar{n}_n - \mu_1 s_4 P_n \bar{n}_t + F_{23F} \bar{n}_{NF2} + \mu s_{2F} F_{23F} \bar{n}_{F2} + F_{z3} \bar{k} - F_{x3u} \bar{j} \\ & - F_{y3u} \bar{j} - \mu F_{x3u} \bar{j} + \mu F_{y3u} \bar{i} + F_{x3L} \bar{i} + F_{y3L} \bar{j} + \mu F_{x3L} \bar{j} - \mu F_{y3L} \bar{i} \\ & = (N_x \bar{i} + N_y \bar{j} + N_z \bar{k}) m_3 \end{aligned} \quad (D-249)$$

Substitution of the appropriate unit vectors according to equations D-143 and D-144 as well as D-245 and D-247 gives

$$\begin{aligned} & -P_n [\sin(\psi + \alpha + \beta_3) \bar{i} - \cos(\psi + \alpha + \beta_3) \bar{j}] - \mu_1 s_4 P_n [-\cos(\psi + \alpha + \beta_3) \bar{i} \\ & - \sin(\psi + \alpha + \beta_3) \bar{j}] + F_{23F} [-\sin(\phi_s - \alpha_{P2}) \bar{i} + \cos(\phi_s - \alpha_{P2}) \bar{j}] \\ & + \mu s_{2F} F_{23F} [\cos(\phi_s - \alpha_{P2}) \bar{i} + \sin(\phi_s - \alpha_{P2}) \bar{j}] + F_{z3} \bar{k} - F_{x3u} \bar{j} - F_{y3u} \bar{j} \\ & - \mu F_{x3u} \bar{j} + \mu F_{y3u} \bar{i} + F_{x3L} \bar{i} + F_{y3L} \bar{j} + \mu F_{x3L} \bar{j} - \mu F_{y3L} \bar{i} \\ & = (N_x \bar{i} + N_y \bar{j} + N_z \bar{k}) m_3 \end{aligned} \quad (D-250)$$

This leads to the following force component equations

$$\begin{aligned} & -P_n \sin(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \cos(\psi + \alpha + \beta_3) - F_{23F} \sin(\phi_s - \alpha_{P2}) \\ & + \mu s_{2F} F_{23F} \cos(\phi_s - \alpha_{P2}) - F_{x3u} + \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \end{aligned} \quad (D-251)$$

$$P_n \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \sin(\psi + \alpha + \beta_3) + F_{23} F \cos(\phi_s - \alpha_{P2}) \\ + \mu s_2 F_{23} F \sin(\phi_s - \alpha_{P2}) - F_{y3u} - \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \quad (D-252)$$

$$F_{z3} = N_z m_3 \quad (D-253)$$

Moment Equations for Escape Wheel and Pinion No. 3 with Mesh 2 in Round-on-Flat Contact

The general moment expression D-169 is also applicable here. The moment sum $\bar{M}_{O_s}$ for the round-on-flat contact must now be found with the help of the free body diagrams D-6a and D-6b

$$\bar{M}_{O_s} = -P_n (A'_1 - B'_1 \mu_1 s_4) \bar{k} - \mu p_{13} F_{z3} \bar{k} + g_2 \bar{F} n_{F2} \times F_{23} F \bar{F} n_{NF2} + (L_u \bar{k} + p_3 \bar{j}) \\ \times (-F_{y3u} \bar{j} + \mu F_{y3u} \bar{i}) + (L_u \bar{k} + p_3 \bar{j}) \times (-F_{x3u} \bar{i} - \mu F_{x3u} \bar{j}) + (-L_L \bar{k} - p_3 \bar{j}) \\ \times (F_{y3L} \bar{j} - \mu F_{y3L} \bar{i}) + (-L_L \bar{k} - p_3 \bar{j}) \times (-F_{x3L} \bar{i} + \mu F_{x3L} \bar{j}) \quad (D-254)$$

For an explanation of the term $-\mu p_{13} F_{z3} \bar{k}$, see the discussion following equation D-170.

Since

$$\bar{n}_{F2} \times \bar{n}_{NF2} = \bar{k} \quad (D-255)$$

equation D-254 may be rewritten as follows

$$\bar{M}_{O_s} = [L_u F_{y3u} + L_u \mu F_{x3u} + L_L F_{y3L} + L_L \mu F_{x3L}] \bar{i} + [L_u \mu F_{y3u} - L_u F_{x3u} \\ + L_L \mu F_{y3L} - L_L F_{x3L}] \bar{j} + [-P_n (A'_1 - B'_1 \mu_1 s_4) + g_2 F_{23} F - \mu p_{13} F_{z3} - p_3 \mu F_{y3u} \\ - p_3 \mu F_{x3u} - p_3 \mu F_{y3L} - p_3 \mu F_{x3L}] \bar{k} \quad (D-256)$$

Substitution of equation D-255 into equation D-169 leads to the following moment component expressions

$$\begin{aligned} & L_u \mu F_{x3u} + L_u F_{y3u} + L_L \mu F_{x3L} + L_L F_{y3L} \\ &= I_{xs} \dot{\omega}_x + I_{zs} \omega_y (\omega_z + \dot{\phi}) - I_{ys} \omega_y \omega_z \end{aligned} \quad (D-257)$$

$$\begin{aligned} & -L_L F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} \\ &= I_{ys} \dot{\omega}_y + I_{xs} \omega_x \omega_z - I_{zs} \omega_x (\omega_z + \dot{\phi}) \end{aligned} \quad (D-258)$$

$$\begin{aligned} & -P_n (A'_1 - B'_1 \mu_1 s_4) + F_{23F} g_2 - \mu \rho_{f3} F_{z3} - \mu \rho_3 [F_{x3u} + F_{y3u} + F_{x3L} + F_{y3L}] \\ &= I_{zs} (\dot{\omega}_z + \ddot{\phi}) \end{aligned} \quad (D-259)$$

Simplification of Force and Moment Equations and Determination of Escape Wheel Pivot Forces

To solve for the pivot forces F_{x3u} , F_{y3u} , F_{x3L} , and F_{y3L} the X and Y components of the force and moment equations must be rewritten in an appropriate form.

X-Component of Force Equation.

Equation D-251 becomes

$$F_{x3u} - \mu F_{y3u} - F_{x3L} + \mu F_{y3L} = P_n A_{33F} + F_{23} A_{34F} + A_{35F} \quad (D-260)$$

where

$$A_{33F} = \mu_1 s_4 \cos (\psi + \alpha + \beta_3) - \sin (\psi + \alpha + \beta_3) \quad (D-261)$$

$$A_{34F} = -\sin (\phi_s - \alpha_{P2}) + \mu s_{2F} \cos (\phi_s - \alpha_{P2}) \quad (D-262)$$

$$A_{35F} = -N_x m_3 \quad (D-263)$$

Y-Component of Force Equation.

Equation D-252 becomes

$$\mu F_{x3u} + F_{y3u} - \mu F_{x3L} - F_{y3L} = P_n A_{36F} + F_{23} A_{37F} + A_{38F} \quad (D-264)$$

where

$$A_{36F} = \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 \sin(\psi + \alpha + \beta_3) \quad (D-265)$$

$$A_{37F} = \cos(\phi_s - \alpha_{p2}) + \mu s_{2F} \sin(\phi_s - \alpha_{p2}) \quad (D-266)$$

$$A_{38F} = -N_y m_3 \quad (D-267)$$

Z-Component of Force Equation.

Equation D-253 cannot be further simplified.

X-Component of Moment Equation.

Equation D-257 becomes

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L} = A_{39F} + A_{40F} \dot{\phi} \quad (D-268)$$

where

$$A_{39F} = I_{xs} \dot{\omega}_x + \omega_y \omega_z (I_{zs} - I_{ys}) \quad (D-269)$$

$$A_{40F} = I_{zs} \omega_y \quad (D-270)$$

Y-Component of Moment Equation.

Equation D-258 becomes

$$-L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} = A_{41F} + A_{42F} \dot{\phi} \quad (D-271)$$

where

$$A_{41F} = I_{ys} \dot{\omega}_y + \omega_x \omega_z (I_{xs} - I_{zs}) \quad (D-272)$$

$$A_{42F} = -I_{zs} \omega_y \quad (D-273)$$

Z-Component of Moment Equation.

For present purposes equation D-259 remains as it is.

Solution of Escape Wheel Pivot Forces. To derive expressions for the escape wheel pivot forces, equations D-260, D-264, D-268, and D-271 must be solved simultaneously. To obtain the same general form as in equation D-67, equations D-260 and D-264 are multiplied by (-1) . The resulting form may then use the solution to equation D-67. Note that A_{11} in equation D-67 is now replaced by μ . Then

$$\begin{bmatrix} -1 & \mu & 1 & -\mu \\ -\mu & -1 & \mu & 1 \\ \mu L_u & L_u & \mu L_L & L_L \\ -L_u & \mu L_u & -L_L & \mu L_L \end{bmatrix} \begin{bmatrix} F_{x3u} \\ F_{y3u} \\ F_{x3L} \\ F_{y3L} \end{bmatrix} = \begin{bmatrix} B_{s1f} \\ B_{s2f} \\ B_{s3f} \\ B_{s4f} \end{bmatrix} \quad (D-274)$$

where

$$B_{s1f} = -[P_n A_{33F} + F_{23} A_{34F} + A_{35F}] \quad (D-275)$$

$$B_{s2f} = -[P_n A_{36F} + F_{23} A_{37F} + A_{38F}] \quad (D-276)$$

$$B_{s3f} = A_{39F} + A_{40F}\dot{\phi} \quad (D-277)$$

$$B_{s4f} = A_{41F} + A_{42F}\dot{\phi} \quad (D-278)$$

Evaluation of the Coefficient Determinant D.

The solution for the coefficient determinant D of equation D-274 is identical to equation D-72. With A_{11} now being equal to μ , the following expression, parallel to equation D-75, is obtained

$$D = [(L_u + L_L)(1 + \mu^2)]^2 \quad (D-279)$$

Evaluation of Pivot Force $\tilde{F}_{x3u}$.

The pivot force F_{x3u} is obtained from

$$F_{x3u} = \frac{D_{F_{x3u}}}{D} \quad (D-280)$$

where

$$D_{F_{x3u}} = \begin{vmatrix} B_{s1f} & \mu & 1 & -\mu \\ B_{s2f} & -1 & \mu & 1 \\ B_{s3f} & L_u & \mu L_L & L_L \\ B_{s4f} & \mu L_u & -L_L & \mu L_L \end{vmatrix} \quad (D-281)$$

If μ is substituted for A_{11} in equation D-77, the identical form as above is obtained and the solution of equation D-80 can be adapted

$$D_{F_{x3u}} = (1 + \mu^2)(L_u + L_L)[-L_L B_{s1f} - \mu L_L B_{s2f} + \mu B_{s3f} - B_{s4f}] \quad (D-282)$$

Now equations D-275 and D-278 are substituted into the above expression and the coefficients of similar terms are collected. In order to get conservative pivot and pivot friction forces, the latter terms are made absolute. Finally, the tilded force $\tilde{F}_{x3u}$ is obtained from the appropriate change of equation D-280

$$\tilde{F}_{x3u} = \frac{\tilde{D}_{F_{x3u}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{21F} + C_{22F}P_n + C_{23F}F_{23F} + C_{24F}\Phi] \quad (D-283)$$

where

$$C_{21F} = |L_L A_{35F} - A_{41F} + \mu (L_L A_{38F} + A_{39F})| \quad (D-284)$$

$$C_{22F} = |L_L (A_{33F} + \mu A_{36F})| \quad (D-285)$$

$$C_{23F} = |L_L (A_{34F} + \mu A_{37F})| \quad (D-286)$$

$$C_{24F} = |\mu A_{40F} - A_{42F}| \quad (D-287)$$

Evaluation of Pivot Force $\tilde{F}_{y3u}$.

The pivot force F_{y3u} is obtained from

$$F_{y3u} = \frac{D_{Fy3u}}{D} \quad (D-288)$$

where

$$D_{Fy3u} = \begin{vmatrix} -1 & B_{s1f} & 1 & -\mu \\ -\mu & B_{s2f} & \mu & 1 \\ \mu L_u & B_{s3f} & \mu L_L & L_L \\ -L_u & B_{s4f} & -L_L & \mu L_L \end{vmatrix} \quad (D-289)$$

Since the form of the above is the same as that of the determinant of equation D-88b, equation D-90, which represents the solution of the latter, may be adapted as follows

$$D_{Fy3u} = (L_u + L_L)(1 + \mu^2)[\mu L_L B_{s1f} - L_L B_{s2f} + B_{s3f} + \mu B_{s4f}] \quad (D-290)$$

Again, substitute the B_{si} terms of equations D-275 to D-278, collect the coefficients of similar terms, and make the result absolute. The tilded pivot force $\tilde{F}_{y3u}$ then becomes parallel to equation D-201

$$\tilde{F}_{y3u} = \frac{\tilde{D}_{Fy3u}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{25F} + C_{26F}P_n + C_{27F}F_{23F} + C_{28F}\dot{\Phi}] \quad (D-291)$$

where

$$C_{25F} = |L_L A_{38F} + A_{39F} + \mu(A_{41F} - L_L A_{35F})| \quad (D-292)$$

$$C_{26F} = |L_L (A_{36F} - \mu A_{33F})| \quad (D-293)$$

$$C_{27F} = |L_L (A_{37F} - \mu A_{34F})| \quad (D-294)$$

$$C_{28F} = |\mu A_{40F} + \mu A_{42F}| \quad (D-295)$$

Evaluation of Pivot Force $\tilde{F}_{x3L}$.

The pivot force F_{x3L} is obtained from

$$F_{x3L} = \frac{D_{F_{x3L}}}{D} \quad (D-296)$$

where

$$D_{F_{x3L}} = \begin{vmatrix} -1 & \mu & B_{s1f} & -\mu \\ -\mu & -1 & B_{s2f} & 1 \\ \mu L_u & L_u & B_{s3f} & L_L \\ -L_u & -L_u & B_{s4f} & \mu L_L \end{vmatrix} \quad (D-297)$$

Since the form of the above is the same as that of equation D-98, equation D-100 may be adapted, i.e.

$$D_{F_{x3L}} = (L_u + L_L)(1 + \mu^2)[L_u B_{s1f} + \mu L_u B_{s2f} + \mu B_{s3f} - B_{s4f}] \quad (D-298)$$

Again, the B_{si} terms are substituted according to equations D-275 to D-278 and the requisite work obtains the tilded determinant $\tilde{D}_{F_{x3L}}$. Then

$$\tilde{F}_{x3L} = \frac{\tilde{D}_{F_{x3L}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{29F} + C_{30F}P_n + C_{31F}F_{23F} + C_{32F}\phi] \quad (D-299)$$

where

$$C_{29F} = |\mu (A_{39F} - L_u A_{38F}) - L_u A_{35F} - A_{41}| \quad (D-300)$$

$$C_{30F} = |L_u (A_{33F} + \mu A_{36F})| \quad (D-301)$$

$$C_{31F} = |L_u (A_{34F} + \mu A_{37F})| \quad (D-302)$$

$$C_{32F} = |\mu A_{40F} - A_{42F}| \quad (D-303)$$

Evaluation of Pivot Force $\tilde{F}_{y3L}$.

The pivot force F_{y3L} is obtained from

$$F_{y3L} = \frac{D_{F_{y3L}}}{D} \quad (D-304)$$

or

$$D_{F_{y3L}} = \begin{vmatrix} -1 & \mu & 1 & B_{s1f} \\ -\mu & -1 & \mu & B_{s2f} \\ \mu L_u & L_u & \mu L_L & B_{s3f} \\ -L_u & \mu L_u & -L_L & B_{s4f} \end{vmatrix} \quad (D-305)$$

Since the form of the above is the same as that of equation D-108, equation D-110 may be adapted to the present situation, therefore

$$D_{F_{y3L}} = (L_u + L_L)(1 + \mu^2)[- \mu L_u B_{s1f} + L_u B_{s2f} + B_{s3f} + \mu B_{s4f}] \quad (D-306)$$

The B_{si} terms are substituted according to equations D-275 to D-278, terms are collected and the tilded pivot force is defined

$$\tilde{F}_{y3L} = \frac{\tilde{D}_{F_{y3L}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{33F} + C_{34F}P_n + C_{35F}F_{23F} + C_{36F}\dot{\phi}] \quad (D-307)$$

where

$$C_{33F} = [\mu(A_{41F} + L_u A_{35F}) + A_{39F} - L_u A_{38F}] \quad (D-308)$$

$$C_{34F} = [L_u (\mu A_{33F} - A_{36F})] \quad (D-309)$$

$$C_{35F} = [L_u (\mu A_{34F} - \mu A_{37F})] \quad (D-310)$$

$$C_{36F} = [A_{40F} + \mu A_{42F}] \quad (D-311)$$

Determinations of Contact Force P_n in Terms of Escape Wheel Parameters (Round-on-Flat Contact)

Substitution of Conservative (Tilded) Pivot Forces into the z-Component of the Moment Equation. Again, let the sum of the tilded pivot forces be first determined. Subsequently, this expression is substituted into the moment equation D-259. Then

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L} = A_{43F} + A_{44F}P_n + A_{45F}F_{23F} + A_{46F}\dot{\phi} \quad (D-312)$$

where

$$L_T = L_U + L_L \quad (D-313)$$

$$A_{43F} = \frac{C_{21F} + C_{25F} + C_{29F} + C_{33F}}{L_T(1 + \mu^2)} \quad (D-314)$$

$$A_{44F} = \frac{C_{22F} + C_{26F} + C_{30F} + C_{34F}}{L_T(1 + \mu^2)} \quad (D-315)$$

$$A_{45F} = \frac{C_{23F} + C_{27F} + C_{31F} + C_{35F}}{L_T(1 + \mu^2)} \quad (D-316)$$

$$A_{46F} = \frac{C_{24F} + C_{28F} + C_{32F} + C_{36F}}{L_T(1 + \mu^2)} \quad (D-317)$$

Equation D-312 is now substituted into equation D-259. As earlier, for round-on-round contact the force F_{z3} of equation D-253 is made conservative, i.e.

$$\tilde{F}_{z3} = A_{47} = |N_z m_3| \quad (D-318)$$

Equation D-259 then becomes

$$\begin{aligned} & -P_n(A_1' - B_1\mu_1 S_4) - F_{23}F_{g2} - \mu P_{f3}A_{47F} - \mu P_3[A_{43F} + A_{44F}P_n \\ & + A_{45F}F_{23F} + A_{46F}\dot{\phi}] = I_{zs}\dot{\omega}_z + I_{zs}\ddot{\phi} \end{aligned} \quad (D-319)$$

Similar to what was done in equations D-236 and D-237, and for the same reasons, indicated near these expressions, the friction moment term $-\mu\rho_3 A_{46F} \dot{\phi}$ above is now modified to read

$$-\mu\rho_3 A_{46F} \frac{\dot{\phi}^2}{|\dot{\phi}|} \quad (D-320)$$

Equation D-319 then becomes

$$P_n \left[-A'_1 + B'_1 \mu_1 s_4 - \mu\rho_3 A_{44F} \right] + F_{23F} g_2 - \mu\rho_3 A_{46F} \frac{\dot{\phi}^2}{|\dot{\phi}|} - \mu [\rho_{f3} A_{47F} + \rho_3 A_{43F}] = I_{zs} \ddot{\phi} + I_{zs} \dot{\omega}_z \quad (D-321)$$

Finally, the above furnishes the contact force P_n

$$P_n = \frac{I_{zs} \ddot{\phi} + A_{48F} \dot{\phi}^2 + F_{23F} A_{49F} + A_{50F}}{A_{51F}} \quad (D-322)$$

where

$$A_{48F} = \frac{\mu\rho_3 A_{46F}}{|\dot{\phi}|} \quad (D-323)$$

$$A_{49F} = -g_2 \quad (D-324)$$

$$A_{50F} = I_{zs} \dot{\omega}_z + \mu [\rho_{f3} A_{47F} + \rho_3 A_{43F}] \quad (D-325)$$

$$A_{51F} = B'_1 \mu_1 s_4 - A'_1 - \mu\rho_3 A_{44F} \quad (D-326)$$

Combined Entrance Coupled Motion Differential Equation with Mesh 2 in Round-on-Flat Contact

Equations D-140 and D-322 are now set equal to each other. This furnishes the following combined coupled motion differential equation for the escapement under entrance conditions and with mesh 2 in the round-on-flat phase of contact

$$\begin{aligned}
& [A_{51F}I_{PR}U - A_{29}I_{zs}] \ddot{\phi} + [A_{51F}(A_{32}U^2 + I_{PR}V) - A_{29}A_{48F}] \dot{\phi}^2 \\
& + A_{51F}A_{31F}U\dot{\phi} = F_{23F}A_{29}A_{49F} + A_{29}A_{50F} - A_{51F}(A_9 + A_{30}) \\
& + A_{51F}m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)
\end{aligned} \tag{D-327}$$

Pallet and Escape Wheel in Exit Coupled Motion

Pallet Equations

The free body diagram of the pallet for exit coupled motion is given by figures D-7a and D-7b. Now (see refs 1 and 2)

$$\bar{P}_n = -P_n \bar{n}_n \tag{D-328}$$

This sign change will be reflected both in the force and in the moment expressions. The following shows the relevant changes in equations D-23 and D-140.

Changes in Force Equations of Pallet

Equation D-24 is modified to accommodate equation D-328. The associated friction forces have their directions determined by the signum functions s_4 and s_5 , as before. Therefore, equation D-24 is changed in its first term only

$$-P_n \bar{n}_n + \mu_1 s_4 P_n \bar{n}_t + \dots \tag{D-329}$$

With the unit vectors of equations D-25 and D-26, the x' -force equation D-27 is modified to

$$P_n \sin(\psi + \alpha) + \mu_1 s_4 P_n \cos(\psi + \alpha) - F_{x'u} - \mu_1 s_5 F_{y'u} + F_{x'L} + \dots \tag{D-330}$$

The terms in the y' -expression D-28 are changed as follows

$$-P_n \cos(\psi + \alpha) + \mu_1 s_4 P_n \sin(\psi + \alpha) - F_{y'u} - \mu_1 s_5 F_{x'u} + F_{y'L} + \dots \tag{D-331}$$

The expression for F_z remains as given by equation D-29.

Pallet rotates cw

Escape wheel rotates ccw

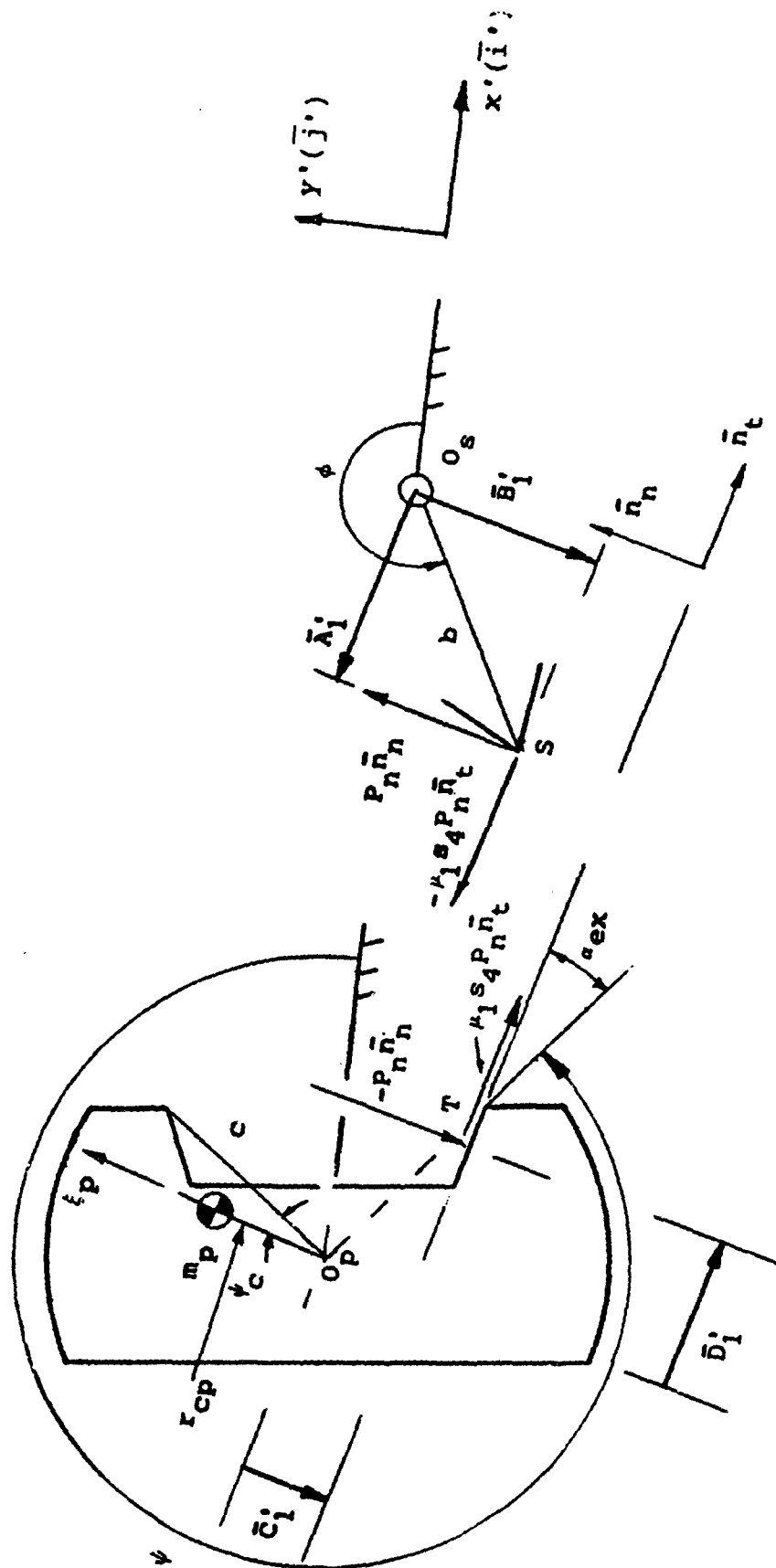
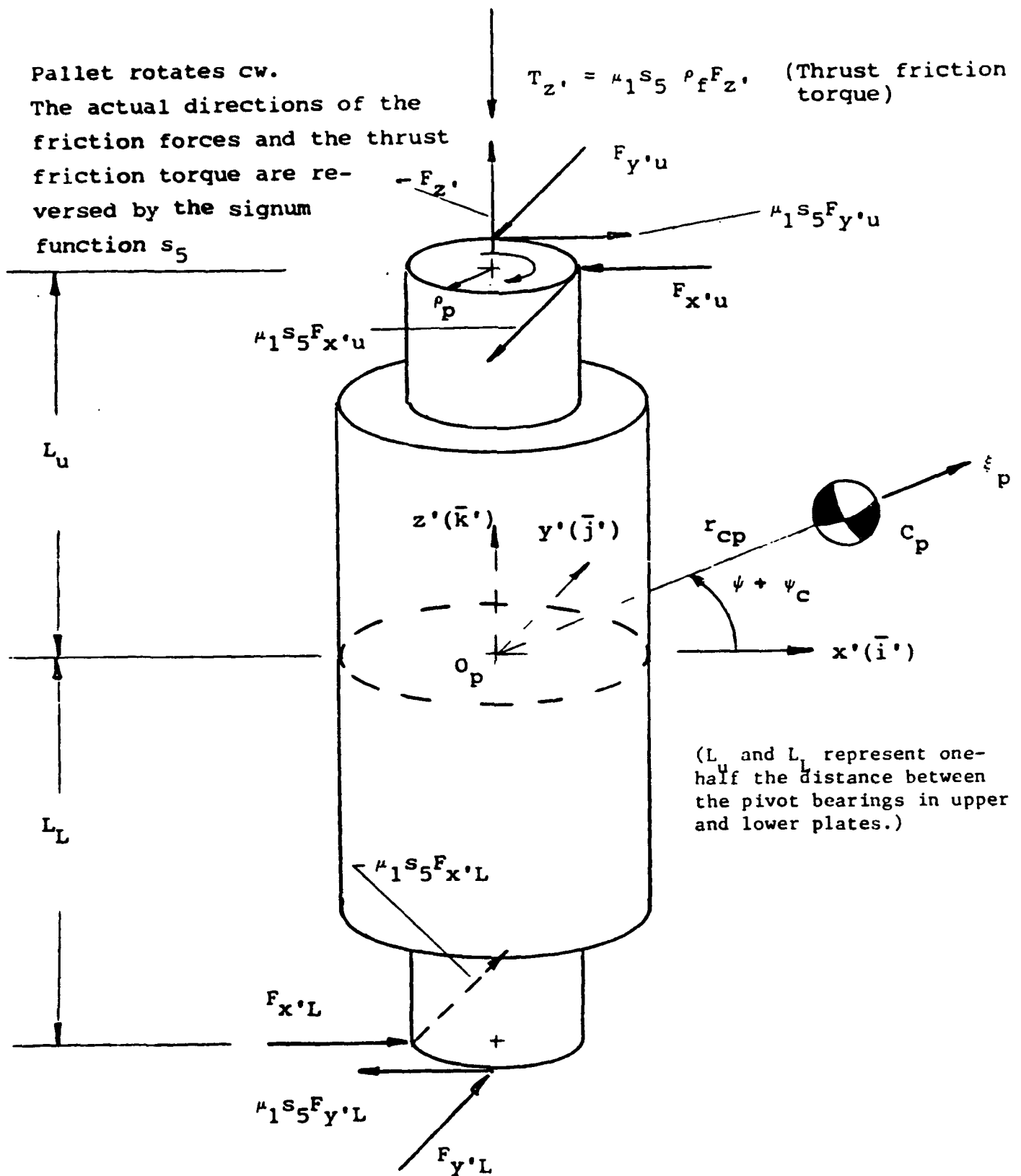


Figure D-7a. Top view free body diagram of pallet in exit coupled motion

● Pallet rotates cw.

The actual directions of the friction forces and the thrust friction torque are reversed by the signum function s_5



● Figure D-7b. Pallet in exit coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots.

Changes in Moment Equations of Pallet

The form of P_n , according to equation D-328, also reflects itself in the expression for $\bar{M}_{Op}$ (eq D-31). Therefore, for the exit case

$$\bar{M}_{Op} = -D_1 P_n \bar{k}' - \mu_1 s_4 C_1 P_n \bar{k}' \dots \dots \quad (D-332)$$

Simplification of Force and Moment Equations and Determination of Pallet Pivot Forces

x'-Force Component

Due to the change shown in equation D-330, the parameter A_{16} in equation D-48 must be changed to become

$$AA_{16} = -[\mu_1 s_4 \cos(\psi + \alpha) - \sin(\psi + \alpha)] \quad (D-333)$$

y'-Force Component

Similarly, because of the change in equation D-331, the parameter A_{21} in equation D-55 must be changed to

$$AA_{21} = -[\mu_1 s_4 \sin(\psi + \alpha) - \cos(\psi + \alpha)] \quad (D-334)$$

z'-Force Component

The z' -force component remains as that given by equation D-61, as stated earlier.

x'- and y'-Moment Component Equations

The x' - and y' -moment component equations remain unchanged from equations D-64 and D-65, respectively, since they do not contain P_n .

z'-Moment Component Equation

Because of the changes shown in equation D-332, the z' -moment component expression D-66 must now be modified to read

$$\begin{aligned} & -P_n (D'_1 + \mu_1 s_4 C'_1) - \rho_f A_{11} F_{z'} - \rho_p A_{11} F_{y'u} - \rho_p A_{11} F_{x'u} \\ & - \rho_p A_{11} F_{y'L} - \rho_p A_{11} F_{x'L} = -m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) + A_9 + A_{10} \ddot{\psi} \end{aligned} \quad (D-335)$$

Solution of Pallet Pivot Forces. The solution for the pivot forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$ is identical to that shown for the entrance coupled motion, keeping in mind that now the parameters AA_{16} and AA_{21} are used instead of A_{16} and A_{21} . Equation D-117 must subsequently be changed to

$$\tilde{F}_{x'u} + \tilde{F}_{y'u} + \tilde{F}_{x'L} + \tilde{F}_{y'L} = A_{24} + \dot{\psi}A_{25} + \dot{\psi}^2A_{26} + \ddot{\psi}A_{27} + P_nAA_{28} \quad (D-336)$$

A_{24} and A_{27} remain the same; so does AA_{28} as long as it is realized that it contains AA_{16} and AA_{21} (eq D-122a).

Substitution of Pallet Pivot Forces into z'-Moment Component Equation: Determination of P_n . Because of the changes in equation D-335, and using the same reasoning as employed for equations D-123 to D-128, equation D-129 becomes for exit coupled motion

$$\begin{aligned} &P_nAA_{29} - A_{30} - A_{31}\dot{\psi} - A_{32}\dot{\psi}^2 \\ &= I_{PR}\ddot{\psi} + A_9 - m_p r_{cp} (K_x \sin\beta - K_y \cos\beta) \end{aligned} \quad (D-337)$$

where

$$AA_{29} = -[D'_1 + C'_1\mu_1 S_4 + \rho_p\mu_1 S_5 AA_{28}] \quad (D-338)$$

Finally, parallel to equation D-137, the contact force P_n becomes

$$P_n = \frac{I_{PR}\ddot{\psi} + A_9 + A_{30} + A_{31}\dot{\psi} + A_{32}\dot{\psi}^2 - m_p r_{cp} (K_x \sin\beta - K_y \cos\beta)}{AA_{29}} \quad (D-339)$$

If this expression is rewritten in terms of the escape wheel variables $\dot{\phi}$ and $\ddot{\phi}$ the following equation which is similar to equation D-140 is obtained

$$\begin{aligned} P_n = & \frac{1}{AA_{29}} [I_{PR}U\ddot{\phi} + (A_{32}U^2 + I_{PR}V)\dot{\phi}^2 + A_{31}U\dot{\phi} \\ & + A_9 + A_{30} - m_p r_{cp} (K_x \sin\beta - K_y \cos\beta)] \end{aligned} \quad (D-340)$$

Changes in Force Equations of Escape Wheel and Pinion No. 3 in Exit Coupled Motion with Mesh No. 2 in Round-on-Round Contact

The free body diagram of the escape wheel and pinion no. 3 in exit coupled motion, with mesh no. 2 in round-on-round contact is shown in figures D-8a and D-8b. When compared to figure D-5a, the contact force $\bar{P}_n$ and its associated friction force are now different, i.e., they account for exit coupled motion.

Equation D-165 must be modified to read

$$P_n \bar{n}_n - \mu_1 S_4 P_n \bar{n}_t + F_{23} \bar{n}_{\lambda 2} + \mu S_2 R F_{23} \bar{n}_{N \lambda 2} + \dots \quad (D-341)$$

With the unit vectors of equations D-143 and D-144, the X-force component equation (changed from D-166) becomes

$$\begin{aligned} & P_n \sin(\psi + \alpha + \beta_3) + \mu_1 S_4 P_n \cos(\psi + \alpha + \beta_3) + F_{23} \cos \lambda_2 \\ & - \mu S_2 R F_{23} \sin \lambda_2 - F_{x3u} + \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \end{aligned} \quad (D-342)$$

The Y-force component is changed from equation D-167 to read

$$\begin{aligned} & -P_n \cos(\psi + \alpha + \beta_3) + \mu_1 S_4 P_n \sin(\psi + \alpha + \beta_3) + F_{23} \sin \lambda_2 \\ & + \mu S_2 R F_{23} \cos \lambda_2 - F_{y3u} - \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \end{aligned} \quad (D-343)$$

The Z-force component remains as in equations D-168, i.e.,

$$F_{z3} = N_3 m_3 \quad (D-344)$$

Escape Wheel and
Pinion No. 3 rotate
in ccw direction

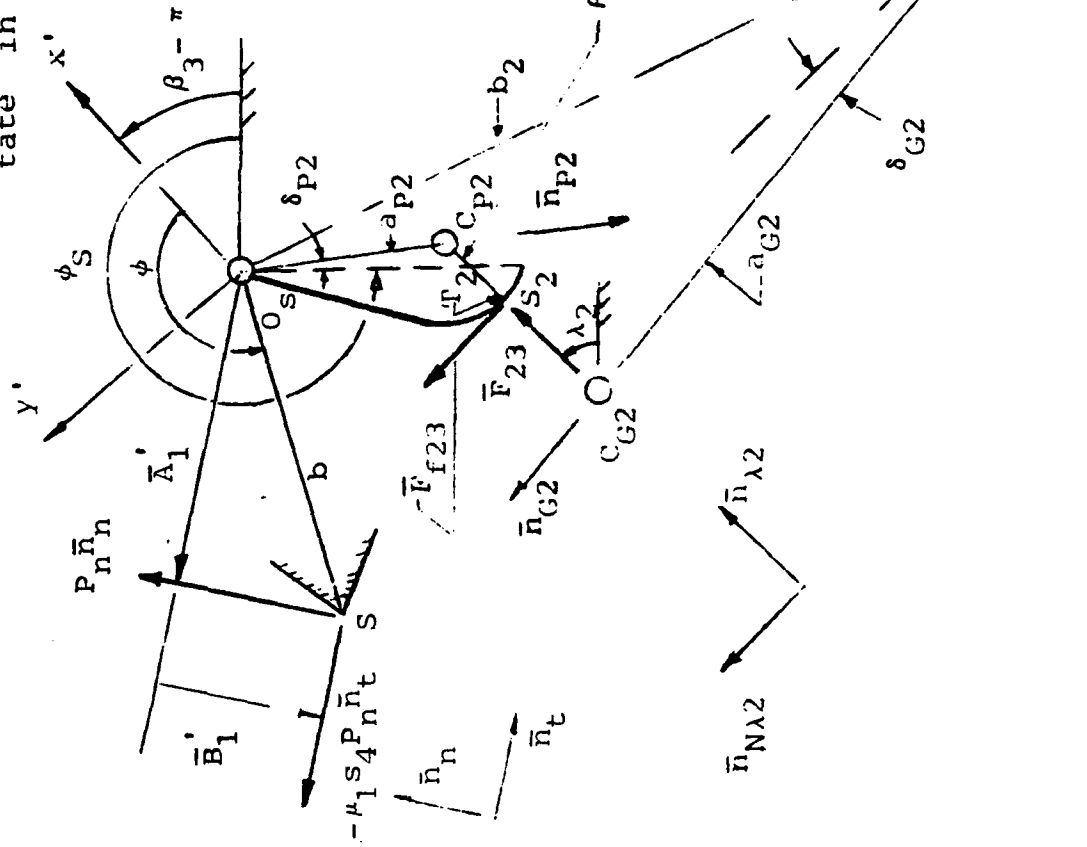


Figure D-8a. Top view of escape wheel and pinion no. 3 in exit coupled motion. Round-on-round contact of mesh no. 2



Changes in Moment Equations of Escape Wheel and Pinion No. 3 in Exit Coupled Motion with Mesh No. 2 in Round-on-Round Contact

Changes in Moment Equations of Escape Wheel. The moment equation D-169 for the escape wheel and pinion no. 3 must also reflect the change in P_n . The lefthand side of the above expression, as given by equation D-170 must be modified, because now the cross product

$$A_1 \bar{n}_1 \times P_n \bar{n}_n = P_n A_1' \bar{k} \quad (D-346)$$

This results in the following change to equation D-170

$$P_n (A_1' + B_1' \mu_1 s_4) \bar{k} - \mu p_{f3} F_{z3} \bar{k} + \dots \quad (D-346)$$

The righthand side of equation D-167 remains unchanged. The resulting X and Y moment component expressions, i.e., equations D-173 and D-174, respectively, are not influenced by the above change. The Z-moment component expression D-175 must now read

$$\begin{aligned} & P_n (A_1' + B_1' \mu_1 s_4) + a_{p2} F_{23} (\sin (\lambda_2 - \phi_s - \delta_{p2}) \\ & + \mu s_{2R} \cos (\lambda_2 - \phi_s - \delta_{p2})) - \dots \quad (D-347) \end{aligned}$$

Simplification of Force and Moment Equations and Determination of Escape Wheel Pivot Forces

X-Force Component

Due to the change in equation D-342 the parameter A_{33R} in equation D-176 must be changed to

$$AA_{33R} = \mu_1 s_4 \cos(\psi + \alpha + \beta_3) + \sin(\psi + \alpha + \beta_3) \quad (D-348)$$

Y-Force Component

Similarly, because of the change in equation D-343 the parameter A_{36R} in equation D-189 now becomes

$$AA_{36R} = \mu_1 s_4 \sin(\psi + \alpha + \beta_3) - \cos(\psi + \alpha + \beta_3) \quad (D-349)$$

Z-Force Component

The Z-force component remains presently as given by equation D-344.

As stated earlier, the X- and Y-components of the moment expressions for the escape wheel need not be changed. They are used in their final form as given by equations D-184 and D-187, respectively. Therefore, the X-component of the moment equations is given by

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L} = A_{39R} + A_{40R} \dot{\phi} \quad (D-350)$$

The Y-component of the moment equation is

$$-L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} = A_{41R} + A_{42R} \dot{\phi} \quad (D-351)$$

Solution of Escape Wheel Pivot Forces for Exit Coupled Motion. Since only the parameters AA_{33R} and A_{36R} differ in the set simultaneous equations D-176, D-181, D-350, and D-351 from those used in the solution for the pivot forces in entrance coupled motion, the latter is adapted to the present situation. Then, according to equation D-199

$$\tilde{F}_{x3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{21R} + CC_{22R}P_n + C_{23R}F_{23} + C_{24R}\dot{\phi}] \quad (D-352)$$

where, now

$$CC_{22R} = |L_L(AA_{33R} + \mu AA_{36R})| \quad (D-353)$$

and, as before

$$C_{21R} = |L_L A_{35R} - A_{41R} + \mu(L_L A_{38R} + A_{39R})|$$

$$C_{23R} = |L_L (A_{34R} + \mu A_{37R})|$$

$$C_{24R} = |\mu A_{40R} - A_{42R}|$$

According to equation D-207

$$\tilde{F}_{y3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{25R} + C_{26R} P_n + C_{27R} F_{23} + C_{28R} \phi] \quad (D-354)$$

where now

$$CC_{26R} = |L_L (AA_{36R} - \mu AA_{33R})| \quad (D-355)$$

and, as before

$$C_{25R} = |L_L A_{38R} + A_{39R} + \mu(A_{41R} - L_L A_{35R})|$$

$$C_{27R} = |L_L (A_{37R} - \mu A_{34R})|$$

$$C_{28R} = |A_{40R} + \mu A_{42R}|$$

According to equation D-215

$$\tilde{F}_{x3L} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{29R} + CC_{30R} P_n + C_{31R} F_{23} + C_{32R} \phi] \quad (D-356)$$

where, now

$$CC_{30R} = |L_u (AA_{33R} + \mu AA_{36R})| \quad (D-357)$$

and, as before

$$C_{29R} = |\mu (A_{39R} - L_U A_{38R}) - L_U A_{35R} - A_{41R}|$$

$$C_{31R} = |L_U (A_{34R} + \mu A_{37R})|$$

$$C_{32R} = |\mu A_{40R} - A_{42R}|$$

According to equation D-223

$$\bar{F}_{y3L} = \frac{1}{(L_U + L_L)(1 + \mu^2)} [C_{33R} + CC_{34R} P_n + C_{35R} F_{23} + C_{36R} \dot{\phi}] \quad (D-358)$$

where now

$$CC_{34R} = |L_U (\mu A A_{33R} - A A_{36R})| \quad (D-359)$$

and, as before

$$C_{33R} = |\mu (A_{41R} + L_U A_{35R}) + A_{39R} - L_U A_{38R}|$$

$$C_{35R} = |L_U (A_{34R} - A_{37R})|$$

$$C_{36R} = |A_{40R} + \mu A_{42R}|$$

Determination of Contact Force P_n in Terms of Escape Wheel Parameters (Exit Coupled Motion and Mesh 2 in Round-on-Round Contact)

Substitution of Conservative (Tilded) Pivot Forces into Z-Moment Expression. The sum of the tilded pivot forces is identical in form to equation D-228. Therefore with equations D-352, D-354, D-356, and D-358, the following is obtained

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L} = A_{43R} + AA_{44R}P_n + A_{45R}F_{23} + A_{46R}\dot{\phi} \quad (D-360)$$

where now

$$AA_{44R} = \frac{CC_{22R} + CC_{26R} + CC_{30R} + CC_{34R}}{L_T (1 + \mu^2)} \quad (D-361)$$

and, as before

$$A_{43R} = \frac{C_{21R} + C_{25R} + C_{29R} + C_{33R}}{L_T (1 + \mu^2)}$$

$$A_{45R} = \frac{C_{23R} + C_{27R} + C_{31R} + C_{35R}}{L_T (1 + \mu^2)}$$

$$A_{46R} = \frac{C_{24R} + C_{28R} + C_{32R} + C_{36R}}{L_T (1 + \mu^2)}$$

Substitution of equations D-234 (for D-344) and D-360 into equation D-347 furnishes the complete Z-component of the escape wheel moment expression for exit coupled motion with mesh 2 in round-on-round contact

$$\begin{aligned} & P_n (A'_1 + B'_1 \mu_1 s_4) + a_{P2} F_{23} (\sin (\lambda_2 - \phi_s - \delta_{P2}) + \mu s_2 R \cos (\lambda_2 - \phi_2 - \delta_{P2})) \\ & - \mu s_2 R P P_2 F_{23} - \mu p_{13} A_{47} - \mu p_3 [A_{43R} + AA_{44R} P_n + A_{45R} F_{23} + A_{46R} \dot{\phi}] \\ & = I_Z \ddot{\omega}_Z + I_Z \ddot{\phi} \end{aligned} \quad (D-362)$$

Using the same reasoning as given in connection with equations D-236 and D-237, equation D-362 is now solved for P_n . Therefore

$$\begin{aligned}
 P_n [A_1' + B_1' \mu_1 S_4 - \mu \rho_3 A A_{44R}] + F_{23} [\alpha_{P2} (\sin (\lambda_2 - \phi_s - \delta_{P2}) \\
 + \mu S_{2R} \cos (\lambda_2 - \phi_s - \delta_{P2})) - \mu S_{2R} P_{P2} - \mu \rho_3 A_{45R}] - \mu \rho_3 A_{46R} \frac{\dot{\phi}^2}{|\phi|} \\
 - \mu [\rho_{13} A_{47} + \rho_3 A_{43R}] = I_{zs} \ddot{\phi} + I_{zs} \dot{\omega}_z
 \end{aligned}
 \tag{D-363}$$

and, similar to equation D-239

$$P_n = \frac{I_{zs} \ddot{\phi} + A_{48R} \dot{\phi}^2 + F_{23} A_{49R} + A_{50R}}{A A_{51R}}
 \tag{D-364}$$

where now

$$A A_{51R} = A_1' + B_1' \mu_1 S_4 - \mu \rho_3 A A_{44R}
 \tag{D-365}$$

while as before

$$A_{48R} = \frac{\mu \rho_3 A_{46R}}{|\phi|}$$

$$A_{49R} = \mu (S_{2R} P_{P2} + \rho_3 A_{45R}) - a_{P2} (\sin (\lambda_2 - \phi_s - \delta_{P2}) + \mu S_{2R} \cos (\lambda_2 - \phi_s - \delta_{P2}))$$

$$A_{50R} = I_{zs} \dot{\omega}_z + \mu [\rho_{13} A_{47} + \rho_3 A_{43R}]$$

Combined Exit Coupled Motion Differential Equation with Mesh 2 in Round-on-Round Contact

Equations D-339 and D-364 are now set equal to each other in order to obtain the combined coupled motion differential equation of the escapement under exit conditions and with mesh 2 in round-on-round contact.

$$\begin{aligned}
& [AA_{51R}I_{PR}U - AA_{29}I_{zs}] \ddot{\phi} + [AA_{51R}(A_{32}U^2 + I_{PR}V) - AA_{29}A_{48R}] \dot{\phi}^2 \\
& + AA_{51R}A_{31}U\dot{\phi} = F_{23}AA_{29}A_{49R} + AA_{29}A_{50R} - AA_{51R}(A_9 + A_{30}) \\
& + AA_{51R}m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)
\end{aligned} \tag{D-366}$$

The above expression has the same form as equation D-244, and the difference between the entrance and exit coupled motion depends on the value of the signum function s_7 which is introduced in the next section.

Common Differential Equation and Common Expressions for Entrance and Exit Coupled Motion of Escapement with Mesh No. 2 in Round-on-Round Contact

It is possible to obtain common expressions for both combined entrance and exit coupled motion differential equations with mesh no. 2 in round-on-round contact. (eqs D-244 and D-366).

The AA_{iR} 's and CC_{iR} 's of the exit coupled motion differ only in certain signs from the A_{iR} 's and C_{iR} 's, of identical subscript i , associated with entrance coupled motion. This is due only to the differences in escapement geometry.

Common expressions for the above parameters result from the introduction of the signum function s_7 , where

s_7 = positive for entrance coupled motion

s_7 = negative for exit coupled motion

With the above, equations D-54 and D-333 are satisfied, if

$$A_{16} = AA_{16} = -[\mu_1 s_4 \cos(\psi + \alpha) - s_7 \sin(\psi + \alpha)] \tag{D-367}$$

Equations D-60 and D-334 are satisfied, if

$$A_{21} = AA_{21} = -[s_7 \cos(\psi + \alpha) + \mu_1 s_4 \sin(\psi + \alpha)] \tag{D-368}$$

Equations D-130 and D-338 are satisfied, if

$$A_{29} = AA_{29} = s_7 D_1' - C_1' \mu_1 s_4 - \rho_p \mu_1 s_5 A_{28} \quad (D-369)$$

A_{28} appears first in equation D-112a and AA_{28} in equation D-336. Both are functions of A_{16} and A_{21} by way of the appropriate C_i 's. (The CC_i 's are not specifically given in conjunction with eq D-336.)

Equations D-177 and D-348 are satisfied, if

$$A_{33} = A_{33R} = AA_{33R} = \mu_1 s_4 \cos(\psi + \alpha + \beta_3) - s_7 \sin(\psi + \alpha + \beta_3) \quad (D-370)$$

Equations D-181 and D-349 are satisfied, if

$$A_{36} = A_{36R} = AA_{36R} = \mu_1 s_4 \sin(\psi + \alpha + \beta_3) + s_7 \cos(\psi + \alpha + \beta_3) \quad (D-371a)$$

In addition, equations D-243 and D-365 are satisfied, if

$$A_{51} = A_{51R} = AA_{51R} = B_1' \mu_1 s_4 - s_7 A_1' - \mu \rho_3 A_{44} \quad (D-371b)$$

In the above, $A_{44} = A_{44R} = AA_{44R}$

A_{44R} appears first in equation D-231 and is a function of A_{33R} and A_{36R} by way of the appropriate CC_{iR} 's.

AA_{44R} appears first in equation D-361 and is a function of AA_{33R} and AA_{36R} by way of the appropriate CC_{iR} 's.

As a consequence, it is also to be noted that

$$\left. \begin{aligned} C_{22R} &= CC_{22R} \\ C_{26R} &= CC_{26R} \\ C_{30R} &= CC_{30R} \\ C_{34R} &= CC_{34R} \end{aligned} \right\} \quad (D-371c)$$

(eqs D-231 and D-361).

Finally, the combined coupled motion differential equation of the escapement with mesh no. 2 in round-on-round contact becomes, regardless of exit or entrance motion, with equations D-244 and D-366:

$$\begin{aligned} & [A_{51} I_{PR} U - A_{29} I_{zs}] \ddot{\phi} + [A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}] \dot{\phi}^2 + A_{51} A_{31} U \dot{\phi} \\ & = F_{23} A_{29} A_{49R} + A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \end{aligned} \quad (D-372)$$

It will be shown later that the common parameters A_{16} , A_{21} , A_{28} , A_{29} , A_{33} , A_{36} , A_{44} , and A_{51} may also be used when mesh no. 2 is in round-on-flat contact. (See work preceding equation D-403.) Further, note that letter subscripts have now been dropped from A_{48} and A_{50} , since these parameters depend on mass or friction only.

Changes in Force Equations of Escape Wheel and Pinion No. 3 in Exit Coupled Motion with Mesh No. 2 in Round-on-Flat Contact

The free body diagram of the escape wheel and the pinion no. 3 in exit coupled motion, with mesh 2 in round-on-flat contact, is shown in figures D-9a and D-9b. Again the contact force P_n and its associated friction force conform to exit coupled motion conditions. The forces F_{23F} and its associated friction force on the flat of the pinion are identical to those shown earlier in figure D-6a. Equation D-249, the force equation for entrance coupled motion with mesh no. 2 in round-on-flat contact, must now be modified to

$$P_n \bar{n}_n - \mu_1 S_4 P_n \bar{n}_t + F_{23F} \bar{n}_{NF2} + \mu S_{2F} \bar{n}_{F2} + F_{23} \bar{k} - \dots \quad (D-373)$$

Escape Wheel and Pinion
No. 3 rotate in ccw direction

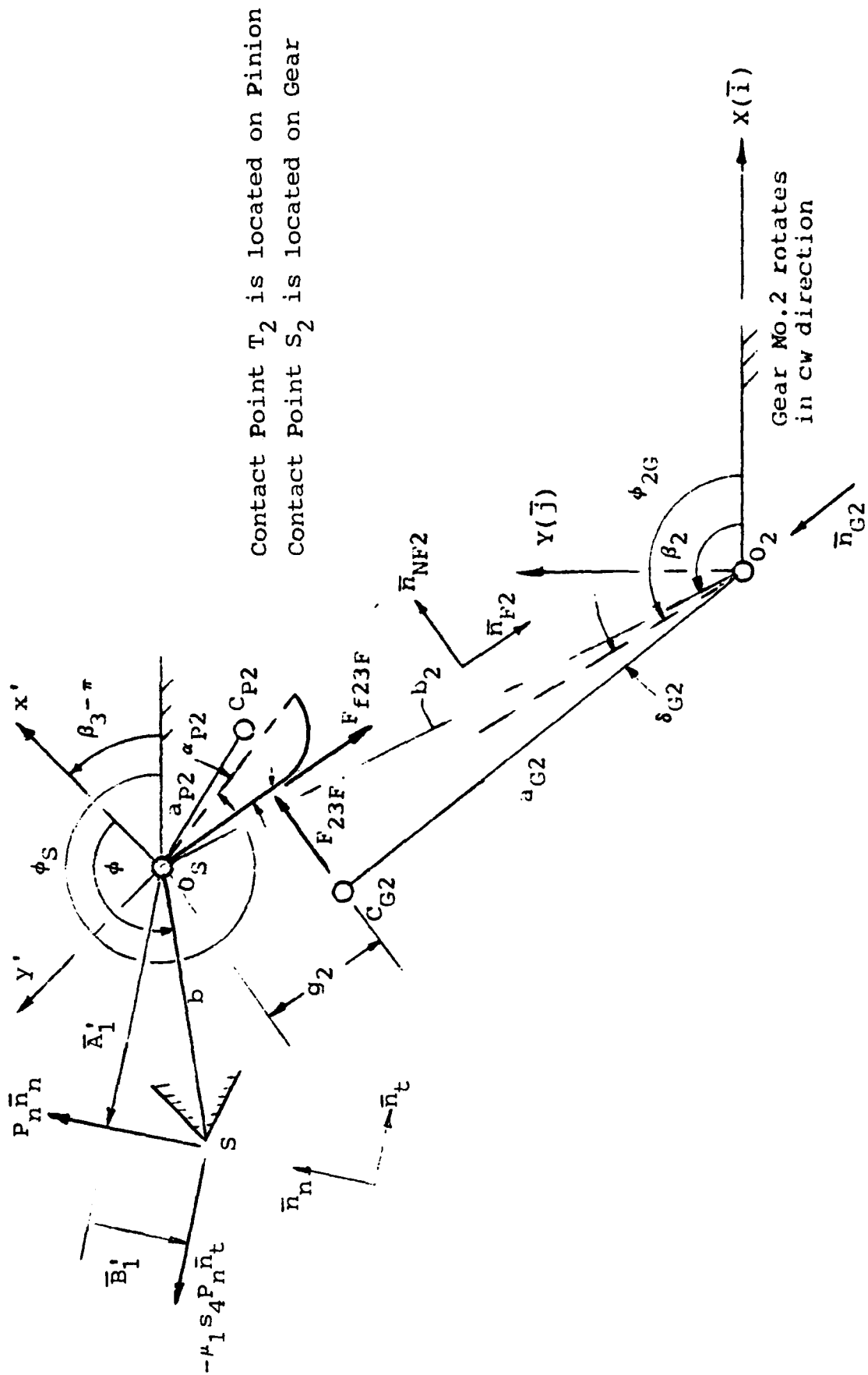


Figure D-9a. Top view of escape wheel and pinion no. 3 in exit coupled motion. Round-on-flat contact of mesh no. 2

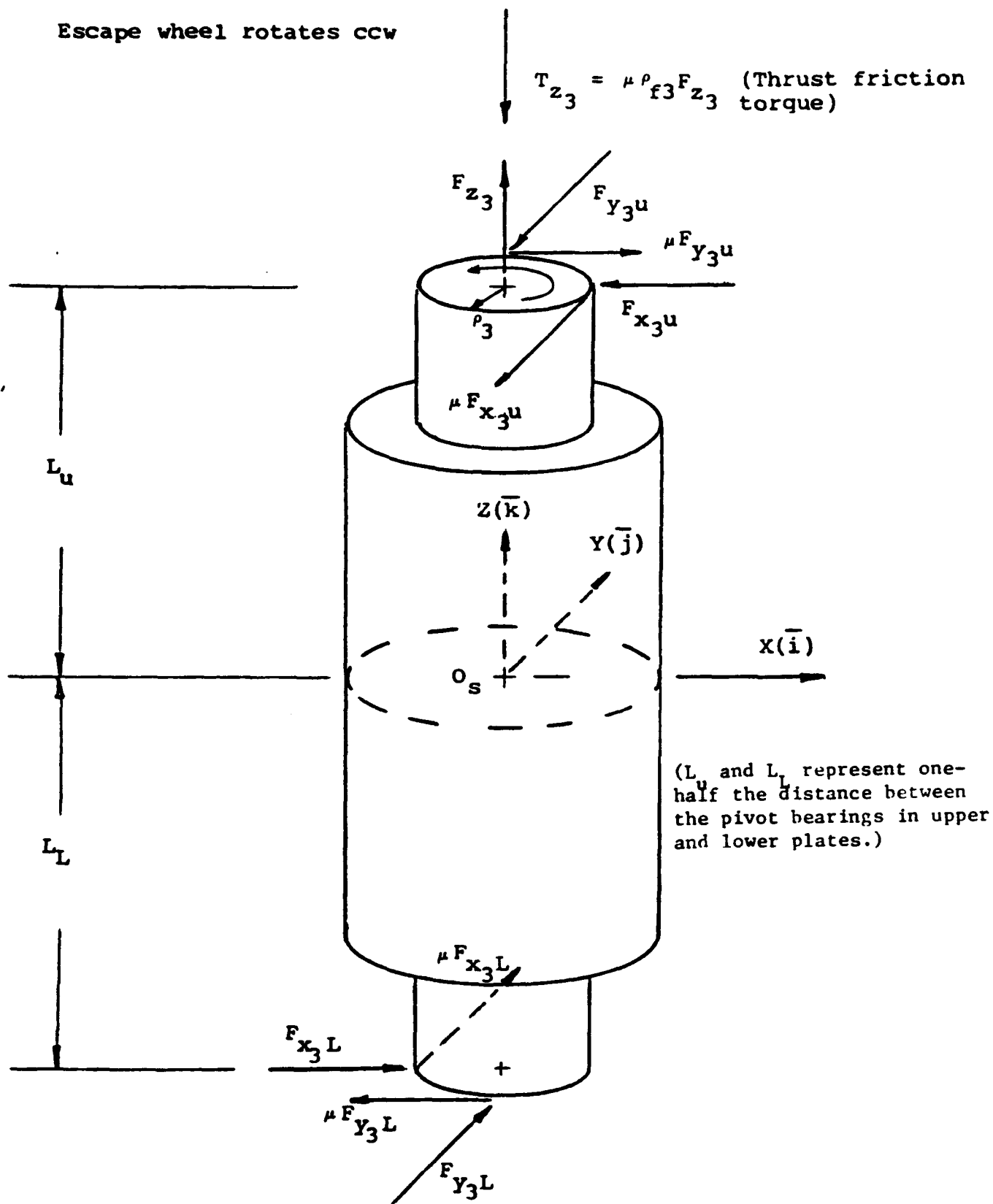


Figure D-9b. Escape wheel and pinion no. 3 in exit coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots. (Same as figure D-8b. Not influenced by type of mesh contact.)

Substitution of the appropriate unit vector, according to equation D-143, D-144, D-245, and D-247, furnishes the following force component equations

X-force component (changed from equation D-251)

$$P_n \sin(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \cos(\psi + \alpha + \beta_3) - F_{23F} \sin(\phi_s - \alpha_{P2}) \\ + \mu s_{2F} F_{23F} \cos(\phi_s - \alpha_{P2}) - F_{x3u} + \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \quad (D-374)$$

The Y-force component is changed from equation D-252 to read

$$- P_n \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \sin(\psi + \alpha + \beta_3) + F_{23F} \cos(\phi_s - \alpha_{P2}) \\ + \mu s_{2F} F_{23F} \sin(\phi_s - \alpha_{P2}) - F_{y3u} - \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \quad (D-375)$$

The Z-force component remains as in equation D-253, i.e.,

$$F_{23} = N_z m_3 \quad (D-376)$$

Changes in Moment Equations of Escape Wheel and Pinion No. 2 in Exit Coupled Motion with Mesh No. 2 in Round-on-Flat Contact

As for round-on-round contact, the moment contribution of the escapement forces leads to the following change of equation D-254. (See also equation D-346)

$$P_n (A'_1 + B'_1 \mu_1 s_4) \bar{k} - \mu \rho_{F3} F_{23} \bar{k} + \dots \quad (D-377)$$

The resulting X and Y moment component expressions, i.e., equations D-257 and D-258, respectively, are not influenced by the above change. The Z-component expression D-259 must now be modified to read

$$P_n (A'_1 + B'_1 \mu_1 s_4) + F_{23F} g_2 - \mu \rho_{13} F_{23} - \dots \quad (D-378)$$

Simplification of Force and Moment Equations and Determination of Escape Wheel Pivot Forces

X-Force Component

Due to the change in equation D-374, the parameter A_{33F} in equation D-261 must be changed to

$$AA_{33F} = \mu_1 s_4 \cos(\psi + \alpha + \beta_3) + \sin(\psi + \alpha + \beta_3) \quad (D-379)$$

Y-Force Component

Similarly, because of the change in equation D-375, the parameter A_{36F} in equation D-265 now becomes

$$AA_{36F} = \mu_1 s_4 \sin(\psi + \alpha + \beta_3) - \cos(\psi + \alpha + \beta_3) \quad (D-380)$$

Z-Force Component

The Z-force component remains presently as given by equation D-376.

As stated earlier, the X- and Y-components of the moment expressions for the escape wheel need not be changed. They are used in their final form as given by equations D-268 and D-271, respectively. Therefore, the X-component of the moment equation is given by

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L} = A_{39F} + A_{40F} \dot{\phi} \quad (D-381)$$

The Y-component of the moment equation is

$$-L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} = A_{41F} + A_{42F} \dot{\phi} \quad (D-382)$$

The Z-component of the moment equation remains in the form of equation D-378.

Solution of Escape Wheel Pivot Forces for Exit Coupled Motion. Since only the parameters AA_{33F} and AA_{36F} differ in the set of simultaneous equations D-374, D-375, D-381, and D-382 from those used in the solution for the pivot forces in entrance coupled motion, the latter is adapted to the present situation. Then, according to equation D-283

$$\tilde{F}_{x3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{21F} + CC_{22F} P_n + C_{23F} F_{23F} + C_{24F} \dot{\phi}] \quad (D-383)$$

where, now

$$CC_{22F} = |L_L (AA_{33F} + \mu AA_{36F})| \quad (D-384)$$

and, as before

$$C_{21F} = |L_L A_{35F} - A_{41F} + \mu(L_L A_{38F} + A_{39F})|$$

$$C_{23F} = |L_L (A_{34F} + \mu A_{37F})|$$

$$C_{24F} = |\mu A_{40F} - A_{42F}|$$

According to equation D-290

$$\tilde{F}_{y3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{25F} + CC_{26F}P_n + C_{27F}F_{23F} + C_{28F}\phi] \quad (D-385)$$

where, now

$$CC_{26F} = |L_L (AA_{36F} - \mu AA_{33F})| \quad (D-386)$$

and, as before

$$C_{25F} = |L_L A_{38F} + A_{39F} + \mu(A_{41F} - L_L A_{35F})|$$

$$C_{27F} = |L_L (A_{37F} - \mu A_{34F})|$$

$$C_{28F} = |A_{40F} + \mu A_{42F}|$$

According to equation D-299

$$\tilde{F}_{x3L} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{29F} + CC_{30F}P_n + C_{31F}F_{23F} + C_{32F}\phi] \quad (D-387)$$

where, now

$$CC_{30F} = |L_u(AA_{33F} + \mu AA_{36F})| \quad (D-388)$$

and, as before

$$C_{29F} = |\mu(A_{39F} - L_u A_{38F}) - L_u A_{35F} - A_{41F}|$$

$$C_{31F} = |L_u(A_{34F} + \mu A_{37F})|$$

$$C_{32F} = |\mu A_{40F} - A_{42F}|$$

According to equation D-307

$$\tilde{F}_{y3L} = \frac{1}{(L_u + L_l)(1 + \mu^2)} [C_{33F} + CC_{34F}P_n + C_{35F}F_{23F} + C_{36F}\phi] \quad (D-389)$$

where, now

$$CC_{34F} = |L_u(\mu AA_{33F} + AA_{36F})| \quad (D-390)$$

and, as before

$$C_{33F} = |\mu(A_{41F} + L_u A_{35F}) + A_{39F} - L_u A_{38F}|$$

$$C_{35F} = |L_u(\mu A_{34F} - A_{37F})|$$

$$C_{36F} = |A_{40F} + \mu A_{42F}|$$

Determination of Contact Force P_n in Terms of Escape Wheel Parameters. (Exit Coupled Motion and Mesh No. 2 in Round-on-Flat Contact)

Substitution of Conservative (Tilded) Pivot Forces into Z-Moment Expressions. The sum of the tilded pivot forces is identical in form to equation D-312. Therefore, with equations D-383, D-385, D-387, and D-389, the following is obtained

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L} = A_{43F} + AA_{44F}P_n + A_{45F}F_{23F} + A_{46F}\dot{\phi} \quad (D-391)$$

where now,

$$AA_{44F} = \frac{CC_{22F} + CC_{26F} + CC_{30F} + CC_{34F}}{L_T(1 + \mu^2)} \quad (D-392)$$

and, as before

$$AA_{43F} = \frac{CC_{21F} + CC_{25F} + CC_{29F} + CC_{33F}}{L_T(1 + \mu^2)}$$

$$AA_{45F} = \frac{CC_{23F} + CC_{27F} + CC_{31F} + CC_{35F}}{L_T(1 + \mu^2)}$$

$$AA_{46F} = \frac{CC_{24F} + CC_{28F} + CC_{32F} + CC_{36F}}{L_T(1 + \mu^2)}$$

Substitution of equations D-318 and D-391 into equation D-378 furnishes the complete Z-component of the escape wheel moment expression for exit coupled motion.

$$P_n \left(A'_1 + B'_1 \mu_1 s_4 \right) + F_{23F} g_2 - \mu p_{13} A_{47} - \mu p_3 \left[A_{43F} + AA_{44F} P_n + A_{45F} F_{23F} + A_{46F} \dot{\phi} \right] = I_{zs} \dot{\omega}_z + I_{zs} \ddot{\phi} \quad (D-393)$$

Using the same reasoning as given in connection with equations D-236 and D-237, equation D-393 is now solved for P_n . Therefore

$$P_n \left[A'_1 + B'_1 \mu_1 s_4 - \mu \rho_3 AA_{44F} \right] + F_{23F} g_2 - \mu \rho_3 A_{46} \frac{\dot{\phi}^2}{|\dot{\phi}|} - \mu [\rho_{13} A_{47} + \rho_3 A_{43}] = I_{zs} \ddot{\phi} + I_{zs} \dot{\omega}_z$$

and, similar to equation D-322

$$P_n = \frac{I_{zs} \ddot{\phi} + A_{48F} \dot{\phi}^2 + F_{23F} A_{49F} + A_{50F}}{AA_{51F}} \quad (D-395)$$

where now

$$AA_{51F} = A'_1 + B'_1 \mu_1 s_4 - \mu \rho_3 AA_{44F} \quad (D-396)$$

while as before

$$A_{48F} = \frac{\mu \rho_3 A_{46F}}{|\dot{\phi}|}$$

$$A_{49F} = g_2$$

$$A_{50F} = I_{zs} \dot{\omega}_z + \mu [\rho_{13} A_{47} + \rho_3 A_{43F}]$$

Combined Exit Coupled Motion Differential Equation with Mesh No. 2 in Round-on-Flat Contact

Equations D-339 and D-395 are now set equal to each other in order to obtain the combined coupled motion differential equation of the escapement under exit conditions

$$\begin{aligned} & [AA_{51F} I_{PR} U - AA_{29} I_{zs}] \ddot{\phi} + [AA_{51F} (A_{32} U^2 + I_{PR} V) - AA_{29} A_{48F}] \dot{\phi}^2 \\ & + AA_{51F} A_{31} U \dot{\phi} = F_{23F} AA_{29} A_{49F} + AA_{29} A_{50F} - AA_{51F} (A_9 + A_{30}) \\ & + AA_{51F} m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \end{aligned} \quad (D-397)$$

The above expression has the same form as equation D-327, and the difference between entrance and exit coupled motion depends, as for the round-on-round regimes, on the value of the signum function s_7 , as defined in preceding equation D-367.

Common Differential Equation and Common Expressions for Entrance and Exit Coupled Motion of the Escapement with Mesh No. 2 in Round-on-Flat Contact

Just as for round-on-round contact of mesh no. 2 (eq D-372) it is possible, with the help of signum functions s_7 , to obtain certain expressions that are common to both entrance and exit coupled motion differential equations for the combined escapement when mesh no. 2 is in round-on-flat contact.

Since the resulting expressions depend only on the escapement geometry, they are not influenced by the type of contact of mesh no. 2, and they are, therefore, identical to those indicated earlier in equations D-367 to D-371c.

The following enumerates these parameters with the appropriate change of the relevant subscriptions.

As in equation D-367, D-54 and D-333 are combined to

$$A_{16} = AA_{16} = -[\mu_1 s_4 \cos(\psi + \alpha) - s_7 \sin(\psi + \alpha)] \quad (D-398)$$

Again, as in equation D-368, D-60 and D-334 have the common form

$$A_{21} = AA_{21} = -[s_7 \cos(\psi + \alpha) + \mu_1 s_4 \sin(\psi + \alpha)] \quad (D-399)$$

Because of the above general expressions, the expressions for C_5 , C_{10} , C_{15} , and C_{20} (eqs D-86, D-96, D-106, and D-116, respectively) which are functions of them, can be used to determine the identical forms of A_{28} and AA_{28} (eqs D-122a and D-336, respectively).

$$A_{29} = AA_{29} = s_7 D_1' - C_1' \mu_1 s_4 - p p \mu_1 s_5 A_{28} \quad (D-400)$$

As in equation D-370, equations D-177 and D-348, as well as D-261 and D-379, will be satisfied with

$$A_{33} = A_{33R} = AA_{33R} = A_{33F} = AA_{33F} = \mu_1 s_4 \cos(\psi + \alpha + \beta_3) - s_7 \sin(\psi + \alpha + \beta_3) \quad (D-401)$$

Also, as in equation D-371a, equations D-181 and D-349, as well as D-265 and D-380 will be satisfied with

$$A_{36} = A_{36R} = AA_{36R} = A_{36F} = AA_{36F} = \mu_1 s_4 \sin(\psi + \alpha + \beta_3) + s_7 \cos(\psi + \alpha + \beta_3) \quad (D-204a)$$

Because of the generality of A_{33} and A_{36} , the following parameters which are functions of A_{33} and A_{36} , also only depend on s_7 and common expressions may be found.

$$\left. \begin{aligned} C_{22} &= C_{22R} = CC_{22R} = C_{22F} = CC_{22F} \text{ (eqs D-201, D-352, D-285, D-384, resp)} \\ C_{26} &= C_{26R} = CC_{26R} = C_{26F} = CC_{26F} \text{ (eqs D-209, D-355, D-293, D-386, resp)} \\ C_{30} &= C_{30R} = CC_{30R} = C_{30F} = CC_{30F} \text{ (eqs D-217, D-357, D-301, D-388, resp)} \\ C_{34} &= C_{34R} = CC_{34R} = C_{34F} = CC_{34F} \text{ (eqs D-225, D-359, D-309, D-390, resp)} \end{aligned} \right\} (D-402b)$$

The above now leads to

$$A_{44} = A_{44R} = AA_{44R} = A_{44F} = AA_{44F} = \frac{C_{22} + C_{26} + C_{30} + C_{34}}{L_T(1 + \mu^2)} \quad (D-402c)$$

with equations D-231, D-361, D-315, and D-392, respectively.

Finally, as in equation D-371b, equations D-243 and D-365, as well as D-326 and D-396 will be satisfied with

$$A_{51} = A_{51R} = AA_{51R} = A_{51F} = AA_{51F} = B_1' \mu_1 s_4 - s_7 A_1' - \mu p_3 A_{44} \quad (D-402d)$$

These considerations now make it possible to write a combined escapement differential equation for coupled motion when mesh no. 2 is in round-on-flat contact

$$[A_{51} I_{PR} U - A_{29} I_{zs}] \ddot{\phi} + [A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}] \dot{\phi}^2 + A_{51} A_{31} U \dot{\phi} \\ = F_{23F} A_{29} A_{49F} + A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_P r_{cp} (K_x \sin \beta - K_y \cos \beta) \quad (D-403)$$

Note the similarity of the above expression with equation D-372. It differs only in the parameters F_{23F} and A_{49F} . The letter subscripts of A_{48} and A_{50} have again been dropped, since these parameters depend only on mass and friction.

DYNAMICS OF ROTOR AND GEAR NO. 1

Before the force and moment equations of the rotor, with mesh no. 1 in round-on-round or round-on-flat contact, can be considered, it is first necessary to obtain expressions for the absolute acceleration of the rotor pivot O_1 and the rotor center of mass C_1 .

A top view of the rotor in the mechanism plane is shown in figure D-10. (fig. A-3).

Absolute Acceleration of Rotor Pivot O_1

The absolute acceleration of the rotor pivot O_1 is given by

$$\bar{A}_{O_1/\text{ground}} = \bar{A}_{O_1/C} + \bar{A}_{C/\text{ground}} \quad (D-404)$$

where

$\bar{A}_{C/\text{ground}}$ = given by equation C-4, appendix C in the projectile fixed X-Y system,

while

$$\bar{A}_{O_1/C} = \bar{\omega} \times (\bar{\omega} \times \bar{R}_1) + \bar{\dot{\omega}} \times \bar{R}_1 \quad (D-405)$$

After substituting

$$\bar{\mathcal{R}}_1 = \mathcal{R}_1 \bar{i} \quad (D-406)$$

and equations A-1 and A-5 for $\bar{\omega}$ and $\dot{\bar{\omega}}$, respectively, the following is obtained

$$\bar{A}_{O_1/C} = L_x \bar{i} + L_y \bar{j} + L_z \bar{k} \quad (D-407)$$

where

$$L_x = -(\omega_y^2 + \omega_z^2) \mathcal{R}_1 \quad (D-408)$$

$$L_y = (\omega_x \omega_y + \dot{\omega}_z) \mathcal{R}_1 \quad (D-409)$$

$$L_z = (\omega_x \omega_z - \dot{\omega}_y) \mathcal{R}_1 \quad (D-410)$$

Together with equations D-87 and C-4, the following is obtained for equation D-404

$$\bar{A}_{O_1/\text{ground}} = O_x \bar{i} + O_y \bar{j} + O_z \bar{k} \quad (D-411)$$

where

$$O_x = G_x + L_x \quad (D-412)$$

$$O_y = G_y + L_y \quad (D-413)$$

$$O_z = G_z + L_z \quad (D-414)$$

Absolute Acceleration of the Rotor Center of Mass C_1

To determine the absolute acceleration of the rotor center of mass in the X-Y-Z system, it is first necessary to find $\bar{A}_{C_1/O_1}$, the acceleration of the rotor center of mass with respect to the rotor pivot O_1 , in the $\xi_1 - \eta_1 - \zeta_1$ system (fig. D-10). Subsequently, this expression is transformed into the X-Y-Z system and added to the absolute acceleration of point O_1 as given by equation D-411. Therefore

$$\bar{A}_{C_1/\text{ground}} = \bar{A}_{C_1/O_1} + \bar{A}_{O_1/\text{ground}} \quad (D-415)$$

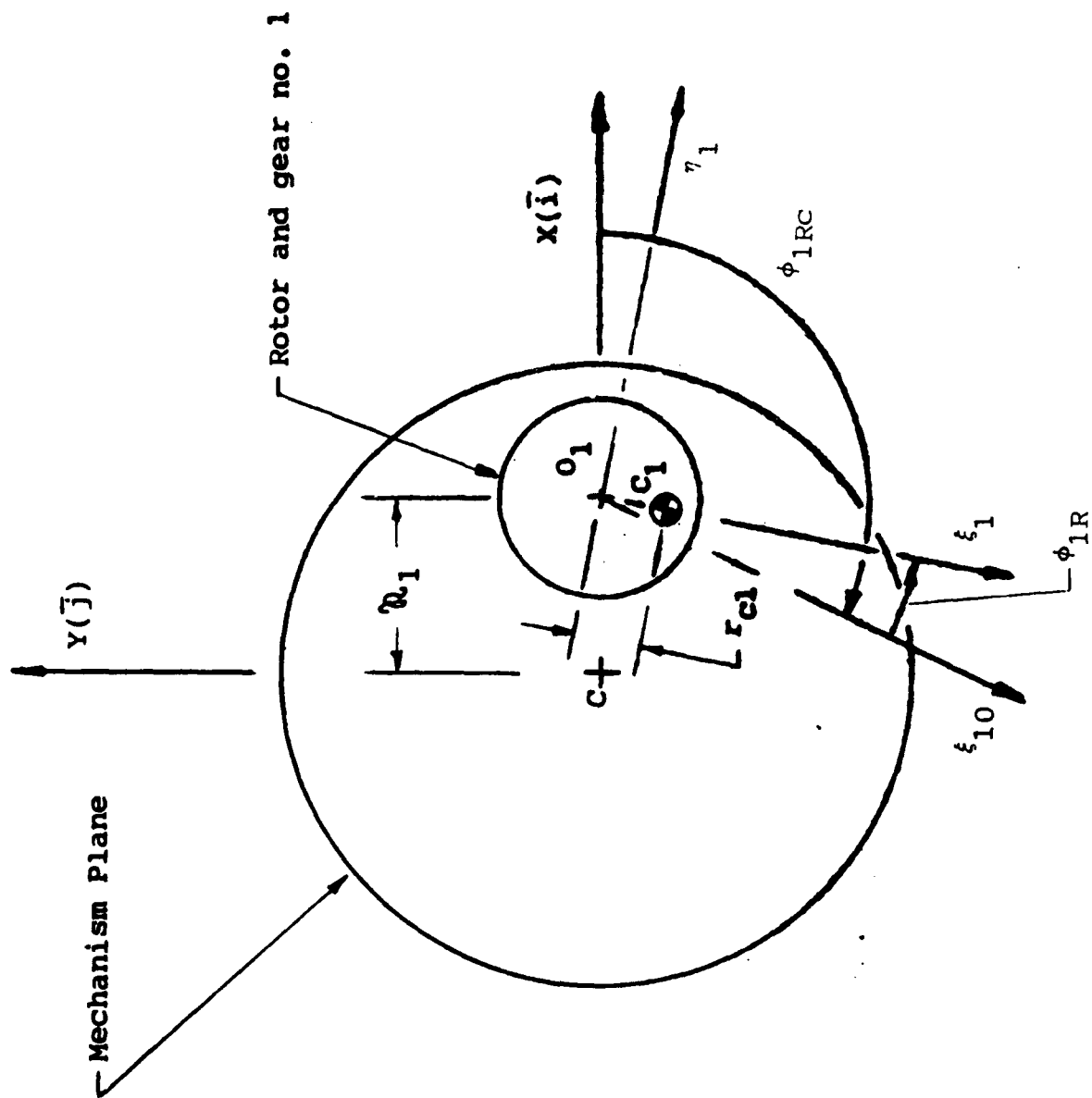


Figure D-10. Top view of rotor and gear no. 1 and mechanism plane

The term $\bar{A}_{C_1/O_1}$ is obtained from

$$\bar{A}_{C_1/O_1} = \bar{\omega}_1 \times (\bar{\omega}_1 \times r_{C1}) + \dot{\bar{\omega}}_1 \times r_{C1} \quad (D-416)$$

where

$$r_{C1} = r_{C1} \bar{n}_{\xi_1} \quad (D-417)$$

The terms $\bar{\omega}_1$ and $\dot{\bar{\omega}}_1$ are taken from equations A-37 and A-41, respectively.

When all operations are performed, equation D-416 becomes

$$\bar{A}_{C_1/O_1} = -r_{C1} [\omega_{\eta_1}^2 + \omega_{\zeta_1}^2] \bar{n}_{\xi_1} + r_{C1} [\omega_{\xi_1} \omega_{\eta_1} + \dot{\omega}_{\zeta_1}] \bar{n}_{\eta_1} + r_{C1} [\omega_{\xi_1} \omega_{\zeta_1} - \dot{\omega}_{\eta_1}] \bar{n}_{\zeta_1} \quad (D-418)$$

With the help of equations A-31 to A-34 substitute for the above body-fixed unit vectors; i.e.

$$\bar{n}_{\xi_1} = \cos \gamma \bar{i} + \sin \gamma \bar{j} \quad (D-419)$$

$$\bar{n}_{\eta_1} = -\sin \gamma \bar{i} + \cos \gamma \bar{j} \quad (D-420)$$

$$\bar{n}_{\zeta_1} = \bar{k} \quad (D-421)$$

where

$$\gamma = \phi_{1Rc} + \phi_{1R} \quad (D-422)$$

This results in

$$\begin{aligned} \bar{A}_{C_1/O_1} = & -r_{C1} [(\omega_{\eta_1}^2 + \omega_{\zeta_1}^2) \cos \gamma + (\omega_{\xi_1} \omega_{\eta_1} + \dot{\omega}_{\zeta_1}) \sin \gamma] \bar{i} - r_{C1} [(\omega_{\eta_1}^2 + \omega_{\zeta_1}^2) \\ & \sin \gamma - (\omega_{\xi_1} \omega_{\eta_1} + \dot{\omega}_{\zeta_1}) \cos \gamma] \bar{j} + r_{C1} (\omega_{\xi_1} \omega_{\zeta_1} - \dot{\omega}_{\eta_1}) \bar{k} \end{aligned} \quad (D-423)$$

Finally, equations A-38 to A-40 and A-42 to A-44 are used to express the angular quantities

$$\begin{aligned}\bar{A}_{C_1/O_1} = & -r_{c1} \{ [\omega_y^2 \cos \gamma - \omega_x \omega_y \sin \gamma + (\omega_z + \dot{\phi}_1)^2 \cos \gamma + (\dot{\omega}_z + \ddot{\phi}_1) \sin \gamma] \bar{i} \\ & + [\omega_x^2 \sin \gamma - \omega_x \omega_y \cos \gamma + (\omega_z + \dot{\phi}_1)^2 \sin \gamma - (\dot{\omega}_z + \ddot{\phi}_1) \cos \gamma] \bar{j} \\ & - [(\omega_x \cos \gamma + \omega_y \sin \gamma)(\omega_z + 2\dot{\phi}_1) + \dot{\omega}_x \sin \gamma - \dot{\omega}_y \cos \gamma] \bar{k} \} \quad (D-424)\end{aligned}$$

The total acceleration $A_{C_1/\text{ground}}$ then becomes according to equation D-415 with equation D-411

$$\begin{aligned}\bar{A}_{C_1/\text{ground}} = & \{-r_{c1} [\omega_y^2 \cos \gamma - \omega_x \omega_y \sin \gamma + (\omega_z + \dot{\phi}_1)^2 \cos \gamma + (\dot{\omega}_z + \ddot{\phi}_1) \sin \gamma] + O_x\} \bar{i} \\ & + \{-r_{c1} [\omega_x^2 \sin \gamma - \omega_x \omega_y \cos \gamma + (\omega_z + \dot{\phi}_1)^2 \sin \gamma - (\dot{\omega}_z + \ddot{\phi}_1) \cos \gamma] + O_y\} \bar{j} \\ & + \{r_{c1} [(\omega_x \cos \gamma + \omega_y \sin \gamma)(\omega_z + 2\dot{\phi}_1) + \dot{\omega}_x \sin \gamma - \dot{\omega}_y \cos \gamma] + O_z\} \bar{k} \quad (D-425)\end{aligned}$$

It must be kept in mind that the angle ϕ_{1R} depends on the total rotational angle ϕ_T of the escape wheel. Because of the clock gearing involved, its value cannot be obtained by a constant gear ratio as for involute gearing, but must be determined from the incremental changes in the two meshes, which depend on the contact modes involved.

The angular velocity $\dot{\phi}_1$ and the angular acceleration $\ddot{\phi}_1$ must be expressed in terms of the escape wheel angular velocity $\dot{\phi}$ and the escape wheel angular acceleration $\ddot{\phi}$, respectively. Appendix F gives closed form expressions for these quantities. They are dependent on whichever of the four possible contact modes of the two meshes governs.

Mesh No. 1 in Round-On-Round Contact

Force Equations for the Rotor and Gear No. 1 With Mesh No. 1 in Round-On-Round Contact

A top view of the rotor and gear no. 1, together with the mechanism plane, is shown in figure D-11a. It indicates the round-on-round contact force $\bar{F}_{21}$ as well as the associated friction force $\bar{F}_{f12}$. Thus, (ref 5) with both forces equal to and opposite to $\bar{F}_{12}$ and F_{f12} , of equations D-611 and D-612, respectively

$$\bar{F}_{21} = -F_{12} \bar{n}_{\lambda 1} \quad (D-426)$$

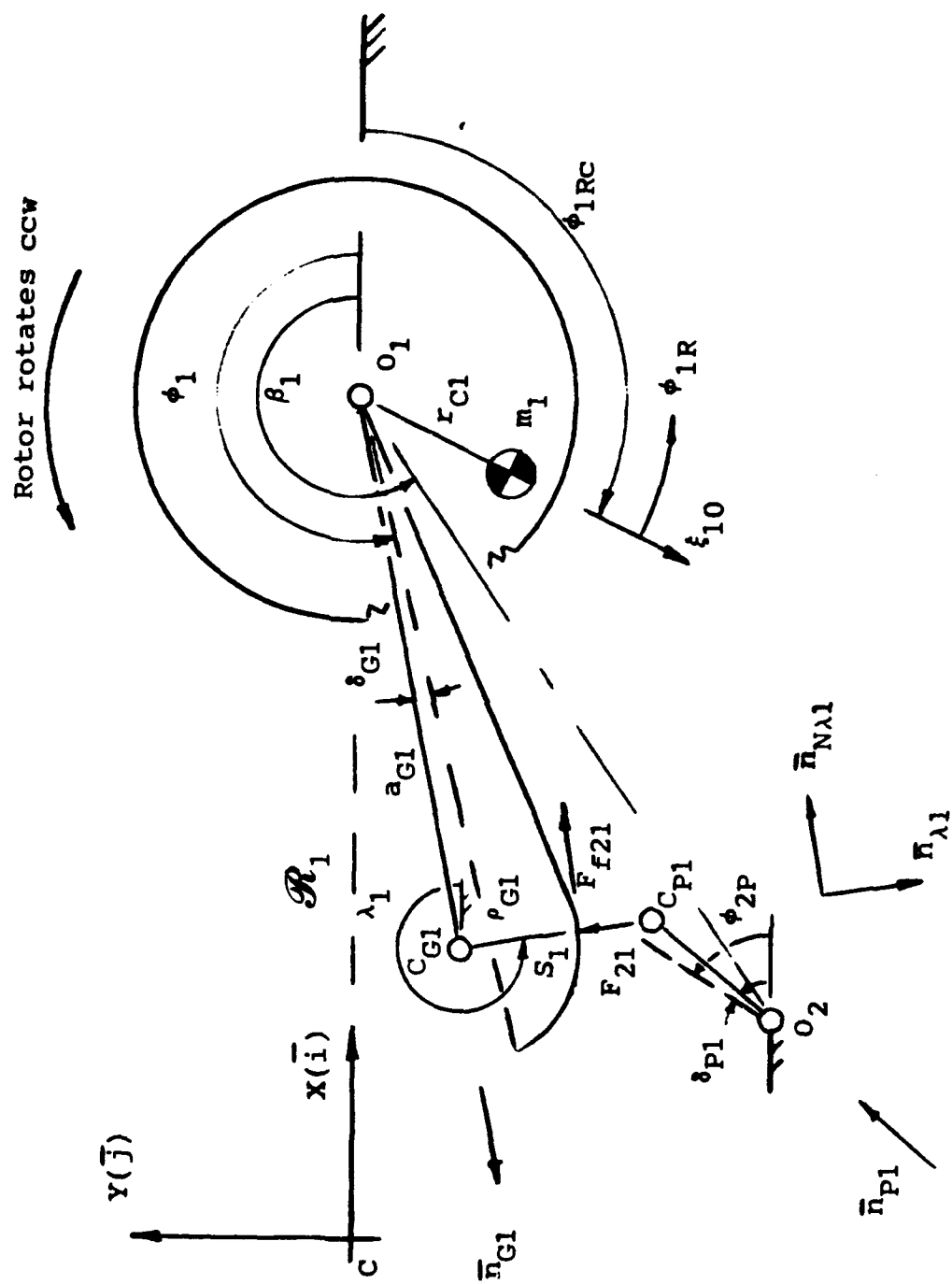


Figure D-11a. Top view of free body diagram of rotor and gear no. 1. Mesh no. 1 is in round-on-round contact.

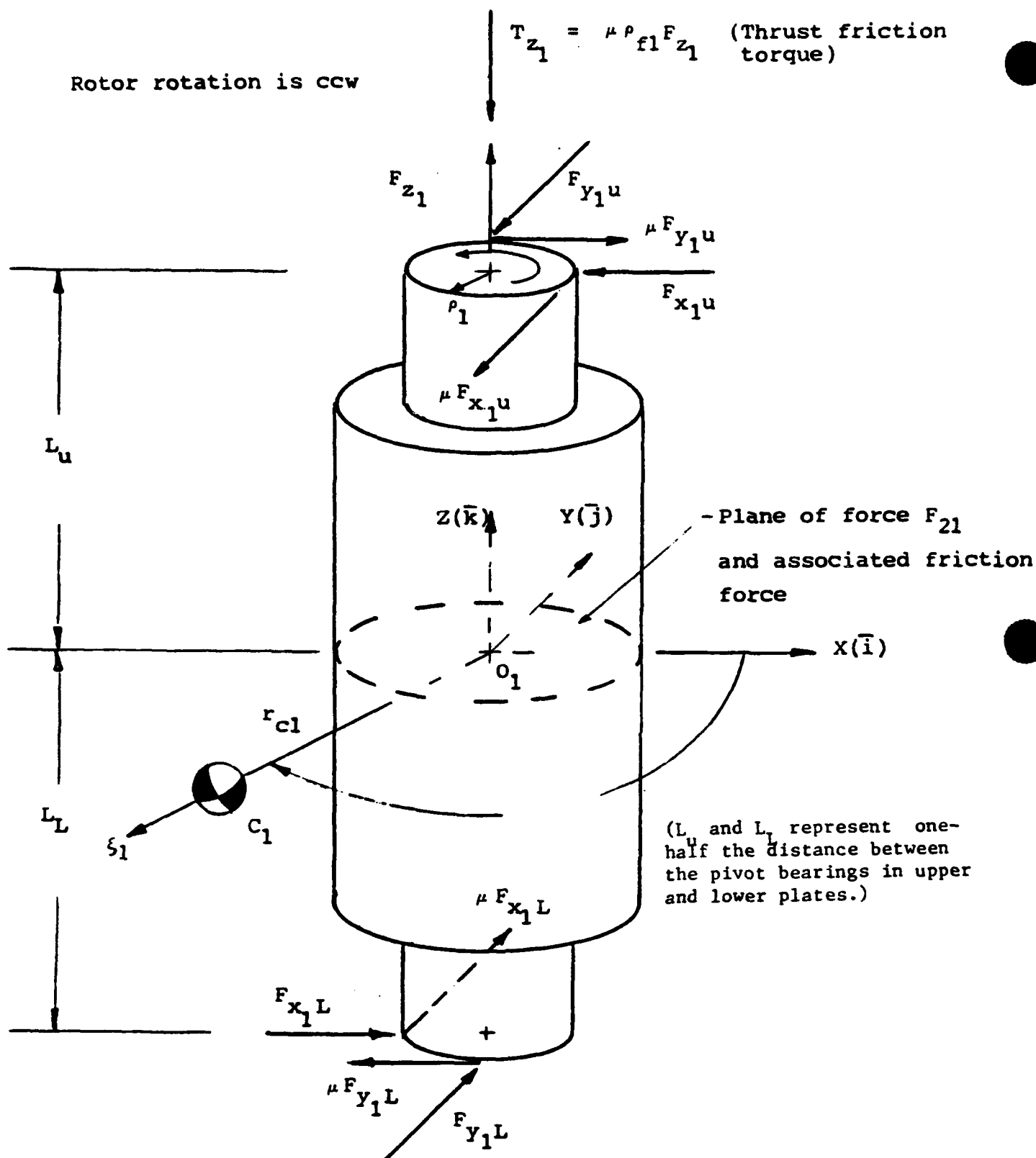


Figure D-11b. Rotor and gear no. 1. Normal forces, friction forces, and thrust friction torque acting on rotor pivots. (Not influenced by type of mesh contact.)

where, according to equation G-2 of reference 5

$$\pi_{\lambda 1} = \cos \lambda_1 \bar{i} + \sin \lambda_1 \bar{j} \quad (D-427)$$

Further,

$$\bar{F}_{121} = -\mu s_{1R} F_{12} \pi_{N\lambda 1} \quad (D-428)$$

where, according to equation G-3 of reference 5

$$\pi_{N\lambda 1} = -\sin \lambda_1 \bar{i} + \cos \lambda_1 \bar{j} \quad (D-429)$$

and, with the help of equation G-21, reference 5, the signum function s_{1R} is defined as (equation F-13, app F).

$$s_{1R} = \frac{V_{s_1/\pi_{1R}}}{|V_{s_1/\pi_{1R}}|} \quad (D-430)$$

A free body diagram of the rotor pivot with all normal and friction forces is shown in figure D-11b.

The force equation for the rotor is given by

$$\Sigma \bar{F} = m_1 \bar{A}_{C_1/\text{ground}} \quad (D-431)$$

where $\bar{A}_{C_1/\text{ground}}$ is given by equation D-425. Therefore

$$\begin{aligned} & -F_{12} \pi_{\lambda 1} - \mu s_{1R} F_{12} \pi_{N\lambda 1} + F_{z1} \bar{k} - F_{x1u} \bar{i} - F_{y1u} \bar{j} - \mu F_{x1u} \bar{j} + \mu F_{y1u} \bar{i} \\ & + F_{x1L} \bar{i} + F_{y1L} \bar{j} + \mu F_{x1L} \bar{j} - \mu F_{y1L} \bar{i} = m_1 \bar{A}_{C_1/\text{ground}} \end{aligned} \quad (D-432)$$

The unit vectors of equations D-427 and D-429 are now substituted into equation D-432. Subsequently, the component expressions of this equation are written with the help of equation D-425

X-Component of Rotor Force Equation

$$-F_{12} \cos \lambda_1 + \mu s_{1R} F_{12} \sin \lambda_1 - F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = m_1 [-r_{C1}$$

$$\{\omega_y^2 \cos \gamma - \omega_x \omega_y \sin \gamma + (\omega_z + \dot{\phi}_1)^2 \cos \gamma + (\dot{\omega}_z + \ddot{\phi}_1) \sin \gamma\} + O_x] \quad (D-433)$$

Y-Component of Rotor Force Equation

$$-F_{12}\sin\lambda_1 - \mu s_{1R}F_{12}\cos\lambda_1 - F_{y1u} - \mu F_{x1u} + F_{y1L} + \mu F_{x1L} = m_1[-r_{c1} \left\{ \omega_x^2 \sin\gamma - \omega_x \omega_y \cos\gamma + (\omega_z + \dot{\phi}_1)^2 \sin\gamma - (\dot{\omega}_z + \ddot{\phi}_1) \cos\gamma \right\} + O_y] \quad (D-434)$$

Z-Component of Rotor Force Equation

$$F_{z1} = m_1 \left\{ r_{c1} \left[(\omega_x \cos\gamma + \omega_y \sin\gamma)(\omega_z + 2\dot{\phi}_1) + \dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma \right] + O_z \right\} \quad (D-435)$$

Moment Equations for the Rotor and Gear No. 1 With Mesh 1 in Round-On-Round Contact

The moment equation for the rotor must be written with respect to the accelerated pivot point O_1 . (This is similar to the manner in which the pallet moment expression D-3c was written with respect to point O_p .) Therefore

$$\bar{M}_{O_1} = \bar{A}_{O_1/\text{ground}} \times m_1 r_{c1} (\cos\gamma \bar{i} + \sin\gamma \bar{j}) + \bar{H}_{O_1} \quad (D-436)$$

where

$\bar{M}_{O_1}$ = sum of external moments about point O_1 . It is assumed that O_1 lies in the plane of the rotor center of mass, and that F_{12} and $\mu s_{1R}F_{12}$ also lie in this plane.

$\bar{A}_{O_1/\text{ground}}$ = absolute acceleration of point O_1 (eq. D411).

$\bar{H}_{O_1}$ = time rate of change of angular momentum of rotor with respect to point O_1 .

It is obtained by adapting equation B-4 of appendix B to the $\xi_1 - \eta_1 - \zeta_1$ system. The appropriate angular velocity and acceleration components are given by equations A-37 and A-41, respectively. The transformation into the X-Y-Z system is accomplished with the help of the unit vector expressions of equations D-419 to D-421.

Determination of $\bar{M}_{O_1}$. The moment $\bar{M}_{F_{21}}$ of the contact force $\bar{F}_{21}$ with respect to pivot O_1 is given by

$$\bar{M}_{F_{21}} = (a_{G1}\bar{n}_{G1} + \rho_{G1}\bar{n}_{\lambda 1}) \times (F_{12}\bar{n}_{\lambda 1} - \mu s_{1R}F_{12}\bar{n}_{N\lambda 1}) \quad (D-437)$$

This becomes, with the help of equations D-423 and D-425, as well as with

$$\bar{n}_{G1} = \cos(\phi_1 - \delta_{G1})\bar{i} + \sin(\phi_1 - \delta_{G1})\bar{j} \quad (D-438)$$

as obtained from equation G-1 reference 5.

$$\bar{M}_{F_{21}} = a_{G1}F_{12}[\sin(\phi_1 - \delta_{G1} - \lambda_1) - \mu s_{1R}\cos(\phi_1 - \delta_{G1} - \lambda_1)]\bar{k} - \mu s_{1R}\rho_{G1}F_{12}\bar{k} \quad (D-439)$$

In addition to the above, the moments due to the various pivot forces may be adapted from equation D-32. Since the rotor always has counter-clockwise rotation, let $s_5 = +1$ in equation D-32. Further, change μ_1 to μ , and adjust the subscripts from the primed to the unprimed coordinate system. Finally, with equation D-439 one obtains for the moments with respect to pivot O_1

$$\begin{aligned} \bar{M}_{O_1} = & [L_u F_{y1u} + \mu L_u F_{x1u} + L_L F_{y1L} + \mu L_L F_{x1L}]\bar{i} + [\mu L_u F_{y1u} - L_u F_{x1u} \\ & + \mu L_L F_{y1L} - L_L F_{x1L}]\bar{j} + [a_{G1}F_{12}(\sin(\phi_1 - \delta_{G1} - \lambda_1) - \mu s_{1R}\cos(\phi_1 - \delta_{G1} - \lambda_1)) \\ & - \mu s_{1R}\rho_{G1}F_{12} - \mu p_{11}\tilde{F}_{z1} - p_1\mu F_{y1u} - p_1\mu F_{x1u} - p_1\mu F_{y1L} - p_1\mu F_{x1L}]\bar{k} \end{aligned} \quad (D-440)$$

Note the tilded form of $\tilde{F}_{z1}$, which will be explained by equation D-474.

Determination of First Term on Right Hand Side of Equation D-436. With the help of equation D-411, the following is obtained for the right hand side of equation D-436

$$\begin{aligned}
 &-(O_x \bar{i} + O_y \bar{j} + O_z \bar{k}) \times m_1 r_{c1} (\cos \gamma \bar{i} + \sin \gamma \bar{j}) = m_1 r_{c1} [O_z \sin \gamma \bar{i} - O_z \cos \gamma \bar{j} \\
 &- (O_x \sin \gamma - O_y \cos \gamma) \bar{k}] \quad (D-441)
 \end{aligned}$$

Determination of Time Rate of Change of Angular Momentum with Respect to Rotor Pivot O_1 . To obtain an expression for $\dot{\bar{H}}_{O_1}$ in the $\xi_1 - \eta_1 - \zeta_1$ rotor-fixed system, equation B-4 is first adapted from the X-Y-Z system. Subsequently, the angular velocity and acceleration of equations A-37 and A-41 are substituted as follows

$$\omega_{\xi_1} = \omega_x \cos \gamma + \omega_y \sin \gamma \quad (D-442)$$

$$\omega_{\eta_1} = -\omega_x \sin \gamma + \omega_y \cos \gamma \quad (D-443)$$

$$\omega_{\zeta_1} = \omega_z + \dot{\phi}_1 \quad (D-444)$$

$$\dot{\omega}_{\xi_1} = \dot{\omega}_x \cos \gamma - \omega_x \dot{\phi}_1 \sin \gamma + \dot{\omega}_y \sin \gamma + \omega_y \dot{\phi}_1 \cos \gamma \quad (D-445)$$

$$\dot{\omega}_{\eta_1} = -\dot{\omega}_x \sin \gamma - \omega_x \dot{\phi}_1 \cos \gamma + \dot{\omega}_y \cos \gamma - \omega_y \dot{\phi}_1 \sin \gamma \quad (D-446)$$

$$\dot{\omega}_{\zeta_1} = \dot{\omega}_z + \ddot{\phi}_1 \quad (D-447)$$

Finally, the body-fixed unit vectors π_{ξ_1} , π_{η_1} , and π_{ζ_1} are given in the X-Y-Z system according to equations D-419 to D-421. This furnishes

$$\begin{aligned}
 \bar{H}_{O_1} = & \{I_{\xi\xi_1}(\dot{\omega}_x \cos \gamma - \omega_x \dot{\phi}_1 \sin \gamma + \dot{\omega}_y \sin \gamma + \omega_y \dot{\phi}_1 \cos \gamma) + (-\dot{\omega}_x \sin \gamma - \omega_x \cos \gamma) \\
 & (\omega_z + \dot{\phi}_1)(I_{\zeta\zeta_1} - I_{\eta\eta_1}) + I_{\xi\eta_1}[(\omega_z + \dot{\phi}_1)(\omega_x \cos \gamma + \omega_y \sin \gamma) - (-\dot{\omega}_x \sin \gamma - \omega_x \dot{\phi}_1 \cos \gamma \\
 & + \dot{\omega}_y \cos \gamma - \omega_y \dot{\phi}_1 \sin \gamma)] - I_{\xi\zeta_1}[(\omega_x \cos \gamma + \omega_y \sin \gamma)(-\omega_x \sin \gamma + \omega_y \cos \gamma)(\dot{\omega}_z + \ddot{\phi}_1)] - I_{\eta\zeta_1} \\
 & [(-\omega_x \sin \gamma + \omega_y \cos \gamma)^2 - (\omega_z + \dot{\phi}_1)^2](\cos \gamma \bar{i} + \sin \gamma \bar{j}) + \{I_{\eta\eta_1}(-\dot{\omega}_x \sin \gamma - \omega_x \dot{\phi}_1 \cos \gamma \\
 & + \dot{\omega}_y \cos \gamma - \omega_y \dot{\phi}_1 \sin \gamma) + (\omega_x \cos \gamma + \omega_y \sin \gamma)(\omega_z + \dot{\phi}_1)(I_{\xi\xi_1} - I_{\zeta\zeta_1}) + I_{\eta\zeta_1}[(\omega_x \cos \gamma \\
 & + \omega_y \sin \gamma)(-\omega_x \sin \gamma + \omega_y \cos \gamma) - (\dot{\omega}_z + \ddot{\phi}_1)] - I_{\xi\eta_1}[(\dot{\omega}_x \cos \gamma - \omega_x \dot{\phi}_1 \sin \gamma + \dot{\omega}_y \sin \gamma \\
 & + \omega_y \dot{\phi}_1 \cos \gamma) + (-\omega_x \sin \gamma + \omega_y \cos \gamma)(\omega_z + \dot{\phi}_1) - I_{\xi\zeta_1}[(\omega_z + \dot{\phi}_1)^2 - (\omega_x \cos \gamma + \omega_y \sin \gamma)^2] \} \\
 & (-\sin \gamma \bar{i} + \cos \gamma \bar{j}) + \{I_{\zeta\zeta_1}(\dot{\omega}_z + \ddot{\phi}_1) + (\omega_x \cos \gamma + \omega_y \sin \gamma)(-\omega_x \sin \gamma + \omega_y \cos \gamma) \times (I_{\eta\eta_1} \\
 & - I_{\xi\xi_1}) + I_{\zeta\xi_1}[(-\omega_x \sin \gamma + \omega_y \cos \gamma)(\omega_z + \dot{\phi}_1) - (\dot{\omega}_x \cos \gamma - \omega_x \dot{\phi}_1 \sin \gamma + \dot{\omega}_y \sin \gamma \\
 & + \omega_y \dot{\phi}_1 \cos \gamma)] - I_{\zeta\eta_1}[(-\dot{\omega}_x \sin \gamma - \omega_x \dot{\phi}_1 \cos \gamma + \dot{\omega}_y \cos \gamma - \omega_y \dot{\phi}_1 \sin \gamma) + (\omega_x \cos \gamma + \omega_y \sin \gamma) \\
 & (\omega_z + \dot{\phi}_1)] - I_{\xi\eta_1}[(\omega_x \cos \gamma + \omega_y \sin \gamma)^2 - (-\omega_x \sin \gamma + \omega_y \cos \gamma)^2] \} \bar{k}
 \end{aligned} \tag{D-448}$$

The components $\dot{H}_{O_{1x}}$, $\dot{H}_{O_{1y}}$, and $\dot{H}_{O_{1z}}$ must now be determined from equation D-448. This leads to

$$\dot{H}_{O_{1x}} = A_{52} + A_{53}\dot{\phi}_1 + A_{54}\dot{\phi}_1^2 + A_{55}\ddot{\phi}_1 \quad (D-449)$$

where

$$\begin{aligned} A_{52} = & \cos\gamma(I_{\xi\xi_1}(\dot{\omega}_x\cos\gamma + \dot{\omega}_y\sin\gamma) + (I_{\zeta\zeta_1} - I_{\eta\eta_1})\omega_z(-\omega_x\sin\gamma - \omega_y\cos\gamma) + I_{\xi\eta_1} \\ & [\omega_z(\omega_x\cos\gamma + \omega_y\sin\gamma) + (\dot{\omega}_x\sin\gamma - \dot{\omega}_y\cos\gamma)] - I_{\xi\zeta_1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\omega_x\sin\gamma \\ & + \omega_y\cos\gamma) + \dot{\omega}_z] - I_{\eta\zeta_1}[(-\omega_x\sin\gamma + \omega_y\cos\gamma)^2 - \omega_z^2] - \sin\gamma[I_{\eta\eta_1}(-\dot{\omega}_x\sin\gamma \\ & + \dot{\omega}_y\cos\gamma) + (I_{\xi\xi_1} - I_{\zeta\zeta_1})\omega_z(\omega_x\cos\gamma + \omega_y\sin\gamma) + I_{\eta\zeta_1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\omega_x\sin\gamma \\ & + \omega_y\cos\gamma) - \dot{\omega}_z] - I_{\xi\eta_1}[(\dot{\omega}_x\cos\gamma + \dot{\omega}_y\sin\gamma) + \omega_z(-\omega_x\sin\gamma + \omega_y\cos\gamma)] - I_{\xi\zeta_1} \\ & [\omega_z^2 - (\omega_x\cos\gamma + \omega_y\sin\gamma)^2]) \end{aligned} \quad (D-450)$$

$$\begin{aligned} A_{53} = & [-\omega_x\sin\gamma + \omega_y\cos\gamma][(I_{\xi\xi_1} + I_{\zeta\zeta_1} - I_{\eta\eta_1})\cos\gamma + 2I_{\xi\eta_1}\sin\gamma] + [\omega_x\cos\gamma \\ & + \omega_y\sin\gamma][(I_{\eta\eta_1} - I_{\xi\xi_1} + I_{\zeta\zeta_1})\sin\gamma + 2I_{\xi\eta_1}\cos\gamma] + 2\omega_z[I_{\eta\xi_1}\cos\gamma + I_{\xi\zeta_1}\sin\gamma] \end{aligned} \quad (D-451)$$

$$A_{54} = I_{\eta\xi_1}\cos\gamma + I_{\xi\zeta_1}\sin\gamma \quad (D-452)$$

$$A_{55} = -I_{\xi\zeta_1}\cos\gamma + I_{\eta\zeta_1}\sin\gamma \quad (D-453)$$

Further

$$\dot{H}_{O_{1y}} = A_{56} + A_{57}\dot{\phi}_1 + A_{58}\dot{\phi}_1^2 + A_{59}\ddot{\phi}_1 \quad (D-454)$$

$$\begin{aligned}
A_{56} = & \sin\gamma \{ I_{\xi\xi_1} (\dot{\omega}_x \cos\gamma + \dot{\omega}_y \sin\gamma) + (I_{\zeta\zeta_1} - I_{\eta\eta_1}) (-\omega_x \sin\gamma + \omega_y \cos\gamma) \omega_z + I_{\xi\eta_1} \\
& [\omega_z (\omega_x \cos\gamma + \omega_y \sin\gamma) - (-\dot{\omega}_x \sin\gamma + \dot{\omega}_y \cos\gamma)] - I_{\xi\zeta_1} [(\omega_x \cos\gamma + \omega_y \sin\gamma) (-\omega_x \sin\gamma \\
& + \omega_y \cos\gamma) + \dot{\omega}_z] - I_{\eta\zeta_1} [(-\omega_x \sin\gamma + \omega_y \cos\gamma)^2 - \omega_z^2] \} + \cos\gamma \{ I_{\eta\eta_1} (-\dot{\omega}_x \sin\gamma \\
& + \dot{\omega}_y \cos\gamma) + (I_{\xi\xi_1} - I_{\zeta\zeta_1}) (\omega_x \cos\gamma + \omega_y \sin\gamma) \omega_z + I_{\eta\zeta_1} [(\omega_x \cos\gamma + \omega_y \sin\gamma) (-\omega_x \sin\gamma \\
& + \omega_y \cos\gamma) - \dot{\omega}_z] - I_{\xi\eta_1} [\dot{\omega}_x \cos\gamma + \dot{\omega}_y \sin\gamma + \omega_z (-\omega_x \sin\gamma + \omega_y \cos\gamma)] - I_{\xi\zeta_1} \\
& [\omega_z^2 - (\omega_x \cos\gamma + \omega_y \sin\gamma)^2] \} \quad (D-455)
\end{aligned}$$

$$\begin{aligned}
A_{57} = & [-\omega_x \sin\gamma + \omega_y \cos\gamma] \times [(I_{\xi\xi_1} + I_{\zeta\zeta_1} - I_{\eta\eta_1}) \sin\gamma - 2I_{\xi\eta_1} \cos\gamma] + [\omega_x \cos\gamma \\
& + \omega_y \sin\gamma] \times [2I_{\xi\eta_1} \sin\gamma + (I_{\xi\xi_1} - I_{\zeta\zeta_1} - I_{\eta\eta_1}) \cos\gamma] + 2\omega_z [I_{\eta\zeta_1} \sin\gamma - I_{\xi\zeta_1} \cos\gamma] \quad (D-456)
\end{aligned}$$

$$A_{58} = I_{\eta\zeta_1} \sin\gamma - I_{\xi\zeta_1} \cos\gamma \quad (D-457)$$

$$A_{59} = -[I_{\xi\zeta_1} \sin\gamma + I_{\eta\zeta_1} \cos\gamma] \quad (D-458)$$

Finally

$$\dot{H}_{O_{1z}} = A_{60} + A_{61} \ddot{\phi}_1 \quad (D-459)$$

where

$$A_{60} = I_{\zeta\zeta_1} \dot{\omega}_z + (I_{\eta\eta_1} - I_{\xi\xi_1})(\omega_x \cos\gamma + \omega_y \sin\gamma) \times (-\omega_x \sin\gamma + \omega_y \cos\gamma) + I_{\zeta\xi_1}$$

$$[(-\omega_x \sin\gamma + \omega_y \cos\gamma)\omega_z - \dot{\omega}_x \cos\gamma - \dot{\omega}_y \sin\gamma] + I_{\zeta\eta_1}[\dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma - \omega_z$$

$$(\omega_x \cos\gamma + \omega_y \sin\gamma)] - I_{\xi\eta_1}[(\omega_x \cos\gamma + \omega_y \sin\gamma)^2 - (-\omega_x \sin\gamma + \omega_y \cos\gamma)^2] \quad (D-460)$$

$$A_{61} = I_{\zeta\zeta_1} \quad (D-461)$$

Simplification of Force and Moment Equations and Determination of Rotor Pivot Forces with Mesh No. 1 in Round-On-Round Contact

X-Component of the Force Equation

Equation D-433 is now rewritten in the following manner

$$-F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = A_{62} + A_{63}\dot{\phi}_1 + A_{64}\dot{\phi}_1^2 + A_{65}\ddot{\phi}_1 + A_{66R}F_{12} \quad (D-462)$$

where

$$A_{62} = m_1 r_{c1} [-\omega_y^2 \cos\gamma + \omega_x \omega_y \sin\gamma - \omega_z^2 \cos\gamma - \dot{\omega}_z \sin\gamma] + m_1 O_x \quad (D-463)$$

$$A_{63} = -2m_1 r_{c1} \omega_z \cos\gamma \quad (D-464)$$

$$A_{64} = -m_1 r_{c1} \cos\gamma \quad (D-465)$$

$$A_{65} = -m_1 r_{c1} \sin\gamma \quad (D-466)$$

$$A_{66R} = \cos\lambda_1 - \mu s_{1R} \sin\lambda_1 \quad (D-467)$$

Y-Component of the Force Equation

Equation D-434 becomes

$$-F_{y1u} - \mu F_{x1u} + F_{y1L} + \mu F_{x1L} = A_{67} + A_{68}\dot{\phi}_1 + A_{69}\dot{\phi}_1^2 + A_{70}\ddot{\phi}_1 + A_{71R}F_{12} \quad (D-468)$$

where

$$A_{67} = m_1 r_{c1} [-\omega_x^2 \sin\gamma + \omega_x \omega_y \cos\gamma - \omega_z^2 \sin\gamma - \dot{\omega}_z \cos\gamma] + m_1 O_y \quad (D-469)$$

$$A_{68} = -2m_1 r_{c1} \omega_z \sin\gamma \quad (D-470)$$

$$A_{69} = -m_1 r_{c1} \sin\gamma \quad (D-471)$$

$$A_{70} = m_1 r_{c1} \cos\gamma \quad (D-472)$$

$$A_{71R} = (\sin\lambda_1 + \mu s_{1R} \cos\lambda_1) \quad (D-473)$$

Z-Component of the Force Equation

Equation D-435 is rewritten in its tilded form directly

$$\tilde{F}_{z1} = A_{72} + A_{73}\dot{\phi}_1 \quad (D-474)$$

where

$$A_{72} = |m_1 r_{c1} [\omega_z (\omega_x \cos\gamma + \omega_y \sin\gamma) + \dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma] + m_1 O_z| \quad (D-475)$$

$$A_{73} = |2m_1 r_{c1} [\omega_x \cos\gamma + \omega_y \sin\gamma]| \quad (D-476)$$

The components of the rotor moment equations are now written according to equation D-436.

X-Component of Moment Equation

With the help of equations D-440, D-441, and D-449, the following is obtained

$$\begin{aligned} \mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L} = m_1 r_{c1} O_z \sin \gamma + A_{52} + A_{53} \dot{\phi}_1 \\ + A_{54} \dot{\phi}_1^2 + A_{55} \ddot{\phi}_1 \end{aligned} \quad (D-477)$$

Y-Component of Moment Equation

Again with the help of equations D-440, D-441, i.e., its y-factors, as well as equation D-454, the following is found

$$\begin{aligned} -L_u F_{x1u} + \mu L_u F_{y1u} + \mu L_L F_{y1L} - L_L F_{x1L} = m_1 r_{c1} O_z \cos \gamma + A_{56} + A_{57} \dot{\phi}_1 \\ + A_{58} \dot{\phi}_1^2 + A_{59} \ddot{\phi}_1 \end{aligned} \quad (D-478)$$

Z-Component of Moment Equation

Again, using the Z-components of equations D-440 and D-441, together with equation D-459, obtained for the Z-component of the moment expression

$$\begin{aligned} a_{G1} F_{12} [\sin (\phi_1 - \delta_{G1} - \lambda_1) - \mu s_{1R} \cos (\phi_1 - \delta_{G1} - \lambda_1)] - \mu s_{1R} \rho_{G1} F_{12} \\ - \mu \rho_{f1} \tilde{F}_{z1} - \mu \rho_1 (F_{x1u} + F_{y1u} + F_{x1L} + F_{y1L}) = -m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma] \\ + A_{60} + A_{61} \ddot{\phi}_1 \end{aligned} \quad (D-479)$$

Solution of Rotor Pivot Forces. To obtain the rotor pivot forces, equations D-462, D-468, D-477, and D-478 must be solved simultaneously. Therefore

$$-F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = B_{11R} \quad (D-480)$$

$$-\mu F_{x1u} - F_{y1u} + \mu F_{x1L} + F_{y1L} = B_{12R} \quad (D-481)$$

$$\mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L} = B_{13} \quad (D-482)$$

$$-L_u F_{x1u} + \mu L_u F_{y1u} - L_L F_{x1L} + \mu L_L F_{y1L} = B_{14} \quad (D-483)$$

where

$$B_{11R} = A_{62} + A_{63}\dot{\phi}_1 + A_{64}\dot{\phi}_1^2 + A_{65}\ddot{\phi}_1 + A_{66R}F_{12} \quad (D-484)$$

$$B_{12R} = A_{67} + A_{68}\dot{\phi}_1 + A_{69}\dot{\phi}_1^2 + A_{70}\ddot{\phi}_1 + A_{71R}F_{12} \quad (D-485)$$

$$B_{13} = m_1 r_{c1} O_z \sin \gamma + A_{52} + A_{53}\dot{\phi}_1 + A_{54}\dot{\phi}_1^2 + A_{55}\ddot{\phi}_1 \quad (D-486)$$

$$B_{14} = -m_1 r_{c1} O_z \cos \gamma + A_{56} + A_{57}\dot{\phi}_1 + A_{58}\dot{\phi}_1^2 + A_{59}\ddot{\phi}_1 \quad (D-487)$$

Since equations D-480 to D-483 together have the same general form as equation D-67 for the pallet, the forms of the pallet pivot force solutions for the rotor pivot forces may be used. It must be kept in mind that for the rotor the factor μ must be substituted for A_{11} . Then, according to equation D-73

$$D_1 = [(L_u + L_L)(1 + \mu^2)]^2 \quad (D-488)$$

Parallel to equation D-80, the determinant $D_{F_{x1u}}$ becomes

$$D_{F_{x1u}} = (L_u + L_L)(1 + \mu^2)[-L_L B_{11R} - \mu L_L B_{12R} + \mu B_{13} - B_{14}] \quad (D-489)$$

After appropriate substitution of equations D-484 to D-487, parallel to equations D-81 to D-87, the following is obtained for the conservative rotor pivot force

$$\tilde{F}_{x1u} = \frac{\tilde{D}_{F_{x1u}}}{D_1} = \frac{1}{L_T (1 + \mu^2)} [C_{37} + C_{38} \dot{\phi}_1 + C_{39} \dot{\phi}_1^2 + C_{40} \ddot{\phi}_1 + C_{41R} F_{12}] \quad (D-490)$$

where

$$C_{37} = [-L_L A_{62} + \mu (A_{52} - L_L A_{67}) - A_{56} + m_1 r_{c1} O_z (\mu \sin \gamma + \cos \gamma)] \quad (D-491)$$

$$C_{38} = [-L_L A_{63} + \mu (A_{53} - L_L A_{68}) - A_{57}] \quad (D-492)$$

$$C_{39} = [-L_L A_{64} + \mu (A_{54} - L_L A_{69}) - A_{58}] \quad (D-493)$$

$$C_{40} = [-L_L A_{65} + \mu (A_{55} - L_L A_{70}) - A_{59}] \quad (D-494)$$

$$C_{41R} = [-L_L (A_{66R} + \mu A_{71R})] \quad (D-495)$$

Parallel to equation D-89, the determinant $D_{F_{y1u}}$ becomes

$$D_{F_{y1u}} = (L_u + L_L)(1 + \mu^2)\{\mu L_L B_{11R} - L_L B_{12R} + B_{13} + \mu B_{14}\} \quad (D-496)$$

After appropriate substitution of equations D-484 to D-487, parallel to equations D-91 to D-96, it is found that

$$\tilde{F}_{y1u} = \frac{\tilde{D}_{F_{y1u}}}{D_1} = \frac{1}{L_T (1 + \mu^2)} [C_{42} + C_{43} \dot{\phi}_1 + C_{44} \dot{\phi}_1^2 + C_{45} \ddot{\phi}_1 + C_{46R} F_{12}] \quad (D-497)$$

where

$$C_{42} = |-L_L A_{67} + \mu (A_{56} + L_L A_{62}) + A_{52} + m_1 r_{c1} O_z (\sin \gamma - \mu \cos \gamma)| \quad (D-498)$$

$$C_{43} = |-L_L A_{68} + \mu (L_L A_{63} + A_{57}) + A_{53}| \quad (D-499)$$

$$C_{44} = |-L_L A_{69} + \mu (L_L A_{64} + A_{58}) + A_{54}| \quad (D-500)$$

$$C_{45} = |-L_L A_{70} + \mu (L_L A_{65} + A_{59}) + A_{55}| \quad (D-501)$$

$$C_{46R} = |L_L (\mu A_{66R} - A_{71R})| \quad (D-502)$$

Parallel to equation D-99, the determinant $D_{F_{x1L}}$ becomes

$$D_{F_{x1L}} = (L_U + L_L) (1 + \mu^2) \{L_U B_{11R} + \mu L_U B_{12R} + \mu B_{13} - B_{14}\} \quad (D-503)$$

Again, equations D-484 to D-487 are substituted into the above. Then proceed parallel to equations D-101 to D-106. Finally

$$\tilde{F}_{x1L} = \frac{\tilde{D}_{F_{x1L}}}{D_1} = \frac{1}{L_T (1 + \mu^2)} [C_{47} + C_{48} \dot{\phi}_1 + C_{49} \dot{\phi}_1^2 + C_{50} \ddot{\phi}_1 + C_{51R} F_{12}] \quad (D-504)$$

where

$$C_{47} = |L_U A_{62} + \mu (L_U A_{67} + A_{52}) - A_{56} + m_1 r_{c1} O_z (\mu \sin \gamma + \cos \gamma)| \quad (D-505)$$

$$C_{48} = |L_U A_{63} + \mu (L_U A_{68} + A_{53}) - A_{57}| \quad (D-506)$$

$$C_{49} = |L_U A_{64} + \mu (L_U A_{69} + A_{54}) - A_{58}| \quad (D-507)$$

$$C_{50} = |L_U A_{65} + \mu (L_U A_{70} + A_{55}) - A_{59}| \quad (D-508)$$

$$C_{51R} = |L_U (A_{66R} + \mu A_{71R})| \quad (D-509)$$

Parallel to equation D-109, the determinant $D_{F_{y1L}}$ becomes

$$D_{F_{y1L}} = (L_u + L_L)(1 + \mu^2) \{-\mu L_u B_{11R} + L_u B_{12R} + B_{13} + \mu B_{14}\} \quad (D-510)$$

After substitution of equations D-484 to D-487, proceed parallel to equation D-111

$$\tilde{F}_{y1L} = \frac{\tilde{D}_{F_{y1L}}}{D_1} = \frac{1}{L_T (1 + \mu^2)} [C_{52} + C_{53} \dot{\phi}_1 + C_{54} \dot{\phi}_1^2 + C_{55} \ddot{\phi}_1 + C_{56R} F_{12}] \quad (D-511)$$

where

$$C_{52} = |L_u A_{67} + \mu(A_{56} - L_u A_{62}) + A_{52} + m_1 r_{c1} O_2 (\sin \gamma - \mu \cos \gamma)| \quad (D-512)$$

$$C_{53} = |L_u A_{68} + \mu(A_{57} - L_u A_{63}) + A_{53}| \quad (D-513)$$

$$C_{54} = |L_u A_{69} + \mu(A_{58} - L_u A_{64}) + A_{54}| \quad (D-514)$$

$$C_{55} = |L_u A_{70} + \mu(A_{59} - L_u A_{65}) + A_{55}| \quad (D-515)$$

$$C_{56R} = |L_u(A_{71R} - \mu A_{66R})| \quad (D-516)$$

Substitution of Tilded Pivot Forces Into Z-Component of Moment Equation. The sum of the pivot forces in equations D-479 is replaced by the sum of the tilded pivot forces, as given by equations D-490, D-497, D-504, and D-511. Then

$$F_{x1u} + F_{y1u} + F_{x1L} + F_{y1L} \approx \tilde{F}_{x1u} + \tilde{F}_{y1u} + \tilde{F}_{x1L} + \tilde{F}_{y1L} = A_{74}$$

$$+ A_{75} \dot{\phi}_1 + A_{76} \dot{\phi}_1^2 + A_{77} \ddot{\phi}_1 + A_{78R} F_{12} \quad (D-517)$$

where

$$A_{74} = \frac{C_{37} + C_{42} + C_{47} + C_{52}}{L_T(1 + \mu^2)} \quad (D-518)$$

$$A_{75} = \frac{C_{38} + C_{43} + C_{48} + C_{53}}{L_T(1 + \mu^2)} \quad (D-519)$$

$$A_{76} = \frac{C_{39} + C_{44} + C_{49} + C_{54}}{L_T(1 + \mu^2)} \quad (D-520)$$

$$A_{77} = \frac{C_{40} + C_{45} + C_{50} + C_{55}}{L_T(1 + \mu^2)} \quad (D-521)$$

$$A_{78R} = \frac{C_{41R} + C_{46R} + C_{51R} + C_{56R}}{L_T(1 + \mu^2)} \quad (D-522)$$

The above is now substituted, together with the thrust friction according to equation D-474, into the moment expression D-479, and all friction moments must be examined for proper sign to oppose motion.

$$a_{G1}F_{12}[\sin(\phi_1 - \delta_{G1} - \lambda_1) - \mu S_{1R} \cos(\phi_1 - \delta_{G1} - \lambda_1)] - \mu S_{1R} P_{G1} F_{12}$$

$$- \mu \rho_{f1} [A_{72} \pm A_{73} \dot{\phi}_1] - \mu \rho_1 [A_{74} \pm A_{75} \dot{\phi}_1 \pm A_{76} \dot{\phi}_1^2 \pm A_{77} \ddot{\phi}_1 + A_{78R} F_{12}]$$

$$= -m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma] + A_{60} + A_{61} \ddot{\phi}_1 \quad (D-523)$$

Equation D-523 is rearranged to

$$\begin{aligned}
 & F_{12} [a_{G1} (\sin (\phi_1 - \delta_{G1} - \lambda_1) - \mu s_{1R} \cos (\phi_1 - \delta_{G1} - \lambda_1)) - \mu s_{1R} p_{G1} - \mu p_1 A_{78R}] \\
 & \pm \mu [p_{f1} A_{72} + p_1 A_{74}] \pm \mu [p_{f1} A_{73} + p_1 A_{75}] \dot{\phi}_1 \pm \mu p_1 A_{76} \dot{\phi}_1^2 \pm \mu p_1 A_{77} \ddot{\phi}_1 \\
 & = A_{60} + A_{61} \ddot{\phi}_1 - m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma]
 \end{aligned} \tag{D-524}$$

Now consider the signs of the various friction moments, recalling that a reversal in the gear train motion will cause a change in the sign of μ in the program. The following moment components must have negative signs during positive rotation

$$1: -\mu F_{12} p_1 A_{78R} \tag{D-525}$$

since F_{12} and p_1 are positive, and A_{78R} is a sum of absolute values.

$$2: -\mu [p_{f1} A_{72} + p_1 A_{74}] \tag{D-526}$$

since p_{f1} and p_1 are positive, while A_{72} and A_{74} are both absolute values.

$$3: -\mu p_1 A_{76} \dot{\phi}_1^2 \tag{D-527}$$

since A_{76} is also a sum of absolute values.

The sign of the term containing $\dot{\phi}_1$ must be decided by the sign of this angular velocity only. Therefore, the coefficient of friction must not change sign on motion reversal, and the expression takes the form

$$-|\mu| [p_{f1} A_{73} + p_1 A_{75}] \dot{\phi}_1 \tag{D-528}$$

The choice of signs in the coefficient of the angular acceleration $\ddot{\phi}_1$ is discussed in detail in appendix F of reference 4. This leads to the computational rules of equations D-535 and D-536 below.

With the above considerations, equation D-524 becomes

$$A_{79R} F_{12} - A_{80} - A_{81} \dot{\phi}_1 A_{82} \dot{\phi}_1^2 = I_{1R} \ddot{\phi}_1 + A_{70} - m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma] \quad (D-529)$$

where

$$A_{79R} = a_{G1} [\sin (\phi_1 - \delta_{G1} - \lambda_1) - \mu s_{1R} \cos (\phi_1 - \delta_{G1} - \lambda_1)] - \mu$$

$$[s_{1R} \rho_{G1} + \rho_1 A_{78R}] \quad (D-530)$$

$$A_{80} = \mu [\rho_{11} A_{72} + \rho_1 A_{74}] \quad (D-531)$$

$$A_{81} = |\mu| [\rho_{11} A_{73} + \rho_1 A_{75}] \quad (D-532)$$

$$A_{82} = \mu \rho_1 A_{76} \quad (D-533)$$

$$A_{83} = |\mu| \rho_1 A_{77} \quad (D-534)$$

Further

$$I_{1R} = A_{61} + A_{83} \quad (D-535)$$

when $\dot{\phi}_1$ and $\ddot{\phi}_1$ have the same signs, and

$$I_{1R} = A_{61} - A_{83} \quad (D-536)$$

when $\dot{\phi}_1$ and $\ddot{\phi}_1$ have opposite signs.

General Form of Contact Force F_{12} in Terms of Rotor Parameters When Mesh No. 1 is in Round-on-Round Contact. Adjustment for Contact Mode of Mesh No. 2.

Equation D-529 may now be rewritten to obtain a general expression for the contact force F_{12} when mesh no. 1 is in round-on-round contact

$$F_{12} = \frac{I_{1R} \ddot{\phi}_1 + A_{81} \dot{\phi}_1 + A_{82} \dot{\phi}_1^2 + A_{80} + A_{60} - m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma]}{A_{79R}} \quad (D-537)$$

When mesh no. 2 is at the same time in the round-on-round mode, the angular velocity $\dot{\phi}_1$ must be obtained from equation F-142 of appendix F, while the angular acceleration $\ddot{\phi}_1$ is given by equation F-143.

For mesh 2 simultaneously in the round-on-flat contact $\dot{\phi}_1$ and $\ddot{\phi}_1$ are given by equations F-154 and F-155, respectively.

Mesh No. 1 in Round-on-Flat Contact

Force Equations for the Rotor and Gear No. 1 With Mesh No. 1 in Round-on-Flat Contact.

A top view of the rotor and gear no. 1 in the round-on-flat contact mode is shown in figure D-12a. The contact force on the gear is now $\bar{F}_{21F}$ and the associated friction force is given by $\bar{F}_{121F}$. Thus, (again, see ref 5) with both forces equal and opposite to F_{12F} and F_{112F} , of equations D-696 and D-697, respectively

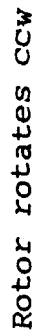
$$\bar{F}_{21F} = F_{12F} \pi_{NF1} \quad , \quad (D-538)$$

where, according to equation G-23 of reference 5

$$\pi_{NF1} = -\sin(\phi_{2P} + \alpha_{P1}) \bar{i} + \cos(\phi_{2P} + \alpha_{P1}) \bar{j} \quad (D-539)$$

Further

$$\bar{F}_{121F} = -\mu S_{1F} F_{12F} \pi_{F1} \quad , \quad (D-540)$$



173

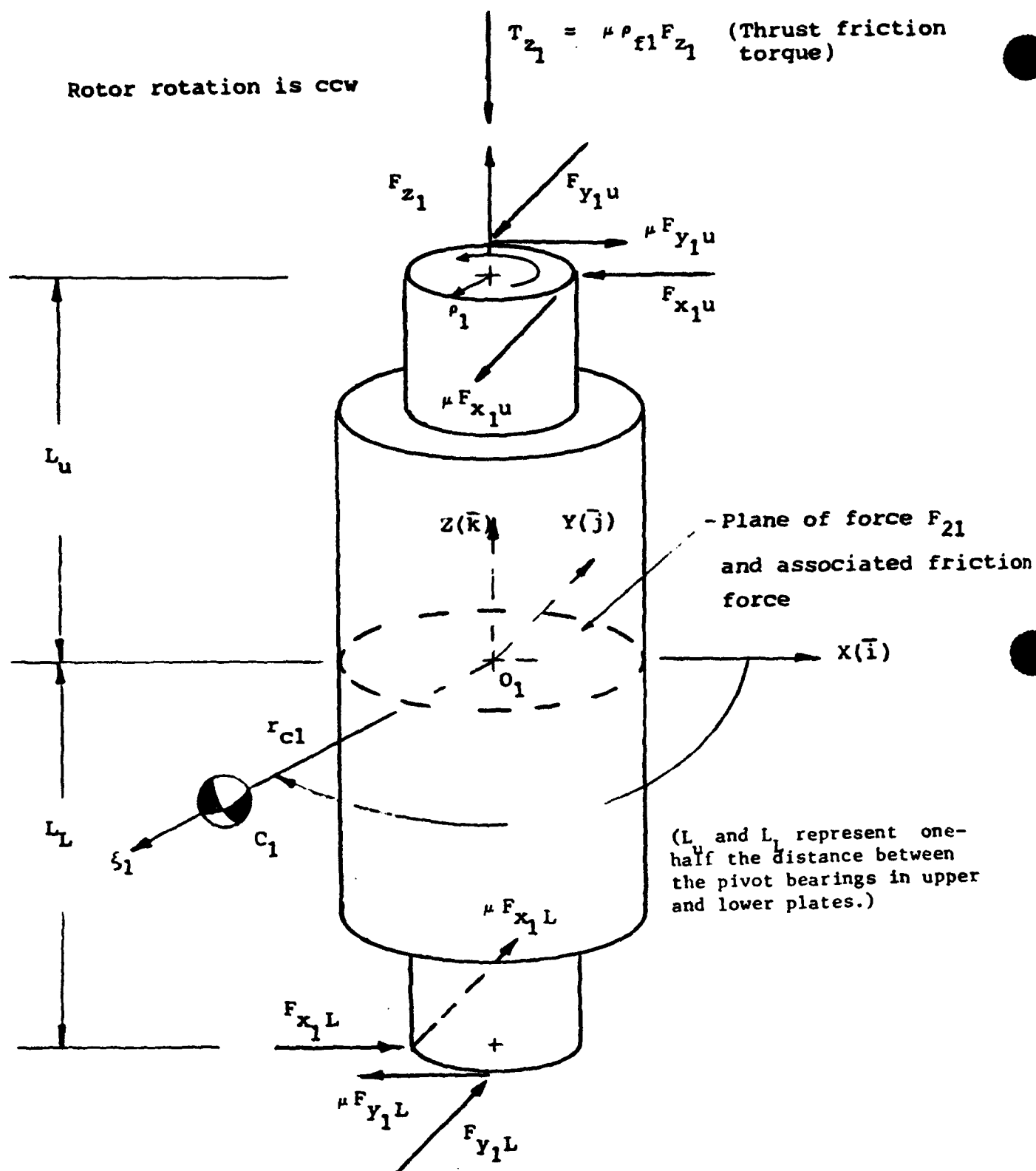


Figure D-12b. Rotor and gear no. 1. Normal forces, friction forces, and thrust friction torque acting on rotor pivots. (Same as figure D-11b. Not influenced by type of mesh contact.)

where, according to equation G-22 of reference 5

$$\bar{n}_{F1} = -\cos(\phi_{2P} + \alpha_{P1})\bar{i} + \sin(\phi_{2P} + \alpha_{P1})\bar{j} \quad (D-541)$$

The signum function s_{1F} becomes with the help of equation G-33 of reference 5, or equation F-24 of appendix F

$$s_{1F} = \frac{V_{s_1, \tau_{1F}}}{|V_{s_1, \tau_{1F}}|} \quad (D-542)$$

A free body diagram of the rotor pivot, with all normal and frictional forces, is given by figure D-12b. Since the rotation direction of the rotor does not depend on the mesh contact type, this figure is the same as figure D-11b.

The force equation of the rotor is formulated according to equation D-431

$$\begin{aligned} F_{12F}\bar{n}_{NF1} - \mu s_{1F}F_{12F}\bar{n}_{F1} + F_{z1}\bar{k} - F_{x1u}\bar{i} - F_{y1u}\bar{j} - \mu F_{x1u}\bar{j} + \mu F_{y1u}\bar{i} \\ + F_{x1L}\bar{i} + F_{y1L}\bar{j} + \mu F_{x1L}\bar{j} - \mu F_{y1L}\bar{i} = m_1\bar{A}_{C1/\text{ground}} \end{aligned} \quad (D-543)$$

The unit vectors of equations D-539 and D-541 are now substituted into equation D-543. Subsequently, the force component expressions may be written with the help of equation D-425

X-Component of Rotor Force Equation

$$\begin{aligned} -F_{12F}\sin(\phi_{2P} + \alpha_{P1}) - \mu s_{1F}F_{12F}\cos(\phi_{2P} + \alpha_{P1}) - F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} \\ = m_1 \left[-r_{c1} \left\{ \omega_y^2 \cos\gamma - \omega_x \omega_y \sin\gamma + (\omega_z + \dot{\phi}_1)^2 \cos\gamma + (\dot{\omega}_z + \ddot{\phi}_1) \sin\gamma \right\} + O_x \right] \end{aligned} \quad (D-544)$$

Y-Component of Rotor Force Equation

$$\begin{aligned} -F_{12F}\cos(\phi_{2P} + \alpha_{P1}) - \mu s_{1F}F_{12F}\sin(\phi_{2P} + \alpha_{P1}) - F_{y1u} - \mu F_{x1u} + F_{y1L} + \mu F_{x1L} \\ = m_1 \left[-r_{c1} \left\{ \omega_y^2 \sin\gamma - \omega_x \omega_y \cos\gamma + (\omega_z + \dot{\phi}_1)^2 \sin\gamma - (\dot{\omega}_z + \ddot{\phi}_1) \cos\gamma \right\} + O_y \right] \end{aligned} \quad (D-545)$$

Z-Component of Rotor Force Equation

$$F_{z1} = m_1 \{ r_{c1} [(\omega_x \cos \gamma + \omega_y \sin \gamma) (\omega_z + 2\dot{\phi}_1) + \dot{\omega}_x \sin \gamma - \dot{\omega}_y \cos \gamma] + O_z \} \quad (D-546)$$

Moment Equations for the Rotor and Gear No. 1 With Mesh No. 1 in Round-on-Flat Contact

The form of the moment equation for the round-on-flat case of the rotor is identical to equation D-436.

Determination of $\bar{M}_{O1}$. The moment $\bar{M}_{21F}$ of the contact force $\bar{F}_{12F}$ with respect to pivot O_1 is given by

$$\bar{M}_{21F} = (a_{G1} \bar{n}_{G1} - \rho_{G1} \bar{n}_{NF1}) \times (F_{12F} \bar{n}_{NF1} - \mu s_{1F} F_{12F} \bar{n}_{F1}) \quad (D-547)$$

This becomes with the help of equations D-549, D-541, and D-438

$$\begin{aligned} \bar{M}_{21F} = & a_{G1} F_{12F} [\cos (\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F} \sin \\ & (\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})] \bar{k} - \mu s_{1F} \rho_{G1} F_{12F} \bar{k} \end{aligned} \quad (D-548)$$

Similar to equation D-440, the moments due to the various pivot forces may also for this contact case be adapted from equation D-32. Again, because of the CCW rotation of the rotor, $s_5 = +1$. Further, μ_1 becomes μ and the subscripts are changed from the primed to the unprimed coordinate system. With equation D-548, the complete expression for $\bar{M}_{O1}$ becomes

$$\begin{aligned} \bar{M}_{O1} = & [L_u F_{y1u} + \mu L_u F_{x1u} + L_L F_{y1L} + \mu L_L F_{x1L}] \bar{i} + [\mu L_u F_{y1u} - \mu L_u F_{x1u} \\ & + \mu L_L F_{y1L} - L_L F_{x1L}] \bar{j} + \{ a_{G1} F_{12F} [\cos (\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F} \sin \\ & (\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})] - \mu s_{1F} \rho_{G1} F_{12F} - \mu \rho_{11} \bar{F}_{z1} - \rho_1 \mu F_{y1u} - \rho_1 \mu F_{x1u} \\ & - \rho_1 \mu F_{y1L} - \rho_1 \mu F_{x1L} \} \bar{k} \end{aligned} \quad (D-549)$$

Note the use of the tilded form of $\tilde{F}_{z1}$ in the above. This has been defined by equation D-474.

First Term on Right Hand Side of Equation D-436. As in equation D-441, the first term on the right hand side of equation D-436 remains

$$m_1 r_{c1} [O_z \sin \gamma \bar{i} - O_z \cos \gamma \bar{j}] - (O_x \sin \gamma - O_y \cos \gamma) \bar{k} \quad (D-550)$$

Time Rate of Change of Angular Momentum $\bar{H}_{O1}$ of Rotor With Respect to Its Pivot O_1 . The applicable component expressions for the second term on the right hand side of equation D-436 remain the same as given earlier for the round-on-round contact mode.

Thus, according to equation D-449

$$\dot{H}_{O1x} = A_{52} + A_{53} \dot{\phi}_1 + A_{54} \dot{\phi}_1^2 + A_{55} \ddot{\phi}_1 \quad (D-551)$$

Further, from equation D-454

$$\dot{H}_{O1y} = A_{56} + A_{57} \dot{\phi}_1 + A_{58} \dot{\phi}_1^2 + A_{59} \ddot{\phi}_1, \quad (D-552)$$

and according to equation D-459

$$\dot{H}_{O1z} = A_{60} + A_{61} \ddot{\phi}_1 \quad (D-553)$$

Simplification of Force and Moment Equations and Determination of Rotor Pivot Forces with Mesh No. 1 in Round-on-Flat Contact

X-Component of the Force Equation

Equation D-544 is now rewritten in the following manner

$$\begin{aligned} & -F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} \\ & = A_{62} + A_{63} \dot{\phi}_1 + A_{64} \dot{\phi}_1^2 + A_{65} \ddot{\phi}_1 + A_{66F} F_{12F} \end{aligned} \quad (D-554)$$

where, A_{62} , A_{63} , A_{64} , and A_{65} remain as given by equations D-463 to D-466, respectively, and now

$$A_{66F} = \sin(\phi_{2P} + \alpha_{P1}) + \mu S_{1F} \cos(\phi_{2P} + \alpha_{P1}) \quad (D-555)$$

Y-Component of the Force Equation

Equation D-545 becomes

$$\begin{aligned} & -F_{y1u} - \mu F_{x1u} + F_{y1L} + \mu F_{x1L} \\ & = A_{67} + A_{68} \dot{\phi}_1 + A_{69} \dot{\phi}_1^2 + A_{70} \ddot{\phi}_1 + A_{71F} F_{12F} \end{aligned} \quad (D-556)$$

where A_{67} , A_{68} , A_{69} , and A_{70} remain as given by equations D-469 to D-472, respectively, and

$$A_{71F} = \mu S_{1F} \sin(\phi_{2P} + \alpha_{P1}) - \cos(\phi_{2P} + \alpha_{P1}) \quad (D-557)$$

Z-Component of Force Equation

Equation D-546 is again rewritten in the tilded form, and is identical with equation D-474, i.e.,

$$\tilde{F}_{Z1} = A_{72} + A_{73} \dot{\phi}_1 \quad (D-558)$$

where A_{72} and A_{73} are given by equations D-475 and D-476, respectively.

The components of the rotor moment equation are again written according to equation D-436.

X-Component of Moment Equation

With the help of equations D-549, D-550, and D-551 the following is obtained

$$\begin{aligned} & \mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L} \\ & = m_1 r_{c1} O_z \sin \gamma + A_{52} + A_{53} \dot{\phi}_1 + A_{54} \dot{\phi}_1^2 + A_{55} \ddot{\phi}_1 \end{aligned} \quad (D-559)$$

Y-Component of Moment Equation

Again with the help of equations D-549 and D-550, i.e., its y-factors, as well as equation D-552 the following is found

$$\begin{aligned} & -L_u F_{x1u} + \mu L_u F_{y1u} + \mu L_L F_{y1L} - L_L F_{x1L} \\ & = -m_1 r_{c1} O_z \cos \gamma + A_{56} + A_{57} \dot{\phi}_1 + A_{58} \dot{\phi}_1^2 + A_{59} \ddot{\phi}_1 \end{aligned} \quad (D-560)$$

Z-Component of Moment Equation

Again, using the Z-components of equations D-549 and D-550 together with equation D-553, obtained for the Z-component of the moment expression

$$\begin{aligned} & a_{G1} F_{12F} [\cos(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F} \sin(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})] \\ & - \mu s_{1F} p_{G1} F_{12F} - \mu p_{11} \tilde{F}_{z1} - \mu p_1 (F_{x1u} + F_{y1u} + F_{x1L} + F_{y1L}) \\ & = -m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma] + A_{60} + A_{61} \ddot{\phi}_1 \end{aligned} \quad (D-561)$$

Solution of Rotor Pivot Forces

To obtain the rotor pivot forces, equations D-554, D-556, D-559, and D-560 must be solved simultaneously. Therefore

$$-F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = B_{11F} \quad (D-562)$$

$$-\mu F_{x1u} - F_{y1u} + \mu F_{x1L} + F_{y1L} = B_{12F} \quad (D-563)$$

$$\mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L} = B_{13} \quad (D-564)$$

$$-L_u F_{x1u} + \mu L_u F_{y1u} - L_L F_{x1L} + \mu L_L F_{y1L} = B_{14} \quad (D-565)$$

where

$$B_{11F} = A_{62} + A_{63} \dot{\phi}_1 + A_{64} \dot{\phi}_1^2 + A_{65} \ddot{\phi}_1 + A_{66F} F_{12F} \quad (D-566)$$

$$B_{12F} = A_{67} + A_{68} \dot{\phi}_1 + A_{69} \dot{\phi}_1^2 + A_{70} \ddot{\phi}_1 + A_{71F} F_{12F} \quad (D-567)$$

$$B_{13} = \text{same as equation D-486}$$

$$B_{14} = \text{same as equation D-487}$$

Similar to the round-on-round case of the rotor (see equations D-480 to D-483 and subsequent discussion) equations D-562 to D-565 together have the same general form as equation D-67 for the pallet. Thus, the pallet pivot force solutions may again be adapted to the present round-on-flat contact case of the rotor. As earlier, the coefficient of friction μ must replace the parameter A_{11} . Then, according to equation D-73

$$D_1 = [(L_u + L_L)(1 + \mu^2)]^2 \quad (D-568)$$

Parallel to equation D-80, the determinant $D_{F_{x1u}}$ becomes

$$D_{F_{x1u}} = (L_u + L_L)(1 + \mu^2)[-L_L B_{11F} - \mu L_L B_{12F} + \mu B_{13} - B_{14}] \quad (D-569)$$

After appropriate substitution of equations D-566, D-567 as well as D-486 and D-487, parallel to equations D-81 to D-87, the following is obtained for the conservation (tilded) rotor pivot force $\tilde{F}_{x1u}$

$$\tilde{F}_{x1u} = \frac{\tilde{D}_{F_{x1u}}}{D_1} = \frac{1}{L_L(1 + \mu^2)} [C_{37} + C_{38} \dot{\phi}_1 + C_{39} \dot{\phi}_1^2 + C_{40} \ddot{\phi}_1 + C_{41F} F_{12F}] \quad (D-570)$$

where

$$C_{37} = \text{same as equation D-491}$$

$$C_{38} = \text{same as equation D-492}$$

$$C_{39} = \text{same as equation D-493}$$

$$C_{40} = \text{same as equation D-494}$$

and

$$C_{41F} = \left| -L_L (A_{66F} + \mu A_{71F}) \right| \quad (D-571)$$

Parallel to equation D-89, the determinant $D_{F_{y1u}}$ becomes

$$D_{F_{y1u}} = (L_u + L_L)(1 + \mu^2) \{ \mu L_L B_{11F} - L_L B_{12F} + B_{13} + \mu B_{14} \} \quad (D-572)$$

After appropriate substitution of equations D-566, D-567, D-486, and D-487, parallel to equations D-91 to D-96, it is found that

$$\tilde{F}_{y1u} = \frac{\tilde{D}_{F_{y1u}}}{D_1} = \frac{1}{L_T(1 + \mu^2)} \left[C_{42} + C_{43} \dot{\phi}_1 + C_{44} \dot{\phi}_1^2 + C_{45} \ddot{\phi}_1 + C_{46F} F_{12F} \right] \quad (D-573)$$

where

C_{42} = same as equation D-498

C_{43} = same as equation D-499

C_{44} = same as equation D-500

C_{45} = same as equation D-501

and

$$C_{46F} = \left| L_L (\mu A_{66F} - A_{71F}) \right| \quad (D-574)$$

Parallel to equation D-99, the determinant $D_{F_{x1L}}$ becomes

$$D_{F_{x1L}} = (L_u + L_L)(1 + \mu^2) \{ L_u B_{11F} + \mu L_u B_{12F} + \mu B_{13} - B_{14} \} \quad (D-575)$$

Again, equations D-566, D-567, D-486, and D-487 are substituted into the above. Then proceed parallel to equations D-101 to D-106. Finally

$$\tilde{F}_{x1L} = \frac{\tilde{D}_{F_{x1L}}}{D_1} = \frac{1}{L_T(1 + \mu^2)} \left[C_{47} + C_{48} \dot{\phi}_1 + C_{49} \dot{\phi}_1^2 + C_{50} \ddot{\phi}_1 + C_{51F} F_{12F} \right] \quad (D-576)$$

where

C_{47} = same as equation D-505

C_{48} = same as equation D-506

C_{49} = same as equation D-507

C_{50} = same as equation D-508

$$C_{51F} = |L_u (A_{66F} + \mu A_{71F})| \quad (D-577)$$

Parallel to equation D-109, the determinant $D_{F_{y1L}}$ becomes

$$D_{F_{y1L}} = (L_u + L_L)(1 + \mu^2) \{-\mu L_u B_{11} + L_u B_{12} + B_{13} + \mu B_{14}\} \quad (D-578)$$

After substitution of equations D-566, D-567, D-486, and D-487 proceed parallel to equation D-111

$$\tilde{F}_{y1L} = \frac{\tilde{D}_{F_{y1L}}}{D_1} = \frac{1}{L_T(1 + \mu^2)} [C_{52} + C_{53} \dot{\phi}_1 + C_{54} \dot{\phi}_1^2 + C_{55} \ddot{\phi}_1 + C_{56F} F_{12F}] \quad (D-579)$$

where

C_{52} = same as equation D-512

C_{53} = same as equation D-513

C_{54} = same as equation D-514

C_{55} = same as equation D-515

and

$$C_{56F} = |L_u (A_{71F} - \mu A_{66F})| \quad (D-580)$$

Substitution of Tilded Pivot Forces Into Z-Component of Moment Equation. The sum of the pivot forces in equation D-561 is replaced by the sum of the tilded pivot forces, as given by equations D-570, D-573, D-576, and D-579. Then

$$\begin{aligned} F_{x1u} + F_{y1u} + F_{x1L} &\approx \tilde{F}_{x1u} + \tilde{F}_{y1u} + \tilde{F}_{x1L} + \tilde{F}_{y1L} \\ &= A_{74} + A_{75} \dot{\phi}_1 + A_{76} \dot{\phi}_1^2 + A_{77} \ddot{\phi}_1 + A_{78F} F_{12F} \end{aligned} \quad (D-581)$$

where

A_{74} = same as equation D-518

A_{75} = same as equation D-519

A_{76} = same as equation D-520

A_{77} = same as equation D-521

and

$$A_{78F} = \frac{C_{41F} + C_{46F} + C_{51F} + C_{56F}}{L_T (1 + \mu^2)} \quad (D-582)$$

The above is now substituted, together with the thrust friction according to equation D-558, into the moment expression D-561. Again all friction moments must be examined for their sign.

$$\begin{aligned} &a_{G1} F_{12F} [\cos(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F} \sin(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})] \\ &- \mu s_{1F} \rho_{G1} F_{12F} - \mu \rho_{11} [A_{72} \pm A_{73} \dot{\phi}_1] \\ &- \mu \rho_1 [A_{74} \pm A_{75} \dot{\phi}_1 \pm A_{76} \dot{\phi}_1^2 \pm A_{77} \ddot{\phi}_1 + A_{78F} F_{12F}] \\ &= -m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma] + A_{60} + A_{61} \ddot{\phi}_1 \end{aligned} \quad (D-583)$$

This is rearranged to

$$\begin{aligned} F_{12F} \{ &a_{G1} [\cos(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F} \sin(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})] \\ &- \mu [s_{1F} \rho_{G1} + \rho_1 A_{78F}] \} \pm \mu [\rho_{F1} A_{72} + \rho_1 A_{74}] \end{aligned}$$

$$\begin{aligned} & \pm \mu [\rho_{f1} A_{73} + \rho_1 A_{75}] \dot{\phi}_1 \pm \mu \rho_1 A_{76} \dot{\phi}_1^2 \pm \mu \rho_1 A_{77} \ddot{\phi}_1 \\ & = A_{60} + A_{61} \ddot{\phi}_1 - m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma] \end{aligned} \quad (D-584)$$

Now consider the signs of the various friction moments again as for equation D-524, recalling that a reversal in the gear train motion will cause a change in the sign of μ in the program. The following moment components must have negative signs during positive rotation

$$1: -\mu F_{12F} \rho_1 A_{78F} \quad (D-585)$$

since F_{12} and ρ_1 are positive, and A_{78F} is a sum of absolute values.

$$2: -\mu [\rho_{f1} A_{72} + \rho_1 A_{74}] \quad (D-586)$$

since ρ_{f1} and ρ_1 are positive, while A_{72} and A_{74} are both absolute values.

$$3: -\mu \rho_1 A_{76} \dot{\phi}_1^2 \quad (D-587)$$

since A_{76} is also a sum of absolute values.

The sign of the term containing $\dot{\phi}_1$ must be decided by the sign of this angular velocity only. Therefore, the coefficient of friction must not change sign on motion reversal, and the expression takes the form

$$- |\mu| [\rho_{f1} A_{73} + \rho_1 A_{75}] \dot{\phi}_1 \quad (D-588)$$

The choice of signs in the coefficient of the angular acceleration $\ddot{\phi}_1$ is discussed in detail in appendix F of reference 4. This leads to the computational rules of equations D-591 and D-592 below.

With the above considerations, equation D-398 becomes

$$\begin{aligned} & A_{79F} F_{12} - A_{80} - A_{81} \dot{\phi}_1 - A_{82} \dot{\phi}_1^2 \\ & = I_{1R} \ddot{\phi}_1 + A_{60} - m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma] \end{aligned} \quad (D-589)$$

where

$$A_{79F} = a_{G1} [\cos (\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F} \sin (\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})] - \mu [s_{1F} \rho_{G1} + \rho_1 A_{78F}] \quad (D-590)$$

$$A_{80} = \text{same as equation D-531}$$

$$A_{81} = \text{same as equation D-532}$$

$$A_{82} = \text{same as equation D-533}$$

$$A_{83} = \text{same as equation D-534}$$

Further, as in equations D-535 and D-536

$$I_{1R} = A_{61} + A_{83} \quad (D-591)$$

when $\dot{\phi}_1$ and $\ddot{\phi}_1$ have the same signs, and

$$I_{1R} = A_{61} - A_{83} \quad (D-592)$$

when $\dot{\phi}_1$ and $\ddot{\phi}_1$ have opposite signs.

General Form of Contact Force F_{12F} in Terms of Rotor Parameters When Mesh No. 1 is in Round-on-Flat Contact. Adjustment for Contact Mode of Mesh No. 2

Equation D-589 may now be rewritten to obtain a general expression for the contact force F_{12F} when mesh no. 1 is in the round-on-flat mode of contact

$$F_{12F} = \frac{I_{1R} \ddot{\phi}_1 + A_{81} \dot{\phi}_1 + A_{82} \dot{\phi}_1^2 + A_{80} + A_{60} - m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma]}{A_{79F}} \quad (D-593)$$

When mesh no. 2 is at the same time in the round-on-round mode, the angular velocity $\dot{\phi}_1$ must be obtained from equation F-146 of appendix F, while the angular acceleration $\ddot{\phi}_1$ is given by equation F-147.

With mesh no. 2 simultaneously in the round-on-flat contact mode $\dot{\phi}_1$ and $\ddot{\phi}_1$ are obtained from equations F-150 and F-151, respectively.

DYNAMICS OF GEAR AND PINION NO. 2

(For force analysis background see reference 1)

Before the force and moment equations for the various mesh contact combinations of gear and pinion no. 2 can be written, it is first necessary to find an expression for the absolute acceleration of the gear and pinion pivot point O_2 , which coincides with the center of mass C_2 of this component. A view of this compound gear in the mechanism plane and in configuration no. 2 is shown in figure D-13.

Absolute Acceleration of Gear and Pinion Pivot O_2

The absolute acceleration of pivot point O_2 is given by

$$\bar{A}_{O_2/\text{ground}} = \bar{A}_{O_2/C} + \bar{A}_{C/\text{ground}} \quad (\text{D-594})$$

where

$\bar{A}_{C/\text{ground}}$ = Absolute acceleration of geometric center C of mechanism plane, as given by equation C-4

and

$$\bar{A}_{O_2/C} = \bar{\omega} \times (\bar{\omega} \times \mathcal{R}_2 \bar{n}_2) + \dot{\bar{\omega}} \times \mathcal{R}_2 \bar{n}_2 \quad (\text{D-595})$$

where

$$\bar{\omega} = \omega_x \bar{i} + \omega_y \bar{j} + \omega_z \bar{k} \quad (\text{D-596})$$

$$\dot{\bar{\omega}} = \dot{\omega}_x \bar{i} + \dot{\omega}_y \bar{j} + \dot{\omega}_z \bar{k} \quad (\text{D-597})$$

Further,

$$\bar{n}_2 = \cos \gamma_2 \bar{i} + \sin \gamma_2 \bar{j} \quad (\text{D-598})$$

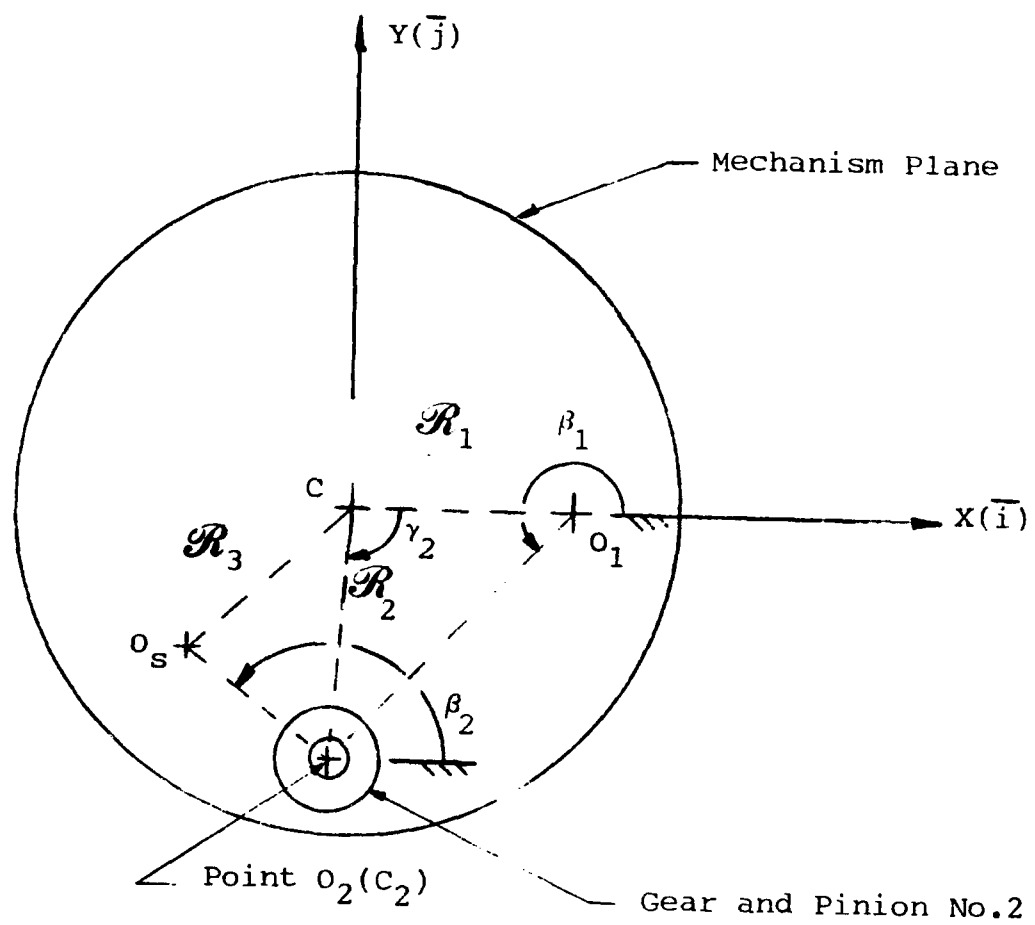


Figure D-13. Gear and pinion no. 2 in mechanism plane (shown in configuration no. 2)

and

$$\mathcal{R}_{2x} = \mathcal{R}_2 \cos \gamma_2 \quad (\text{D-599})$$

$$\mathcal{R}_{2y} = \mathcal{R}_2 \sin \gamma_2 \quad (\text{D-600})$$

With the above, equation D-595 becomes

$$\bar{\mathbf{A}}_{O_2/C} = P_x \bar{\mathbf{i}} + P_y \bar{\mathbf{j}} + P_z \bar{\mathbf{k}} \quad (\text{D-601})$$

where

$$P_x = \omega_x \omega_y \mathcal{R}_{2y} - (\omega_y^2 + \omega_z^2) \mathcal{R}_{2x} - \dot{\omega}_z \mathcal{R}_{2y} \quad (\text{D-602})$$

$$P_y = \omega_x \omega_y \mathcal{R}_{2x} - (\omega_x^2 + \omega_z^2) \mathcal{R}_{2y} + \dot{\omega}_z \mathcal{R}_{2x} \quad (\text{D-603})$$

$$P_z = (\omega_x \mathcal{R}_{2x} + \omega_y \mathcal{R}_{2y}) \omega_z + \dot{\omega}_x \mathcal{R}_{2y} - \dot{\omega}_y \mathcal{R}_{2x} \quad (\text{D-604})$$

Finally, equation D-594 becomes

$$\bar{\mathbf{A}}_{O_2/\text{ground}} = Q_x \bar{\mathbf{i}} + Q_y \bar{\mathbf{j}} + Q_z \bar{\mathbf{k}} \quad (\text{D-605})$$

where, with the help of equations C-4 and D-601

$$Q_x = G_x + P_x \quad (\text{D-606})$$

$$Q_y = G_y + P_y \quad (\text{D-607})$$

$$Q_z = G_z + P_z \quad (\text{D-608})$$

Dynamics of Gear and Pinion No. 2 with Mesh No. 2 and Mesh No. 1 in Round-on-Round Contact

A schematic top view free body diagram of gear and pinion no. 2 with both meshes in the round-on-round contact mode is shown in figure D-14a. It shows the contact force

$$\bar{\mathbf{F}}_{32} = -\bar{\mathbf{F}}_{23} = -\bar{\mathbf{F}}_{23} \bar{\mathbf{n}}_{\lambda 2} \quad (\text{D-609})$$

of pinion no. 3 on gear no. 2, opposite to force $\bar{F}_{23}$, as given by equation D-145a. The associated friction force $\bar{F}_{f32}$ is opposite to $\bar{F}_{f23}$, as given by equation D-146. Thus,

$$\bar{F}_{f32} = -\bar{F}_{f23} = -\omega s_{2R} F_{23} \bar{n}_{N\lambda 2} \quad (D-610)$$

The contact force $\bar{F}_{12}$ of gear no. 1 on pinion no. 2 is also shown in figure D-14a. This force is opposite in direction to contact force $\bar{F}_{21}$, which is given by equation D-426. Then

$$\bar{F}_{12} = -\bar{F}_{21} = F_{23} \bar{n}_{\lambda 1} \quad (D-611)$$

The associated friction force $\bar{F}_{f12}$ is opposite in direction to the friction force $\bar{F}_{f21}$ of equation D-428, i.e.

$$\bar{F}_{f12} = -\bar{F}_{f21} = \mu s_{1R} F_{12} \bar{n}_{N\lambda 1} \quad (D-612)$$

A free body diagram of the pivot shaft of gear and pinion no. 2 is shown in figure D-14b. This representation of normal, friction and thrust forces and torques acting on the CW rotating component is valid regardless of the instantaneous combination of mesh contact modes.

Force Equations

The force equation is again based on Newton's law, i.e.

$$\Sigma \bar{F} = m_2 \bar{A}_{O_2/\text{ground}} \quad (D-613)$$

where

$\Sigma \bar{F}$ = sum of the pivot forces as well as the various contact forces

m_2 = mass of gear and pinion no. 2

$\bar{A}_{O_2/\text{ground}}$ = acceleration of the component center of mass, i.e., equation D-605

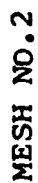
$$Y(\bar{J})$$


Figure D-14a.

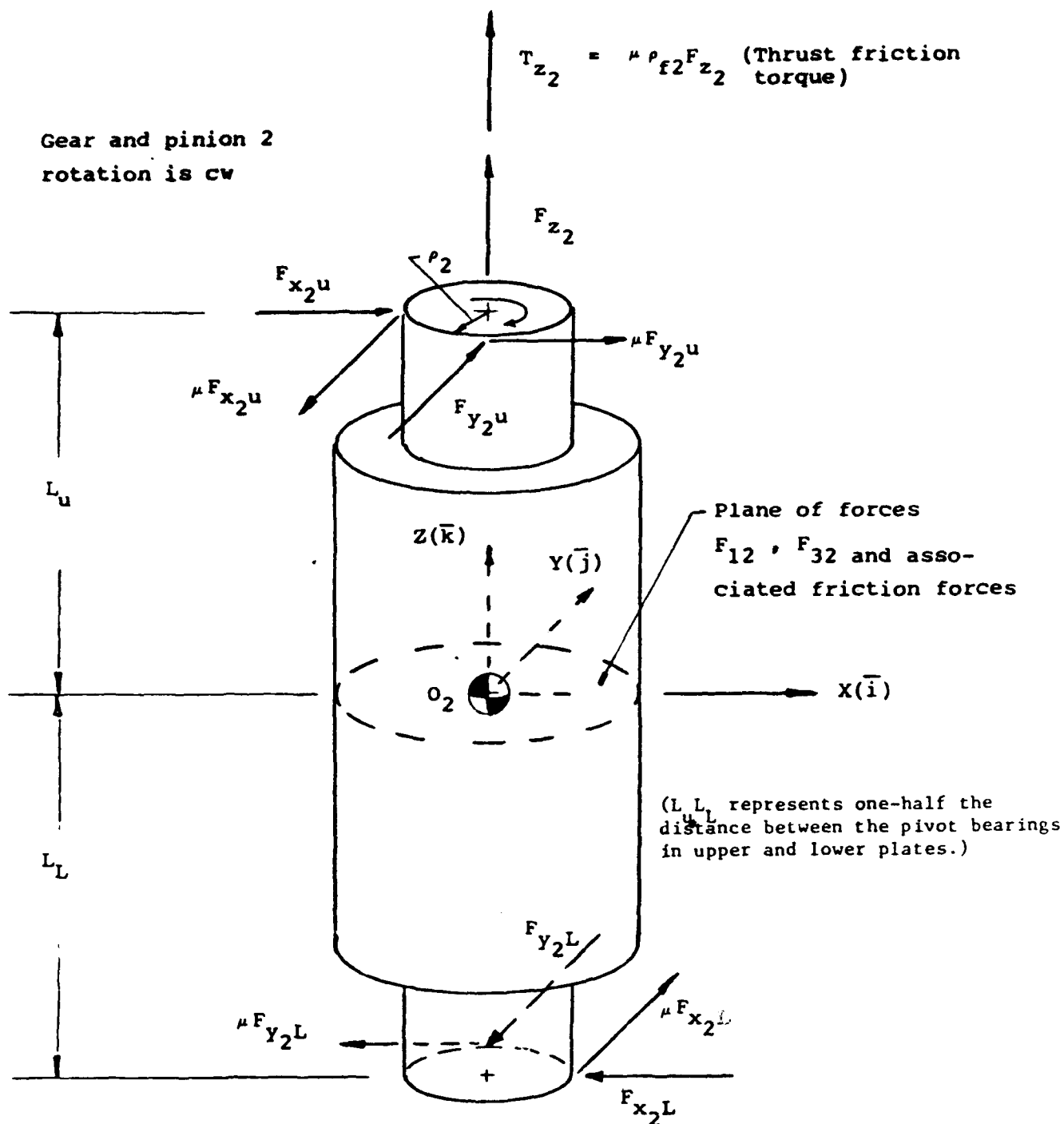


Figure D-14b. Gear pinion no. 2. Normal forces, friction forces, and thrust friction torque on pivots. (Same for all types of mesh combinations.)

The full force equation is now obtained with the help of figures D-14a and D-14b, as well as equations D-609 to D-612

$$\begin{aligned}
 & -F_{23} \bar{n}_{\lambda_2} - s_{2R} \mu F_{23} \bar{n}_{N\lambda_2} + F_{12} \bar{n}_{\lambda_1} + \mu s_{1R} F_{12} \bar{n}_{N\lambda_1} \\
 & + F_{x2u} \bar{i} - \mu F_{x2u} \bar{j} + F_{y2u} \bar{j} + \mu F_{y2u} \bar{i} + F_{z2} \bar{k} \\
 & - F_{x2L} \bar{i} + \mu F_{x2L} \bar{j} - F_{y2L} \bar{j} - \mu F_{y2L} \bar{i} = m_2 (Q_x \bar{i} + Q_y \bar{j} + Q_z \bar{k})
 \end{aligned} \tag{D-614}$$

In the above, $\bar{n}_{\lambda_2}$ and $\bar{n}_{N\lambda_2}$ are given by equations D-145b and D-147, respectively. The unit vectors $\bar{n}_{\lambda_1}$ and $\bar{n}_{N\lambda_1}$ were defined by equations D-427 and D-429. Appropriate substitution and subsequent separation into x and y components furnishes

X-Component of Force Equation

$$\begin{aligned}
 & -F_{23} \cos \lambda_2 + \mu s_{2R} F_{23} \sin \lambda_2 + F_{12} \cos \lambda_1 - \mu s_{1R} F_{12} \sin \lambda_1 \\
 & + F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2 Q_x
 \end{aligned} \tag{D-615}$$

Y-Component of Force Equation

$$\begin{aligned}
 & -F_{23} \sin \lambda_2 - \mu s_{2R} F_{23} \cos \lambda_2 + F_{12} \sin \lambda_1 + \mu s_{1R} F_{12} \cos \lambda_1 \\
 & - \mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 Q_y
 \end{aligned} \tag{D-616}$$

Z-Component of Force Equation

This thrust force is best expressed in tilded form, so that,

$$\tilde{F}_{z2} = |m_2 Q_z| \tag{D-617}$$

Moment Equations

Since gear and pinion no. 2 represents a symmetrical body without products of inertia, its moment equation may be expressed in terms of the projectile-fixed X-Y-Z system by the appropriate adaptation of equation B-13 of appendix B.

The angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$, of gear and pinion no. 2 with respect to the projectile must eventually be expressed in terms of the escape wheel angular velocity $\dot{\phi}$ and angular acceleration $\ddot{\phi}$ in such a way that the round-on-round contact of mesh no. 2 is taken into account.

This gives the moment equation the following form (note that the pivot point O_2 and the center of mass C_2 coincide)

$$\begin{aligned}\bar{M}_{O_2} = & \left[I_{x2}\dot{\omega}_x + I_{z2}\omega_y(\omega_z + \dot{\phi}_2) - I_{y2}\omega_y\omega_z \right] \bar{i} \\ & + \left[I_{y2}\dot{\omega}_y + I_{x2}\omega_x\omega_z - I_{z2}\omega_x(\omega_z + \dot{\phi}_2) \right] \bar{j} + I_{z2}(\dot{\omega}_z + \ddot{\phi}_2) \bar{k}\end{aligned}\quad (D-618)$$

The moment $\bar{M}_{O_2}$ about point O_2 is now found with the help of the pivot shaft free-body diagram of figures D-14a and D-14b. Note that the thrust torque $\mu\rho_{z2}\tilde{F}_{z2}\bar{k}$ uses the tilded form of F_{z2} of equation D-617 in order to always make this friction moment positive, i.e., oppose the clockwise rotation of the component. The parameter ρ_{t2} represents the thrust friction radius, while ρ_2 is the radius of the pivot shaft. Then

$$\begin{aligned}\bar{M}_{O_2} = & (a_{G2}\bar{n}_{G2} + \rho_{G2}\bar{n}_{\lambda 2}) \times (-F_{23}\bar{n}_{\lambda 2} - \mu s_{2R}F_{23}\bar{n}_{N\lambda 2}) \\ & + (a_{P1}\bar{n}_{P1} - \rho_{P1}\bar{n}_{\lambda 1}) \times (F_{12}\bar{n}_{\lambda 1} + \mu s_{1R}F_{12}\bar{n}_{N\lambda 1}) \\ & + \mu\rho_{t2}\tilde{F}_{z2}\bar{k} + (L_u\bar{k} - \rho_2\bar{i}) \times (F_{x2u}\bar{i} - \mu F_{x2u}\bar{j}) \\ & + (L_u\bar{k} - \rho_2\bar{j}) \times (F_{y2u}\bar{j} + \mu F_{y2u}\bar{i}) + (-L_L\bar{k} + \rho_2\bar{i}) \times (-F_{x2L}\bar{i} + \mu F_{x2L}\bar{j}) \\ & + (-L_L\bar{k} + \rho_2\bar{j}) \times (-F_{y2L}\bar{j} - \mu F_{y2L}\bar{i})\end{aligned}\quad (D-619)$$

With equations G-2, G-3, G-4 and G-47, G-48, G-49 of ref 5, the above becomes

$$\begin{aligned}\bar{M}_{O_2} = & [\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} + L_L F_{y2L}] \bar{i} + [L_u F_{x2u} \\ & + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}] \bar{j} + [F_{23} \{ a_{G2} (\sin(\phi_{2G} + \delta_{G2} - \lambda_1) \\ & - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R} \} + F_{12} \{ a_{P1} (-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) \\ & + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu \rho_{P1} s_{1R} \} + \mu \rho_{F2} \tilde{F}_{z2} \\ & + \mu \rho_2 (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L})] \bar{k}\end{aligned}\quad (D-620)$$

Substitution of equation D-260 into equation D-618 yields the following moment component expressions

X-Component of Gear and Pinion Moment Equation

$$\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L} = I_{x2} \dot{\omega}_x + I_{z2} \omega_y (\omega_z + \dot{\phi}_2) - I_{y2} \omega_y \omega_z \quad (D-621)$$

Y-Component of Gear and Pinion Moment Equation

$$L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L} = I_{y2} \dot{\omega}_y + I_{x2} \omega_x \omega_z - I_{z2} \omega_x (\omega_z + \dot{\phi}_2) \quad (D-622)$$

Z-Component of Gear and Pinion Moment Equation

$$\begin{aligned} & F_{23} [a_{G2} (\sin (\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos (\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R}] \\ & + F_{12} [a_{P1} (-\sin (\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R} \cos (\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu \rho_{P1} s_{1R}] \\ & + \mu \rho_{12} \ddot{F}_{z2} + \mu \rho_2 (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}) = I_{z2} (\dot{\omega}_z + \ddot{\phi}_2) \end{aligned} \quad (D-623)$$

Simplification of Force and Moment Equations and Determination of Pivot Forces of Gear and Pinion No. 2

X-Component of the Force Equation

Equation D-615 is now rewritten

$$-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = A_{84RR} F_{23} + A_{85RR} F_{12} + A_{86} \quad (D-624)$$

where

$$A_{84RR} = -(\cos \lambda_2 + \mu s_{2R} \sin \lambda_2) \quad (D-625)$$

$$A_{85RR} = \cos \lambda_1 - \mu s_{1R} \sin \lambda_1 \quad (D-626)$$

$$A_{86} = -M_2 Q_x \quad (D-627)$$

Y-Component of the Force Equation

Equation D-616 is rewritten

$$\mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} = A_{87RR}F_{23} + A_{88RR}F_{12} + A_{89} \quad (D-628)$$

where

$$A_{87RR} = (\sin\lambda_2 + \mu S_{2R}\cos\lambda_2) \quad (D-629)$$

$$A_{88RR} = \sin\lambda_1 + \mu S_{1R}\cos\lambda_1 \quad (D-630)$$

$$A_{89} = -m_2 Q_y \quad (D-631)$$

The Z-component of the force equation remains as in equation D-617.

X-Component of the Moment Equation

Equation D-621 is rewritten

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91}\dot{\phi}_2 \quad (D-632)$$

where

$$A_{90} = [I_{x2}\dot{\omega}_x + \omega_y\omega_z(I_{z2} - I_{y2})] \quad (D-633)$$

$$A_{91} = -I_{z2}\omega_y \quad (D-634)$$

Y-Component of the Moment Equation

Equation D-622 is rewritten

$$-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = A_{92} + A_{93}\dot{\phi}_2 \quad (D-635)$$

where

$$A_{92} = -[I_{y2}\dot{\omega}_y + \omega_x\omega_z(I_{x2} - I_{z2})] \quad (D-636)$$

$$A_{93} = I_{z2}\omega_x \quad (D-637)$$

Equation D-623 for the Z-component of the moment remains as is.

Simultaneous Solution of Pivot Forces. Equations D-624, D-628, D-632, and D-635 are now solved simultaneously for the pivot forces. Therefore

$$\left. \begin{aligned} -F_{x2u} - \mu F_{y2u} - F_{x2L} + \mu F_{y2L} &= B_{21} \\ \mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} &= B_{22} \\ -\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} &= B_{24} \end{aligned} \right\} \quad (D-638)$$

where

$$B_{21} = A_{84RR}F_{23} + A_{85RR}F_{12} \quad (D-639)$$

$$B_{22} = A_{87RR}F_{23} + A_{88RR}F_{12} + A_{89RR} \quad (D-640)$$

$$B_{23} = A_{90} + A_{91}\phi_2 \quad (D-641)$$

$$B_{24} = A_{92} + A_{93}\phi_2 \quad (D-642)$$

NOTE: Since the B_{2i} do not appear in the computer program, their subscripts will not be adjusted for the various mesh contact modes. Only the A's and C's will reflect these variations.

To use the solutions of equation D-67, equation D-638 has to be changed to a form that has the same signs as this set of expressions. This may be accomplished by substituting

$$\mu^* = -\mu \quad (D-643)$$

(This replaces $A_{11} = \mu_1 s_5$ in equation D-67.) Equation D-638 then becomes

$$\left. \begin{aligned} -F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} &= B_{21} \\ -\mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} &= B_{22} \\ \mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} &= B_{24} \end{aligned} \right\} \quad (D-644)$$

With the above substitution (i.e., eq D-643) the coefficient determinant of equation D-644 becomes according to equation D-75

$$D = [(L_u + L_L)(1 + \mu^2)]^2 \quad (D-645)$$

According to equation D-80, the determinant $D_{F_{x2u}}$ now becomes with the appropriate changes

$$D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2)[-L_L B_{21} + \mu L_L B_{22} - \mu B_{23} - B_{24}] \quad (D-646)$$

Now substitute for the B_{2i} 's according to equations D-639 to D-642

$$\begin{aligned} D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2) \{ & -L_L [A_{84RR} F_{23} + A_{85RR} F_{12} + A_{86}] \\ & + \mu L_L [A_{87RR} F_{23} + A_{88RR} F_{12} + A_{89}] \\ & - \mu [A_{90} + A_{91} \dot{\phi}_2] - [A_{92} + A_{93} \dot{\phi}_2] \} \end{aligned} \quad (D-647)$$

After collecting of terms, the tilded force $\tilde{F}_{x2u}$ becomes

$$\tilde{F}_{x2u} = \frac{\tilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{57} + C_{58} \dot{\phi}_2 + C_{59RR} F_{23} + C_{60RR} F_{12}] \quad (D-648)$$

where

$$C_{57} = |-L_L A_{86} + \mu(L_L A_{89} - A_{90}) - A_{92}| \quad (D-649)$$

$$C_{58} = |\mu A_{91} + A_{93}| \quad (D-650)$$

$$C_{59RR} = |L_L(\mu A_{87RR} - A_{84RR})| \quad (D-651)$$

$$C_{60RR} = |L_L(\mu A_{88RR} - A_{85RR})| \quad (D-652)$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes

$$D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2)[- \mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}] \quad (D-653)$$

Substitution of equations D-639 to D-642 gives

$$\begin{aligned} D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2) \{ & - \mu L_L [A_{84RR} F_{23} + A_{85RR} F_{12} + A_{86}] \\ & - L_L [A_{87RR} F_{23} + A_{88RR} F_{12} + A_{89}] \end{aligned}$$

$$+ [A_{90} + A_{91}\dot{\phi}_2] - \mu[A_{92} + A_{93}\dot{\phi}_2] \quad (D-654)$$

After appropriate collecting of terms, the tilded force $\tilde{F}_{y2u}$ becomes

$$\tilde{F}_{y2u} = \frac{\tilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{61} + C_{62}\dot{\phi}_2 + C_{63RR}F_{23} + C_{64RR}F_{12}] \quad (D-655)$$

where

$$C_{61} = |-L_L A_{89} - \mu(L_L A_{86} + A_{92}) + A_{90}| \quad (D-656)$$

$$C_{62} = |A_{91} - \mu A_{93}| \quad (D-657)$$

$$C_{63RR} = |L_L(\mu A_{84RR} + A_{87RR})| \quad (D-658)$$

$$C_{64RR} = |L_L(\mu A_{85RR} + A_{88RR})| \quad (D-659)$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes

$$D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2) \{L_u B_{21} - \mu L_u B_{22} - \mu B_{23} - B_{24}\} \quad (D-660)$$

Substitute equations D-639 to D-642

$$\begin{aligned} D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2) \{ & L_u [A_{84RR}F_{23} + A_{85RR}F_{12} + A_{86}] \\ & - \mu L_u [A_{87RR}F_{23} + A_{88RR}F_{12} + A_{89}] \\ & - \mu [A_{90} + A_{91}\dot{\phi}] - [A_{92} + A_{93}\dot{\phi}_2] \} \end{aligned} \quad (D-661)$$

After collecting of terms, the tilded force F_{x2L} becomes

$$\tilde{F}_{x2L} = \frac{\tilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{65} + C_{66}\dot{\phi}_2 + C_{67RR}F_{23} + C_{68RR}F_{12}] \quad (D-662)$$

where

$$C_{65} = |-\mu(L_u A_{89} + A_{90}) + L_u A_{86} - A_{92}| \quad (D-663)$$

$$C_{66} = |\mu A_{91} + A_{93}| \quad (D-664)$$

$$C_{67RR} = |L_u (A_{84RR} - \mu A_{87RR})| \quad (D-665)$$

$$C_{68RR} = |L_u (A_{85RR} - \mu A_{88RR})| \quad (D-666)$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicable adaption becomes

$$D_{F_{y2L}} = (L_u + L_l) (1 + \mu^2) \{ \mu L_u B_{21} + L_u B_{22} + B_{23} - \mu B_{24} \} \quad (D-667)$$

Substitution of equations D-639 to D-642 leads to

$$\begin{aligned} D_{F_{y2L}} = (L_u + L_l) (1 + \mu^2) \{ & \mu L_u [A_{84RR} F_{23} + A_{85RR} F_{12} + A_{86}] \\ & + L_u [A_{87RR} F_{23} + A_{88RR} F_{12} + A_{89}] \\ & + [A_{90} + A_{91} \dot{\phi}_2] - \mu [A_{92} + A_{93} \dot{\phi}_2] \} \end{aligned} \quad (D-668)$$

Again, terms are collected and an expression for the tilded force F_{y2L} is found. Therefore

$$\tilde{F}_{y2L} = \frac{\tilde{D}_{F_{y2L}}}{D} = \frac{1}{L_l (1 + \mu^2)} [C_{69} + C_{70} \dot{\phi}_2 + C_{71RR} F_{23} + C_{72RR} F_{12}] \quad (D-669)$$

where

$$C_{69} = |L_u A_{89} + \mu (L_u A_{86} - A_{92}) + A_{90}| \quad (D-670)$$

$$C_{70} = |A_{91} - \mu A_{93}| \quad (D-671)$$

$$C_{71RR} = |L_u (\mu A_{84RR} + A_{87RR})| \quad (D-672)$$

$$C_{72RR} = |L_u (\mu A_{85RR} + A_{88RR})| \quad (D-673)$$

Determination of Contact Force $\bar{F}_{23}$ in Terms of Contact Force $\bar{F}_{12}$ and Gear and Pinion No. 2 Parameters with Both Meshes in Round-on-Round Contact

Substitution of equations D-648, D-655, D-662, D-669, and D-617 into the Z-moment equation D-623 is now required. First, let the tilded forces be added

$$\tilde{F}_{x2u} + \tilde{F}_{y2u} + \tilde{F}_{x2L} + \tilde{F}_{y2L} = A_{94} + A_{95}\dot{\phi} + A_{96RR}F_{23} + A_{97RR}F_{12} \quad (D-674)$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T(1 + \mu^2)} \quad (D-675)$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T(1 + \mu^2)} \quad (D-676)$$

$$A_{96RR} = \frac{C_{59RR} + C_{63RR} + C_{67RR} + C_{71RR}}{L_T(1 + \mu^2)} \quad (D-677)$$

$$A_{97RR} = \frac{C_{60RR} + C_{64RR} + C_{68RR} + C_{72RR}}{L_T(1 + \mu^2)} \quad (D-678)$$

Further, let equation D-617 be expressed as

$$\tilde{F}_{22} = A_{98} = |m_2 Q_z| \quad (D-679)$$

Equation D-623 then becomes

$$\begin{aligned} & F_{23} [a_{G2} (\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R}] \\ & + F_{12} [a_{P1} (-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu \rho_{P1} s_{1R}] \\ & + \mu \rho_{12} A_{98} + \mu \rho_2 [A_{94} \pm A_{95}\dot{\phi}_2 + A_{96RR}F_{23} + A_{97RR}F_{12}] \\ & = I_{22} (\dot{\omega}_z + \ddot{\phi}) \end{aligned} \quad (D-680)$$

or

$$\begin{aligned}
& F_{23}[a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R} + \mu \rho_2 A_{96RR}] \\
& + F_{12}[a_{P1}(-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu \rho_{P1} s_{1R} + \mu \rho_2 A_{97RR}] \\
& + \mu[\rho_{12} A_{98} + \rho_2 A_{94}] \pm \mu \rho_2 A_{95} \dot{\phi}_2 = A_{99} + A_{100} \ddot{\phi}_2
\end{aligned} \tag{D-681}$$

where

$$A_{99} = I_{z2} \dot{\omega}_z \tag{D-682}$$

$$A_{100} = I_{z2} \tag{D-683}$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction and the following friction moments must be positive.

$$\mu F_{23} \rho_2 A_{96RR} \text{ (} A_{96RR} \text{ is sum of absolute values)} \tag{D-684}$$

$$\mu F_{12} \rho_2 A_{97RR} \text{ (} A_{97RR} \text{ is sum of absolute values)} \tag{D-685}$$

$$\mu[\rho_{12} A_{98} + \rho_2 A_{94}] \text{ (} A_{94} \text{ and } A_{98} \text{ are absolute values)} \tag{D-686}$$

The moment represented by the term containing $\dot{\phi}_2$ must always act opposite to the direction of rotation of gear and pinion no. 2. Therefore, the term must have a negative sign and the absolute value of μ must be used

$$- |\mu| \rho_2 A_{95} \dot{\phi}_2 \tag{D-687}$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-681 becomes

$$\begin{aligned}
& F_{23}[a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_1) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R} + \mu \rho_2 A_{96RR}] \\
& + F_{12}[a_{P1}(-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu \rho_{P1} s_{1R} + \mu \rho_2 A_{97RR}] \\
& + \mu[\rho_{12} A_{98} + \rho_2 A_{94}] - |\mu| \rho_2 A_{95} \dot{\phi}_2 = A_{99} + A_{100} \ddot{\phi}_2
\end{aligned} \tag{D-688}$$

Gear and Pinion No.2
Rotate in cw Direction

The diagram illustrates the free body of Gear and Pinion No. 2, which rotates clockwise. It shows the following elements:

- Coordinate Systems:** A global coordinate system with $\bar{Y}(\bar{j})$ (vertical) and $\bar{X}(\bar{i})$ (horizontal) axes. A local coordinate system $\bar{X}(\bar{i})$ is also shown along the horizontal axis.
- Centers and Points:** O_1 is the center of the pinion. O_2 is the center of the gear. O_S is a support point. C is a contact point. C_{P1} is the center of pressure.
- Forces and Moments:**
 - F_{32F} and F_{f32F} are forces acting on the gear at point C .
 - F_{12F} and F_{f12F} are forces acting on the pinion at point C .
 - $\bar{n}_{G2}$ and $\bar{n}_{NF2}$ are normal and tangential force vectors at O_S .
 - $\bar{n}_{F1}$ and $\bar{n}_{NF1}$ are normal and tangential force vectors at C_{P1} .
 - T_1 is a torque vector at O_2 .
- Geometry and Angles:**
 - ϕ_{2G} and ϕ_{2P} are angles at O_2 .
 - ϕ_{G2} is an angle at C .
 - ϕ_{P1} is an angle at C_{P1} .
 - δ_{G2} is a distance from O_2 to the line of action of F_{32F} .
 - δ_{G2} is a distance from O_2 to the line of action of F_{f32F} .
 - δ_{G2} is a distance from O_2 to the line of action of F_{12F} .
 - δ_{G2} is a distance from O_2 to the line of action of F_{f12F} .
 - δ_{G2} is a distance from O_2 to the line of action of T_1 .
 - δ_{G2} is a distance from O_2 to the line of action of $\bar{n}_{F1}$.
 - δ_{G2} is a distance from O_2 to the line of action of $\bar{n}_{NF1}$.
 - δ_{G2} is a distance from O_2 to the line of action of $\bar{n}_{G2}$.
 - δ_{G2} is a distance from O_2 to the line of action of $\bar{n}_{NF2}$.
- Mesh Labels:** MESH NO. 1 is labeled near the pinion, and MESH NO. 2 is labeled near the gear.

Finally, the above is solved for F_{23}

$$F_{23} = \frac{A_{102RR} F_{12} - A_{103} + A_{104} \dot{\phi}_2 + A_{99} + A_{100} \ddot{\phi}_2}{A_{101RR}} \quad (D-689)$$

where

$$A_{101RR} = a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R} + \mu \rho_2 A_{96RR} \quad (D-690)$$

$$A_{102RR} = -[a_{P1}(-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu \rho_{P1} s_{1R} + \mu \rho_2 A_{97RR}] \quad (D-691)$$

$$A_{103} = \mu[\rho_{12} A_{98} + \rho_2 A_{94}] \quad (D-692)$$

$$A_{104} = |\mu| \rho_2 A_{95} \quad (D-693)$$

Dynamics of Gear and Pinion No. 2 with Mesh No. 2 and Mesh No. 1 in Round-on-Flat Contact

A schematic top view free body diagram of gear and pinion no. 2 with both meshes in the round-on-flat contact mode is shown in figure D-15. It shows the contact force

$$\bar{F}_{32F} = -\bar{F}_{23F} = -F_{23F} \bar{n}_{NF2} \quad (D-694)$$

of pinion no. 3 on gear no. 2, opposite to force $\bar{F}_{23F}$, as given by equation D-245a. The associated friction force $\bar{F}_{132F}$ is opposite to $\bar{F}_{123F}$, as given by equation D-246. Thus

$$\bar{F}_{132F} = -\bar{F}_{123F} = -\mu s_{2F} F_{23F} \bar{n}_{F2} \quad (D-695)$$

The contact force $\bar{F}_{12F}$ of gear no. 1 on pinion no. 2 is also shown in figure D-15. This force is opposite in direction to contact force $\bar{F}_{21F}$, which is given by equation D-538. Then

$$\bar{F}_{12F} = -\bar{F}_{21F} = -F_{12F} \bar{n}_{NF1} \quad (D-696)$$

The associated friction force $\bar{F}_{112F}$ is opposite in direction to the friction force $\bar{F}_{112F}$ of equation D-540, i.e.

$$\bar{F}_{112F} = -\bar{F}_{121F} = \mu s_{1F} F_{12F} \bar{n}_{F1} \quad (D-697)$$

Figure D-14b may also be used for the present case as a free body diagram of the pivot shaft of gear and pinion no. 2. As stated earlier, this representation of normal, friction and thrust forces and torques acting on the CW rotating component is valid regardless of the instantaneous combination of mesh contact modes.

Force Equations

The force equation is again based on Newton's law, i.e.

$$\Sigma \bar{F} = m_2 \bar{A}_{O_2/\text{ground}} \quad (\text{D-698})$$

where

$\Sigma \bar{F}$ = Sum of the pivot forces as well as the various contact forces

m_2 = Mass of gear and pinion no. 2

$\bar{A}_{O_2/\text{ground}}$ = Acceleration of the component center of mass, i.e., equation

D-605

The full force equation is now obtained with the help of figures D-15 and D-14b, as well as equations D-694 to D-697

$$\begin{aligned} & -F_{23F} \bar{n}_{NF2} - \mu s_{2F} F_{23F} \bar{n}_{F2} - F_{12F} \bar{n}_{NF1} + \mu s_{1F} F_{12F} \bar{n}_{F1} \\ & + F_{x2u} \bar{i} - \mu F_{x2u} \bar{j} + F_{y2u} \bar{j} + \mu F_{y2u} \bar{i} + F_{z2} \bar{k} \\ & - F_{x2L} \bar{i} + \mu F_{x2L} \bar{j} - F_{y2L} \bar{j} - \mu F_{y2L} \bar{i} = m_2 (Q_x \bar{i} + Q_y \bar{j} + Q_z \bar{k}) \end{aligned} \quad (\text{D-699})$$

In the above, $\bar{n}_{NF2}$ and $\bar{n}_{F2}$ are given by equations D-245b and D-247, respectively. The unit vectors $\bar{n}_{NF1}$ and $\bar{n}_{F1}$ were defined by equations D-539 and D-541.

Appropriate substitution and subsequent component separation furnished the following

X-Component of Force Equation

$$\begin{aligned} & F_{23F} \sin(\phi_S - \alpha_{P2}) - \mu s_{2F} F_{23F} \cos(\phi_S - \alpha_{P2}) \\ & + F_{12F} \sin(\phi_{2P} + \alpha_{P1}) + \mu s_{1F} F_{12F} \cos(\phi_{2P} + \alpha_{P1}) \\ & + F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2 Q_x \end{aligned} \quad (\text{D-700})$$

Y-Component of Force Equation

$$\begin{aligned} & -F_{23F} \cos(\phi_S - \alpha_{P2}) - \mu S_{2F} F_{23F} \sin(\phi_S - \alpha_{P2}) \\ & -F_{12F} \cos(\phi_{2P} + \alpha_{P1}) + \mu S_{1F} F_{12F} \sin(\phi_{2P} + \alpha_{P1}) \\ & -\mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 Q_y \end{aligned} \quad (D-701)$$

Z-Component of Force Equation

This thrust force is best expressed in tilded form, so that,

$$\tilde{F}_{z2} = |m_2 Q_z| \quad (D-702)$$

Moment Equations

Again, the moment equation is expressed in terms of the projectile-fixed coordinate system. The angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$ must now reflect the round-on-flat contact of mesh no. 2, when these quantities are expressed in terms of the escape wheel angular velocity and acceleration. With the above, equation D-618 is again applicable.

The expression for the moment $\bar{M}_{O2}$ is now found with the help of the free body diagrams of figures D-15 and D-14b. The remarks concerning the thrust friction torque, following equation D-618, still hold. Then

$$\begin{aligned} \bar{M}_{O2} = & (a_{G2} \bar{n}_{G2} + \rho_{G2} \bar{n}_{NF2}) \times (-F_{23F} \bar{n}_{NF2} - \mu S_{2F} F_{23F} \bar{n}_{F2}) + g_1 \bar{n}_{F1} \times (-F_{12F} \bar{n}_{NF1}) \\ & + \mu \rho_{12} \tilde{F}_{z2} \bar{k} + (L_u \bar{k} - \rho_2 \bar{i}) \times (F_{x2u} \bar{i} - \mu F_{x2u} \bar{j}) + (L_u \bar{k} - \rho_2 \bar{j}) \times (F_{y2u} \bar{j} + \mu F_{y2u} \bar{i}) \\ & + (-L_L \bar{k} + \rho_2 \bar{i}) \times (-F_{x2L} \bar{i} + \mu F_{x2L} \bar{j}) \\ & + (-L_L \bar{k} + \rho_2 \bar{j}) \times (-F_{y2L} \bar{j} - \mu F_{y2L} \bar{i}) \end{aligned} \quad (D-703)$$

The above becomes with equations G-22, G-23, G-47, G-64, and G-65 of ref 5

$$\begin{aligned}
 \bar{M}_{O_2} = & [\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L}] \bar{i} \\
 & + [L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}] \bar{j} \\
 & + [F_{23F} \{a_{G2} (-\cos(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})) \\
 & + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})\} + \rho_{G2} \mu s_{2F}] - g_1 F_{12F} \\
 & + \mu p_{12} \tilde{F}_{z2} + \mu p_2 (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}) \bar{k}
 \end{aligned} \tag{D-704}$$

Substitution of equation D-704 into equation D-618 yields the following moment component expressions.

X-Component of Gear and Pinion Moment Equation

$$\begin{aligned}
 & \mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L} \\
 & = I_{y2} \dot{\omega}_x + I_{z2} \omega_y (\omega_z + \dot{\phi}_2) - I_{y2} \omega_y \omega_z
 \end{aligned} \tag{D-705}$$

Y-Component of Gear and Pinion Moment Equation

$$\begin{aligned}
 & L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L} \\
 & = I_{y2} \dot{\omega}_y + I_{x2} \omega_x \omega_z - I_{z2} \omega_x (\omega_z + \dot{\phi}_2)
 \end{aligned} \tag{D-706}$$

Z-Component of Gear and Pinion Moment Equation

$$\begin{aligned}
 & F_{23F} \{a_{G2} (-\cos(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})\} \\
 & + \rho_{G2} \mu s_{2F} - g_1 F_{12F} + \mu p_{12} \tilde{F}_{z2} + \mu p_2 (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}) \\
 & = I_{z2} (\dot{\omega}_z + \ddot{\phi}_2)
 \end{aligned} \tag{D-707}$$

Simplification of Force and Moment Equations and Determination of Pivot Forces on Gear and Pinion No. 2

X-Component of the Force Equation

Equation D-700 is now rewritten

$$-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = A_{84FF} F_{23F} + A_{85FF} F_{12F} + A_{86} \tag{D-708}$$

where

$$A_{84FF} = \sin(\phi_s - \alpha_{P2}) - \mu S_{2F} \cos(\phi_s - \alpha_{P2}) \quad (D-709)$$

$$A_{85FF} = \sin(\phi_{2P} + \alpha_{P1}) + \mu S_{1F} \cos(\phi_{2P} + \alpha_{P1}) \quad (D-710)$$

$$A_{86} = -m_2 Q_x \quad (D-711)$$

Y-Component of the Force Equation

Equation D-701 is rewritten

$$\mu F_{x2u} - F_{y2u} - F_{x2L} + F_{y2L} = A_{87FF} F_{23F} + A_{88FF} F_{12F} + A_{89} \quad (D-712)$$

where

$$A_{87FF} = -(\cos(\phi_s - \alpha_{P2}) + \mu S_{2F} \sin(\phi_s - \alpha_{P2})) \quad (D-713)$$

$$A_{88FF} = -\cos(\phi_{2P} + \alpha_{P1}) + \mu S_{1F} \sin(\phi_{2P} + \alpha_{P1}) \quad (D-714)$$

$$A_{89} = -m_2 Q_y \quad (D-715)$$

The Z-component of the force equation remains as in equation D-702.

X-Component of the Moment Equation

Equation D-705 is rewritten

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91} \dot{\phi}_2 \quad (D-716)$$

where

$$A_{90} = [I_{x2} \dot{\omega}_x + \omega_y \omega_z (I_{z2} - I_{y2})] \quad (D-717)$$

$$A_{91} = -I_{z2} \omega_y \quad (D-718)$$

Y-Component of the Moment Equation

Equation D-706 is rewritten

$$-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = A_{92} + A_{93} \dot{\phi}_2 \quad (D-719)$$

where

$$A_{92} = -[I_{y2}\dot{\omega}_y + \omega_x\omega_z(I_{x2} - I_{z2})] \quad (D-720)$$

$$A_{93} = I_{z2}\omega_z \quad (D-721)$$

Equation D-707 for the Z-component of the moment equation remains as is.

Simultaneous Solution of Pivot Forces. Equations D-708, D-712, D-716, and D-719 are now solved simultaneously for the pivot forces. Therefore,

$$\left. \begin{aligned} -F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} &= B_{21} \\ \mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} &= B_{22} \\ -\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} &= B_{24} \end{aligned} \right\} \quad (D-722)$$

where

$$B_{21} = A_{84FF}F_{23F} + A_{85FF}F_{12F} + A_{86} \quad (D-723)$$

$$B_{22} = A_{87FF}F_{23F} + A_{88FF}F_{12F} + A_{89} \quad (D-724)$$

$$B_{23} = A_{90} + A_{91}\dot{\phi}_2 \quad (D-725)$$

$$B_{24} = A_{92} + A_{93}\dot{\phi}_2 \quad (D-726)$$

As decided earlier, since the B_{2i} do not appear in the computer program, their subscripts will not be adjusted for the various mesh contact modes. Only the A's and C's will reflect these variations.

To use the solutions of equation D-67, equation D-722 has to be changed again to a form that has the same signs as this set of expressions. This may be accomplished by substituting

$$\mu^* = -\mu \quad (D-727)$$

(This replaces $A_{11} = \mu_1 s_5$ in equation D-67.) Equation D-722 then becomes

$$\left. \begin{aligned} -F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} &= B_{21} \\ -\mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} &= B_{22} \\ \mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} &= B_{24} \end{aligned} \right\} \quad (D-728)$$

With the above substitution (i.e., equation D-727) the coefficient determinant of equation D-728 becomes according to equation D-75

$$D = [(L_u + L_L)(1 + \mu^2)]^2 \quad (D-729)$$

According to equation D-80, the determinant $D_{F_{x2u}}$ now becomes with the appropriate changes

$$D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2)[-L_L B_{21} + \mu L_L B_{22} - \mu B_{23} - B_{24}] \quad (D-730)$$

Now substitute for the B_{2i} 's according to equations D-723 to D-726

$$\begin{aligned} D_{F_{x2u}} &= (L_u + L_L)(1 + \mu^2)[-L_L [A_{84FF} F_{23F} + A_{85FF} F_{12F} + A_{86}] \\ &\quad + \mu L_L [A_{87FF} F_{23F} + A_{88FF} F_{12F} + A_{89}] \\ &\quad - \mu [A_{90} + A_{91}\dot{\phi}_2] - [A_{92} + A_{93}\dot{\phi}_2]] \end{aligned} \quad (D-731)$$

After collecting the terms, the tilded force $\tilde{F}_{x2u}$ becomes

$$\tilde{F}_{x2u} = \frac{\tilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{57} + C_{58}\dot{\phi}_2 + C_{59FF} F_{23F} + C_{60FF} F_{12F}] \quad (D-732)$$

where

$$C_{57} = [-L_L A_{86} + \mu(L_L A_{89} - A_{90}) - A_{92}] \quad (D-733)$$

$$C_{58} = [\mu A_{91} + A_{93}] \quad (D-734)$$

$$C_{59FF} = [L_L (\mu A_{87FF} - A_{84FF})] \quad (D-735)$$

$$C_{60FF} = [L_L (\mu A_{88FF} - A_{85FF})] \quad (D-736)$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes

$$D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2)[- \mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}] \quad (D-737)$$

Substitution of equations D-723 to D-726 gives

$$\begin{aligned} D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2) \{ & - \mu L_L [A_{84FF} F_{23F} + A_{85FF} F_{12F} + A_{86}] \\ & - L_L [A_{87FF} F_{23F} + A_{88FF} F_{12F} + A_{89}] \\ & + [A_{90} + A_{91} \dot{\phi}_2] - \mu [A_{92} + A_{93} \dot{\phi}_2] \} \end{aligned} \quad (D-738)$$

After appropriate collecting of terms, the tilded force $\tilde{F}_{y2u}$ becomes

$$\tilde{F}_{y2u} = \frac{\tilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{61} + C_{62} \dot{\phi}_2 + C_{63FF} F_{23F} + C_{64FF} F_{12F}] \quad (D-739)$$

where

$$C_{61} = [-L_L A_{89} - \mu(L_L A_{86} + A_{92}) + A_{90}] \quad (D-740)$$

$$C_{62} = [A_{91} - \mu A_{93}] \quad (D-741)$$

$$C_{63FF} = [L_L (\mu A_{84FF} + A_{87FF})] \quad (D-742)$$

$$C_{64FF} = [L_L (\mu A_{85FF} + A_{88FF})] \quad (D-743)$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes

$$D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2)\{L_u B_{21} - \mu L_u B_{22} - \mu B_{23} - B_{24}\} \quad (D-744)$$

Substitute equations D-723 to D-726

$$\begin{aligned} D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2) \{ & L_u [A_{84FF} F_{23F} + A_{85FF} F_{12F} + A_{86}] \\ & - \mu L_u [A_{87FF} F_{23F} + A_{88FF} F_{12F} + A_{89}] \\ & - \mu [A_{90} + A_{91} \dot{\phi}_2] - [A_{92} + A_{93} \dot{\phi}_2] \} \end{aligned} \quad (D-745)$$

After collecting of terms, the tilded force $\tilde{F}_{x2L}$ becomes

$$\tilde{F}_{x2L} = \frac{\tilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{65} + C_{66} \dot{\phi}_2 + C_{67FF} F_{23} + C_{68FF} F_{12F}] \quad (D-746)$$

where

$$C_{65} = |-\mu(L_U A_{89} + A_{90}) + L_U A_{86} - A_{92}| \quad (D-747)$$

$$C_{66} = |\mu A_{91} + A_{93}| \quad (D-748)$$

$$C_{67FF} = |L_U(A_{84FF} - \mu A_{87FF})| \quad (D-749)$$

$$C_{68FF} = |L_U(A_{85FF} - \mu A_{88FF})| \quad (D-750)$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicable adaptation becomes

$$D_{F_{y2L}} (L_U + L_L)(1 + \mu^2) \{ \mu L_U B_{21} + L_U B_{22} + B_{23} - \mu B_{24} \} \quad (D-751)$$

Substitution of equations D-723 to D-726 leads to

$$\begin{aligned} D_{F_{y2L}} = & (L_U + L_L)(1 + \mu^2) \{ \mu L_U [A_{84FF} F_{23F} + A_{85FF} F_{12F} + A_{86}] \\ & + L_U [A_{87FF} F_{23F} + A_{88FF} F_{12F} + A_{89}] \\ & + [A_{90} + A_{91} \dot{\phi}_2] - \mu [A_{92} + A_{93} \dot{\phi}_2] \} \end{aligned} \quad (D-752)$$

Again, terms are collected and an expression for the tilded force $\tilde{F}_{y2L}$ is found. Therefore

$$\tilde{F}_{y2L} = \frac{\tilde{D}_{F_{y2L}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{69} + C_{70} \dot{\phi}_2 + C_{71FF} F_{23F} + C_{72FF} F_{12F}] \quad (D-753)$$

where

$$C_{69} = |L_U A_{89} + \mu(L_U A_{86} - A_{92}) + A_{90}| \quad (D-754)$$

$$C_{70} = |A_{91} - \mu A_{93}| \quad (D-755)$$

$$C_{71FF} = |L_u(\mu A_{84FF} + A_{87FF})| \quad (D-756)$$

$$C_{72FF} = |L_u(\mu A_{85FF} + A_{88FF})| \quad (D-757)$$

Determination of Contact Force F_{23F} in Terms of Contact Force F_{12F} and Gear and Pinion No. 2 Parameters with Both Meshes in Round-on-Flat Contact

Substitution of equations D-732, D-739, D-746, D-753, and D-702 into the Z-moment equation D-701 is now required. First, let the tilded forces be added

$$\tilde{F}_{x2u} + \tilde{F}_{y2u} + \tilde{F}_{x2L} + \tilde{F}_{y2L} = A_{94} + A_{95}\dot{\phi} + A_{96FF}F_{23F} + A_{97FF}F_{12F} \quad (D-758)$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T(1 + \mu^2)} \quad (D-759)$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T(1 + \mu^2)} \quad (D-760)$$

$$A_{96FF} = \frac{C_{59FF} + C_{63FF} + C_{67FF} + C_{71FF}}{L_T(1 + \mu^2)} \quad (D-761)$$

$$A_{97FF} = \frac{C_{60FF} + C_{64FF} + C_{68FF} + C_{72FF}}{L_T(1 + \mu^2)} \quad (D-762)$$

Further, let equation D-702 be expressed as

$$\dot{F}_{z2} = A_{98} = |m_2 Q_z| \quad (D-763)$$

Equation D-707 then becomes

$$\begin{aligned} & F_{23F} \{ a_{G2} (-\cos(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2})) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}) \} \\ & + \mu \rho_{G2} s_{2F} \} - g_1 F_{12F} + \mu \rho_{f2} A_{98} + \mu \rho_2 [A_{94} \pm A_{95}\dot{\phi}_2 + A_{96FF}F_{23F} + A_{97FF}F_{12F}] \\ & = I_{z2}(\dot{\omega}_z + \ddot{\phi}_2) \end{aligned} \quad (D-764)$$

or

$$\begin{aligned}
 & F_{23}[a_{G2}(-\cos(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2})) \\
 & + \mu s_{2F} \rho_{G2} + \mu \rho_2 A_{96FF}] - F_{12F}[g_1 - \mu \rho_2 A_{97FF}] \\
 & + \mu[\rho_{12} A_{98} + \rho_2 A_{94}] \pm \mu \rho_2 A_{95} \dot{\phi}_2 = A_{99} + A_{100} \ddot{\phi}_2
 \end{aligned} \tag{D-765}$$

where again, as in equations D-682 and D-683

$$A_{99} = I_{z2} \dot{\omega}_z \tag{D-766}$$

$$A_{100} = I_{z2} \tag{D-767}$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction and the following friction moments must be positive.

$$\mu F_{23} \rho_2 A_{96FF} \text{ (} A_{96FF} \text{ is the sum of absolute values) } \tag{D-768}$$

$$\mu F_{12} \rho_2 A_{97FF} \text{ (} A_{97FF} \text{ is the sum of absolute values) } \tag{D-769}$$

$$\mu[\rho_{12} A_{98} + \rho_2 A_{94}] \text{ (} A_{94} \text{ and } A_{98} \text{ are absolute values) } \tag{D-770}$$

The moment represented by the term containing $\dot{\phi}_2$ must always act opposite to the direction of rotation of gear and pinion no. 2. Therefore the term must have a negative sign and the absolute value of μ must be used

$$-|\mu| \rho_2 A_{95} \dot{\phi}_2 \tag{D-771}$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-765 becomes

$$\begin{aligned}
 & F_{23F}[a_{G2}(-\cos(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2})) \\
 & + \mu s_{2F} \rho_{G2} + \mu \rho_2 A_{96FF}] - F_{12F}[g_1 - \mu \rho_2 A_{97FF}] \\
 & + \mu[\rho_{12} A_{98} + \rho_2 A_{94}] - |\mu| \rho_2 A_{95} \dot{\phi}_2 = A_{99} + A_{100} \ddot{\phi}_2
 \end{aligned} \tag{D-772}$$

Finally, the above is solved for F_{23F}

$$F_{23F} = \frac{A_{102FF}F_{12F} - A_{103} + A_{104}\dot{\phi}_2 + A_{99} + A_{100}\ddot{\phi}_2}{A_{101FF}} \quad (D-773)$$

where

$$A_{101FF} = a_{G2}(-\cos(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})) \\ + \mu(\rho_2 A_{96FF} + s_{2F} \rho_{G2}) \quad (D-774)$$

$$A_{102FF} = g_1 - \mu \rho_2 A_{97FF} \quad (D-775)$$

$$A_{103} = \mu[\rho_{12} A_{98} + \rho_2 A_{94}] \quad (D-776)$$

$$A_{104} = |\mu| \rho_2 A_{95} \quad (D-777)$$

Dynamics of Gear and Pinion No. 2, with Mesh No. 2 in Round-on-Round Contact and Mesh No. 1 in Round-on-Flat Contact

A schematic top view of a free body diagram of gear and pinion no. 2 with mesh no. 2 in round-on-round contact and mesh no. 2 in round-on-flat contact is represented in figure D-16. It shows the contact force

$$\bar{F}_{32} = -\bar{F}_{23} = -F_{23}\bar{n}_{\lambda 2} \quad (D-778)$$

of pinion no. 3 and gear no. 2, opposite to force $\bar{F}_{23}$ as given by equation D-145a. The associated friction force $\bar{F}_{f32}$ is opposite to $\bar{F}_{f23}$ of eq. D-146. Thus,

$$\bar{F}_{f32} = -\bar{F}_{f23} = \mu s_{2R} F_{23} \bar{n}_{N\lambda 2} \quad (D-779)$$

Further, the contact force $\bar{F}_{12F}$ of gear no. 1 and pinion no. 2 is shown in figure D-16. This force is opposite to $\bar{F}_{21F}$ of equation D-538. Then

$$\bar{F}_{12F} = -\bar{F}_{21F} = -F_{12F} \bar{n}_{NF1} \quad (D-780)$$

The associated friction force $\bar{F}_{f12F}$ is opposite in direction to the friction force $\bar{F}_{f21F}$ of equation D-540, i.e.,

$$\bar{F}_{f12F} = -\bar{F}_{f21F} = \mu s_{1F} F_{12F} \bar{n}_{F1} \quad (D-781)$$

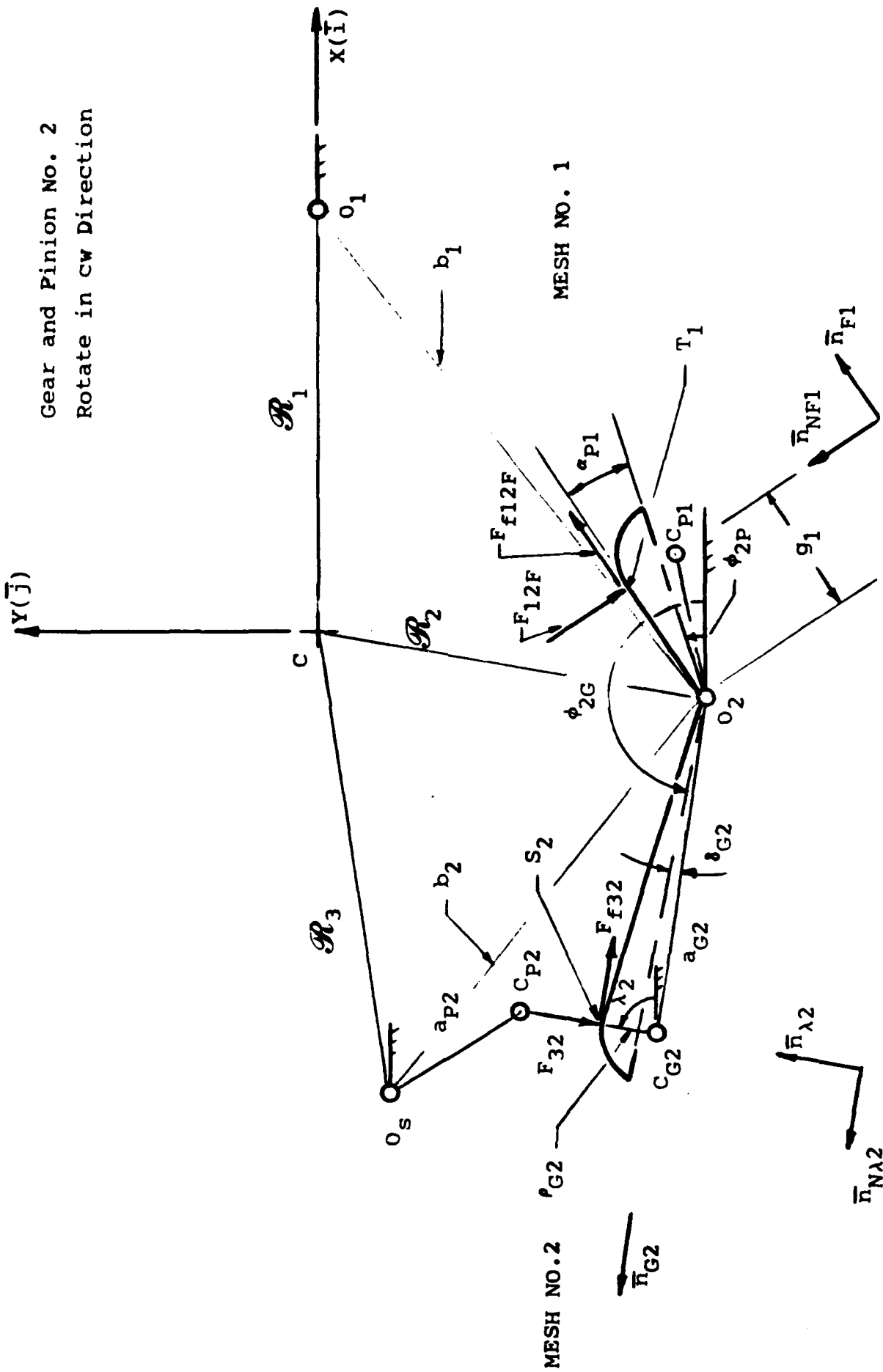


Figure D-16. Top view of free body diagram of gear and pinion no. 2. Mesh no. 2 is in round-on-round contact and mesh no. 1 is in round-on-flat contact

Again, figure D-14b represents the appropriate free body diagram of the pivot shaft of gear and pinion no. 2.

Force Equations

The force equation is again based on Newton's law, i.e.

$$\Sigma \vec{F} = m_2 \vec{A}_{O_2/\text{ground}} \quad (\text{D-782})$$

where

$\Sigma \vec{F}$ = Sum of the pivot forces as well as the various contact forces

m_2 = Mass of gear and pinion no. 2

$\vec{A}_{O_2/\text{ground}}$ = Acceleration of the component center of mass, i.e., equation D-605

The full force equation is now obtained with the help of figures D-16 and D-14b, as well as equations D-778 to D-781

$$\begin{aligned} & -F_{23}\bar{n}_{\lambda 2} - \mu S_2 R F_{23}\bar{n}_{N\lambda 2} - F_{12}F\bar{n}_{NF1} + \mu S_1 F F_{12}F\bar{n}_{F1} \\ & + F_{x2u}\bar{i} - \mu F_{x2u}\bar{j} + F_{y2u}\bar{j} + \mu F_{y2u}\bar{i} + F_{z2}\bar{k} - F_{x2L}\bar{i} + \mu F_{x2L}\bar{j} \\ & - F_{y2L}\bar{j} - \mu F_{y2L}\bar{i} = m_2 (Q_x\bar{i} + Q_y\bar{j} + Q_z\bar{k}) \end{aligned} \quad (\text{D-783})$$

In the above, $\bar{n}_{\lambda 2}$ and $\bar{n}_{N\lambda 2}$ are given by equations D-145b and D-147, respectively. The unit vectors $\bar{n}_{NF1}$ and $\bar{n}_{F1}$ are defined by equations D-539 and D-541. Appropriate substitution and subsequent separation of components furnishes the following:

X-Component of Force Equations

$$\begin{aligned} & -F_{23}\cos\lambda_2 + \mu S_2 R F_{23}\sin\lambda_2 + F_{12}F\sin(\phi_{2P} + \alpha_{P1}) \\ & + \mu S_1 F F_{12}F\cos(\phi_{2P} + \alpha_{P1}) + F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2 Q_x \end{aligned} \quad (\text{D-784})$$

Y-Component of Force Equation

$$\begin{aligned}
 & -F_{23}\sin\lambda_2 - \mu S_{2R}F_{23}\cos\lambda_2 - F_{12F}\cos(\phi_{2P} + \alpha_{P1}) + \mu S_{1F}F_{12F}\sin(\phi_{2P} + \alpha_{P1}) \\
 & - \mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 Q_y
 \end{aligned} \tag{D-785}$$

Z-Component of Force Equation

This thrust force is again expressed in tilded form, so that

$$\tilde{F}_{z2} = |m_2 Q_z| \tag{D-786}$$

Moment Equations

The moment equation is again expressed in terms of the projectile-fixed coordinate system by way of equation D-618.

The angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$ must in this case reflect the round-on-round contact of mesh no. 2, when these quantities are expressed in terms of the escape wheel angular velocity and acceleration.

The applicable expression for the moment $\bar{M}_{O_2}$ is now found with the help of the free body diagrams of figures D-16 and D-14b. The remarks concerning the thrust friction torque following equation D-618 still holds. Then

$$\begin{aligned}
 \bar{M}_{O_2} = & (a_{G2}\bar{n}_{G2} + \rho_{G2}\bar{n}_{\lambda 2}) \times (-F_{23}\bar{n}_{\lambda 2} - \mu S_{2R}F_{23}\bar{n}_{N\lambda 2}) \\
 & + g_1\bar{n}_{F1} \times (-F_{12F}\bar{n}_{NF1}) + \mu\rho_{12}\tilde{F}_{z2}\bar{k} + (L_u\bar{k} - \rho_2\bar{i}) \times (F_{x2u}\bar{i} - \mu F_{x2u}\bar{j}) \\
 & + (L_u\bar{k} - \rho_2\bar{j}) \times (F_{y2u}\bar{j} + \mu F_{y2u}\bar{i}) + (-L_L\bar{k} + \rho_2\bar{i}) \times (-F_{x2L}\bar{i} + \mu F_{x2L}\bar{j}) \\
 & + (-L_L\bar{k} + \rho_2\bar{j}) \times (-F_{y2L}\bar{j} - \mu F_{y2L}\bar{i})
 \end{aligned} \tag{D-787}$$

The above becomes with equations G-47, G-48, G-49, and G-22 and G-23 of ref 5

$$\begin{aligned}
 \bar{M}_{O_2} = & [\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L}] \bar{i} \\
 & + [L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}] \bar{j} \\
 & + [F_{23} \{a_{G2} (\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu S_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} S_{2R}\} \\
 & - g_1 F_{12F} + \mu \rho_{12} \tilde{F}_{z2} + \mu \rho_2 (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L})] \bar{k}
 \end{aligned} \tag{D-788}$$

Substitution of equation D-788 into equation D-618 yields the following moment component expressions

X-Component of Gear and Pinion Moment Equation

$$\begin{aligned} & \mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L} \\ & = I_{x2} \dot{\omega}_x + I_{z2} \omega_y (\omega_z + \dot{\phi}_2) - I_{y2} \omega_y \omega_z \end{aligned} \quad (D-789)$$

Y-Component of Gear and Pinion Moment Equation

$$\begin{aligned} & L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L} \\ & = I_{y2} \dot{\omega}_y + I_{x2} \omega_x \omega_z - I_{z2} \omega_x (\omega_z + \dot{\phi}_2) \end{aligned} \quad (D-790)$$

Z-Component of Gear and Pinion Moment Equation

$$\begin{aligned} & F_{23} [a_{G2} (\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R}] \\ & - g_1 F_{12F} + \mu \rho_{12} \tilde{F}_{z2} + \mu \rho_2 (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}) \\ & = I_{z2} (\dot{\omega}_z + \ddot{\phi}_2) \end{aligned} \quad (D-791)$$

Simplification of Force and Moment Equations and Determination of Pivot Forces on Gear and Pinion No. 2

X-Component of the Force Equation

Equation D-784 is now rewritten

$$-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = A_{84RF} F_{12} + A_{85RF} F_{12} + A_{86} \quad (D-792)$$

where

$$A_{84RF} = -\cos \lambda_2 + \mu s_{2R} \sin \lambda_2 \quad (D-793)$$

$$A_{85RF} = \sin(\phi_{2P} + \alpha_{P1}) + \mu s_{1F} \cos(\phi_{2P} + \alpha_{P1}) \quad (D-794)$$

$$A_{86} = -m_2 Q_x \quad (D-795)$$

Y-Component of the Force Equation

Equation D-785 is rewritten

$$\mu F_{x2u} - F_{y2u} - F_{x2L} + F_{y2L} = A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89} \quad (D-796)$$

where

$$A_{87RF} = (\sin\lambda_2 + \mu S_{2R}\cos\lambda_2) \quad (D-797)$$

$$A_{88RF} = -\cos(\phi_{2P} + \alpha_{P1}) + \mu S_{1F}\sin(\phi_{2P} + \alpha_{P1}) \quad (D-798)$$

$$A_{89} = -m_2 Q_y \quad (D-799)$$

Z-Component of the Force Equation

Remains as in equation D-786.

X-Component of the Moment Equation

Equation D-789 is rewritten

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91}\dot{\phi}_2 \quad (D-800)$$

where

$$A_{90} = [I_{x2}\dot{\omega}_x + \omega_y\omega_z(I_{z2} - I_{y2})] \quad (D-801)$$

$$A_{91} = -I_{z2}\omega_y \quad (D-802)$$

Y-Component of the Moment Equation

Equation D-790 is rewritten

$$-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = A_{92} + A_{93}\dot{\phi}_2 \quad (D-803)$$

where

$$A_{92} = [I_{y2}\dot{\omega}_y + \omega_x\omega_z(I_{x2} - I_{z2})] \quad (D-804)$$

$$A_{93} = I_{z2}\omega_x \quad (D-805)$$

Equation D-791 for the Z-component of the moment remains as is.

Simultaneous Solution of Pivot Forces

Equations D-792, D-796, D-800, and D-803 are now solved simultaneously for the pivot forces. Therefore,

$$\left. \begin{aligned} -F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} &= B_{21} \\ \mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} &= B_{22} \\ -\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} &= B_{24} \end{aligned} \right\} \quad (D-806)$$

where

$$B_{21} = A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86} \quad (D-807)$$

$$B_{22} = A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89} \quad (D-808)$$

$$B_{23} = A_{90} + A_{91}\phi_2 \quad (D-809)$$

$$B_{24} = A_{92} + A_{93}\phi_2 \quad (D-810)$$

Again, as before the B_{2i} do not reflect the mesh contact modes. The A's and C's account for these variations as needed.

To use the solutions of equation D-67, equation D-806 has to be changed to a form that has the same signs as this set of expressions. This may be accomplished by substituting

$$\mu^* = -\mu \quad (D-811)$$

(This replaces $A_{11} = \mu_1 s_5$ in equation D-67.) Equation D-806 then becomes

$$\left. \begin{aligned} -F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} &= B_{21} \\ -\mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} &= B_{22} \\ \mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} &= B_{24} \end{aligned} \right\} \quad (D-812)$$

With this substitution (i.e., equation D-811) the coefficient determinant of equation D-812 becomes according to equation D-75

$$D = [(L_u + L_L)(1 + \mu^2)]^2 \quad (D-813)$$

According to equation D-80, the determinant $D_{F_{x2u}}$ now becomes with the appropriate changes

$$D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2)[-L_L B_{21} + \mu L_L B_{22} - \mu B_{23} - B_{24}] \quad (D-814)$$

Now substitute for the B_{2i} 's according to equations D-807 and D-810

$$\begin{aligned} D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2) \{ & -L_L [A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86}] \\ & + \mu L_L [A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89}] \\ & - \mu [A_{90} + A_{91}\dot{\phi}_2] - [A_{92} + A_{93}\dot{\phi}_2] \} \end{aligned} \quad (D-815)$$

After collecting of terms, the tilded force $\tilde{F}_{x2u}$ becomes

$$\tilde{F}_{x2u} = \frac{\tilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{57} + C_{58}\dot{\phi}_2 + C_{59RF}F_{23} + C_{60RF}F_{12F}] \quad (D-816)$$

where

$$C_{57} = [-L_L A_{86} + \mu (L_L A_{89} - A_{90}) - A_{92}] \quad (D-817)$$

$$C_{58} = [\mu A_{91} + A_{93}] \quad (D-818)$$

$$C_{59RF} = [L_L (\mu A_{87RF} - A_{84RF})] \quad (D-819)$$

$$C_{60RF} = [L_L (\mu A_{88RF} - A_{85RF})] \quad (D-820)$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes

$$D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2)[- \mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}] \quad (D-821)$$

Substitution of equations D-807 to D-810 gives

$$\begin{aligned} D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2) \{ & -\mu L_L [A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86}] \\ & - L_L [A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89}] \\ & + [A_{90} + A_{91}\dot{\phi}_2] - \mu [A_{92} + A_{93}\dot{\phi}_2] \} \end{aligned} \quad (D-822)$$

After appropriate collecting of terms, the tilded force $\tilde{F}_{y2u}$ becomes

$$\tilde{F}_{y2u} = \frac{\tilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{61} + C_{62}\dot{\phi}_2 + C_{63RF}F_{23} + C_{64RF}F_{12F}] \quad (D-823)$$

where

$$C_{61} = [-L_L A_{89} - \mu(L_L A_{86} + A_{92}) + A_{90}] \quad (D-824)$$

$$C_{62} = [A_{91} - \mu A_{93}] \quad (D-825)$$

$$C_{63RF} = [L_L (\mu A_{84RF} + A_{87RF})] \quad (D-826)$$

$$C_{64RF} = [L_L (\mu A_{85RF} + A_{88RF})] \quad (D-827)$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes

$$D_{F_{x2L}} = (L_U + L_L)(1 + \mu^2) \{L_U B_{21} - \mu L_U B_{22} - \mu B_{23} - B_{24}\} \quad (D-828)$$

Substitute equations D-807 to D-810

$$\begin{aligned} D_{F_{x2L}} = (L_U + L_L)(1 + \mu^2) \{ & L_U [A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86}] \\ & - \mu L_U [A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89}] \\ & - [A_{90} + A_{91}\dot{\phi}_2] - [A_{92} + A_{93}\dot{\phi}_2] \} \end{aligned} \quad (D-829)$$

After collecting of terms, the tilded force $\tilde{F}_{x2L}$ becomes

$$\tilde{F}_{x2L} = \frac{\tilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{65} + C_{66}\dot{\phi}_2 + C_{67RF}F_{23} + C_{68RF}F_{12F}] \quad (D-830)$$

where

$$C_{65} = [-\mu(L_U A_{89} + A_{90}) + L_U A_{86} - A_{92}] \quad (D-831)$$

$$C_{66} = [\mu A_{91} + A_{93}] \quad (D-832)$$

$$C_{67RF} = [L_U (A_{84RF} - \mu A_{87RF})] \quad (D-833)$$

$$C_{68RF} = [L_U (A_{85RF} - \mu A_{88RF})] \quad (D-834)$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicable adaptation becomes

$$D_{F_{y2L}} = (L_u + L_l)(1 + \mu^2) \{ \mu L_u B_{21} + L_u B_{22} + B_{23} - \mu B_{24} \} \quad (D-835)$$

Substitution of equations D-807 to D-810 leads to

$$\begin{aligned} D_{F_{y2L}} = & (L_u + L_l)(1 + \mu^2) \{ \mu L_u [A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86}] \\ & + L_u [A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89}] \\ & + [A_{90} + A_{91}\dot{\phi}_2] - \mu [A_{92} + A_{93}\dot{\phi}_2] \} \end{aligned} \quad (D-836)$$

Again, terms are collected and an expression for the tilded force $\tilde{F}_{y2L}$ is found. Therefore

$$\tilde{F}_{y2L} = \frac{\tilde{D}_{F_{y2L}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{69} + C_{70}\dot{\phi}_2 + C_{71RF}F_{23} + C_{72RF}F_{12F}] \quad (D-837)$$

where

$$C_{69} = |L_u A_{89} + \mu (L_u A_{86} - A_{92}) + A_{90}| \quad (D-838)$$

$$C_{70} = |A_{91} - \mu A_{93}| \quad (D-839)$$

$$C_{71RF} = |L_u (\mu A_{84RF} + A_{87RF})| \quad (D-840)$$

$$C_{72RF} = |L_u (\mu A_{85RF} + A_{88RF})| \quad (D-841)$$

Determination of Contact Force $\bar{F}_{23}$ In Terms of Contact Force $\bar{F}_{12F}$ and Gear and Pinion Parameters. Mesh No. 2 is in Round-on-Round Contact and Mesh No. 1 in Round-on-Flat Contact

Substitution of equations D-786, D-816, D-823, D-830, and D-837 into the Z-moment equation D-791 is now required. First, let the tilded forces be added

$$\tilde{F}_{x2u} + \tilde{F}_{y2u} + \tilde{F}_{x2L} + \tilde{F}_{y2L} = A_{94} + A_{95}\dot{\phi} + A_{96RF}F_{23} + A_{97RF}F_{12F} \quad (D-842)$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T(1 + \mu^2)} \quad (D-843)$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T(1 + \mu^2)} \quad (D-844)$$

$$A_{96RF} = \frac{C_{59RF} + C_{63RF} + C_{67RF} + C_{71RF}}{L_T(1 + \mu^2)} \quad (D-845)$$

$$A_{97RF} = \frac{C_{60RF} + C_{64RF} + C_{68RF} + C_{72RF}}{L_T(1 + \mu^2)} \quad (D-846)$$

Further, let equation D-786 be expressed as

$$\tilde{F}_{z2} = A_{98} = |m_2 Q_d| \quad (D-847)$$

Equation D-791 then becomes

$$\begin{aligned} & F_{23} [a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R}] \\ & - g_1 F_{12F} + \mu \rho_{12} A_{98} + \mu \rho_2 [A_{94} \pm A_{95} \dot{\phi}_2 + A_{96RF} F_{23} + A_{97RF} F_{12F}] \\ & = I_{z2} (\dot{\omega}_z + \ddot{\phi}_2) \end{aligned} \quad (D-848)$$

or

$$\begin{aligned} & F_{23} [a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R} + \mu \rho_2 A_{96RF}] \\ & - F_{12F} [g_1 - \mu \rho_2 A_{97RF}] + \mu [\rho_{12} A_{98} + \rho_2 A_{94}] \pm \mu \rho_2 A_{95} \dot{\phi}_2 \\ & = A_{99} + A_{100} \ddot{\phi}_2 \end{aligned} \quad (D-849)$$

where again, as in equation D-682 and D-683

$$A_{99} = I_{z2} \dot{\omega}_z \quad (D-850)$$

$$A_{100} = I_{z2} \quad (D-851)$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction and the following friction moments must be positive.

$$\mu F_{23} \rho_2 A_{96RF} \quad (D-852)$$

$$\mu F_{12} \rho_2 A_{97RF} \quad (D-853)$$

$$\mu[\rho_{12} A_{98} + \rho_2 A_{94}] \quad (A_{94} \text{ and } A_{98} \text{ are absolute values}) \quad (D-854)$$

The moment represented by the term containing $\dot{\phi}_2$ must always act opposite to the direction of rotation of gear and pinion no. 2. Therefore the term must have a negative sign and the absolute value of μ must be used

$$- |\mu| \rho_2 A_{95} \dot{\phi}_2 \quad (D-855)$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-849 becomes

$$\begin{aligned} & F_{23} [a_{G2} (\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R} + \mu \rho_2 A_{96RF}] \\ & - F_{12F} [g_1 - \mu \rho_2 A_{97RF}] + \mu[\rho_{12} A_{98} + \rho_2 A_{94}] - |\mu| \rho_2 A_{95} \dot{\phi}_2 \\ & = A_{99} + A_{100} \ddot{\phi}_2 \end{aligned} \quad (D-856)$$

Finally, the above is solved for F_{23}

$$F_{23} = \frac{A_{102RF} F_{12F} - A_{103} + A_{104} \dot{\phi}_2 + A_{99} + A_{100} \ddot{\phi}_2}{A_{101RF}} \quad (D-857)$$

$$\begin{aligned} A_{101RF} &= a_{G2} (\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) \\ &\quad - \mu(\rho_{G2} s_{2R} - \rho_2 A_{96RF}) \end{aligned} \quad (D-858)$$

$$A_{102RF} = g_1 - \mu \rho_2 A_{97RF} \quad (D-859)$$

$$A_{103} = \mu[\rho_{12} A_{98} + \rho_2 A_{94}] \quad (D-860)$$

$$A_{104} = |\mu| \rho_2 A_{95} \quad (D-861)$$

Gear and Pinion No.2
Rotate in cw Direction

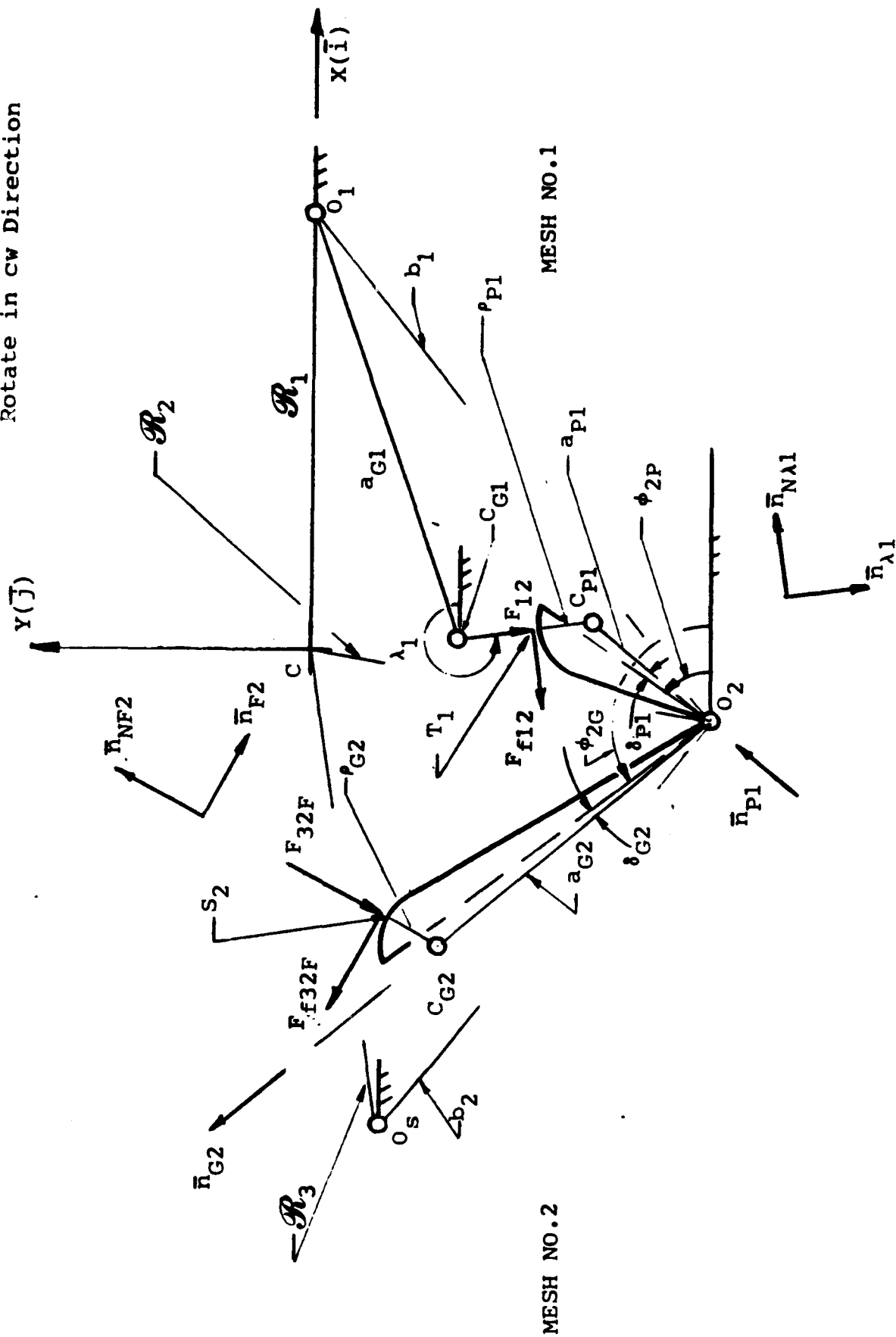


Figure D-17. Top view of free body diagram of gear and pinion no. 2. Mesh no. 2 is in round-on-flat contact and mesh no. 1 is in round-on-round contact

Dynamics of Gear and Pinion No. 2 with Mesh No. 2 in Round-on-Flat Contact and Mesh No. 1 in Round-on-Round Contact

A schematic topview of a free body diagram of gear and pinion no. 2 with mesh no. 2 in round-on-flat contact and mesh no. 1 in round-on-round contact is shown in figure D-17. It shows the contact force

$$\bar{F}_{32F} = -\bar{F}_{23F} = -F_{23F}\bar{n}_{NF2} \quad (D-862)$$

of pinion no. 3 on gear no. 2, opposite to force $\bar{F}_{23F}$, as given by equation 245a. The associated friction force $\bar{F}_{f32F}$ is opposite to $\bar{F}_{23F}$, as given by equation D-246. Thus

$$\bar{F}_{f32F} = -\bar{F}_{f23F} = -\mu S_{2F}F_{23F}\bar{n}_{NF2} \quad (D-863)$$

Figure D-17 further shows the contact force $\bar{F}_{12}$ gear no. 1 and pinion no. 2. This force is opposite in direction to contact force $\bar{F}_{21}$, which is given by equation D-426. Thus

$$\bar{F}_{12} = -\bar{F}_{21} = F_{12}\bar{n}_{\lambda 1} \quad (D-864)$$

The associated friction force $\bar{F}_{f12}$ is opposite in direction to the friction force $\bar{F}_{f21}$ of equation D-428, i.e.

$$\bar{F}_{f12} = -\bar{F}_{f21} - \mu S_{1R}F_{12}\bar{n}_{N\lambda 1} \quad (D-865)$$

Again, figure D-14b represents the applicable free body diagram for the pivot shaft of gear and pinion no. 2.

Force Equations

The force equation is again based on Newton's law, i.e.

$$\Sigma \bar{F} = m_2 \bar{A}_{O2/\text{ground}} \quad (D-866)$$

where

$\Sigma \bar{F}$ = sum of the pivot forces as well as the various contact forces

m_2 = mass of gear and pinion no. 2

$\bar{A}_{O2/\text{ground}}$ = acceleration of the component center of mass, i.e.,
equation D-605

The full force equation is now obtained with the help of figures D-14a and D-14b, as well as equations D-862 to D-865

$$\begin{aligned}
 & -F_{23}F\bar{n}_{NF2} - \mu S_2 F_{23}F\bar{n}_{F2} + F_{12}\bar{n}_{\lambda 1} + \mu S_1 R F_{12}\bar{n}_{N\lambda 1} \\
 & + F_{x2u}\bar{i} - \mu F_{x2u}\bar{j} + F_{y2u}\bar{j} + \mu F_{y2u}\bar{i} + F_{z2}\bar{k} - F_{x2L}\bar{i} \\
 & + \mu F_{x2L}\bar{j} - F_{y2L}\bar{j} - \mu F_{y2L}\bar{i} = m_2 (Q_x\bar{i} + Q_y\bar{j} + Q_z\bar{k})
 \end{aligned} \tag{D-867}$$

In the above, $\bar{n}_{NF2}$ and $\bar{n}_{F2}$ are given by equations D-245b and D-247, respectively. The unit vectors $\bar{n}_{\lambda 1}$ and $\bar{n}_{N\lambda 1}$ are in turn defined by equations D-427 and D-429.

Appropriate substitution of the above unit vectors into equation D-867 and subsequent separation of components furnishes the following:

X-Component of Force Equation

$$\begin{aligned}
 & F_{23}F\sin(\phi_s - \alpha_{P2}) - \mu S_2 F_{23}F\cos(\phi_s - \alpha_{P2}) + F_{12}\cos\lambda_1 \\
 & - \mu S_1 R F_{12}\sin\lambda_1 + F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2 Q_x
 \end{aligned} \tag{D-868}$$

Y-Component of Force Equation

$$\begin{aligned}
 & -F_{23}F\cos(\phi_s - \alpha_{P2}) - \mu S_2 F_{23}F\sin(\phi_s - \alpha_{P2}) + F_{12}\sin\lambda_1 \\
 & + \mu S_1 R F_{12}\cos\lambda_1 - \mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 Q_y
 \end{aligned} \tag{D-869}$$

Z-Component of Force Equation

This thrust force is again expressed in tilded form, so that

$$\tilde{F}_{z2} = |m_2 Q_z| \tag{D-870}$$

Moment Equations

The moment equation is again expressed in terms of the projectile-fixed coordinate system by way of equation D-618.

The angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$ must in this case reflect the round-on-flat contact of mesh no. 2, when these quantities are expressed in terms of the escape wheel angular velocity and acceleration.

The applicable expression for the moment $\bar{M}_{O_2}$ is now found with the help of the free body diagrams of figures D-17 and D-14b. The remarks concerning the thrust friction torque following equation D-618 still holds. Then

$$\begin{aligned}
 \bar{M}_{O_2} = & (a_{G2}\bar{n}_{G2} + \rho_{G2}\bar{n}_{NF2}) \times (-F_{23F}\bar{n}_{NF2} - \mu S_{2F}F_{23F}\bar{n}_{F2}) \\
 & + (a_{P1}\bar{n}_{P1} - \rho_{P1}\bar{n}_{\lambda 1}) \times (F_{12}\bar{n}_{\lambda 1} + \mu S_{1R}F_{12}\bar{n}_{N\lambda 1}) \\
 & + \mu p_{12}\tilde{F}_{z2}\bar{k} + (L_u\bar{k} - \rho_2\bar{j}) \times (F_{x2u}\bar{i} - \mu F_{x2u}\bar{j}) \\
 & + (L_u\bar{k} - \rho_2\bar{j}) \times (F_{y2u}\bar{j} + \mu F_{y2u}\bar{i}) \\
 & + (-L_L\bar{k} + \rho_2\bar{i}) \times (-F_{x2L}\bar{i} + \mu F_{x2L}\bar{j}) \\
 & + (-L_L\bar{k} + \rho_2\bar{j}) \times (-F_{y2L}\bar{j} - \mu F_{y2L}\bar{i})
 \end{aligned} \tag{D-871}$$

The above becomes with the help of equations G-2, G-3, G-4, and G-47, G-64, and G-65 of ref 5

$$\begin{aligned}
 \bar{M}_{O_2} = & [\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L}] \bar{i} \\
 & + [L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}] \bar{j} \\
 & + [F_{23F} \{a_{G2} (-\cos(\phi_{G2} + \delta_{G2} - \phi_s + \alpha_{P2}) + \mu S_{2F} \sin(\phi_{G2} - \delta_{G2} - \phi_2 + \alpha_{P2})) \\
 & + \rho_{G2} \mu S_{2F}\} + F_{12} \{a_{P1} (-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu S_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) \\
 & - \mu p_{P1} S_{1R}\} + \mu p_{12} \tilde{F}_{z2} + \mu p_2 (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L})] \bar{k}
 \end{aligned} \tag{D-872}$$

Substitution of equation D-872 into equation D-618 yields the following moment components expressions

X-Component of Gear and Pinion Moment Equation

$$\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L} = I_{x2} \dot{\omega}_x + I_{z2} \omega_y (\omega_z + \dot{\phi}_2) - I_{y2} \omega_x \omega_z \tag{D-873}$$

Y-Component of Gear and Pinion Moment Equation

$$L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L} = I_{y2} \dot{\omega}_y + I_{x2} \omega_x \omega_z - I_{z2} \omega_x (\omega_z + \dot{\phi}_2) \tag{D-874}$$

Z-Component of Gear and Pinion Moment Equation

$$\begin{aligned} & F_{23F} \{ a_{G2} (-\cos(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}) \} \\ & + \mu p_{G2} s_{2F} \} + F_{12} \{ a_{P1} (-\sin(\phi_{2P} - \delta_{2P} - \lambda_1) + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu p_{P1} s_{1R} \} \\ & + \mu p_{12} \tilde{F}_{z2} + \mu p_2 (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}) = I_{z2} (\dot{\omega} + \ddot{\phi}_2) \end{aligned} \quad (D-875)$$

Simplification of Force and Moment Equations and Determination of Pivot Forces on Gear and Pinion No. 2

X-Component of the Force Equation

Equation D-868 is now rewritten

$$-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = A_{84FR} F_{23F} + A_{85FR} F_{12} + A_{86} \quad (D-876)$$

where

$$A_{84FR} = \sin(\phi_s - \alpha_{P2}) - \mu s_{2F} \cos(\phi_s - \alpha_{P2}) \quad (D-877)$$

$$A_{85FR} = \cos \lambda_1 - \mu s_{1R} \sin \lambda_1 \quad (D-878)$$

$$A_{86} = -m_2 Q_x \quad (D-879)$$

Y-Component of the Force Equation

Equation D-869 is rewritten

$$\mu F_{x2u} - F_{y2u} - F_{x2L} + F_{y2L} = A_{87FR} F_{23F} + A_{88FR} F_{12} + A_{89} \quad (D-880)$$

where

$$A_{87FR} = (-\cos(\phi_s - \alpha_{P2}) + \mu s_{2F} \sin(\phi_s - \alpha_{P2})) \quad (D-881)$$

$$A_{88FR} = \sin \lambda_1 + \mu s_{1R} \cos \lambda_1 \quad (D-882)$$

$$A_{89} = -m_2 Q_y \quad (D-883)$$

Z-Component of the Force Equation

Remains as in equation D-870.

X-Component of the Moment Equation

Equation D-873 is rewritten

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91} \dot{\phi}_2 \quad (D-884)$$

where

$$A_{90} = -[I_{x2} \dot{\omega}_x + \omega_y \omega_z (I_{z2} - I_{y2})] \quad (D-885)$$

$$A_{91} = -I_{z2} \omega_y \quad (D-886)$$

Y-Component of the Moment Equation

Equation D-874 is rewritten

$$-L_u F_{x2u} + \mu L_u F_{y2u} - L_L F_{x2L} + \mu L_L F_{y2L} = A_{92} + A_{93} \dot{\phi}_2 \quad (D-887)$$

where

$$A_{92} = [I_{y2} \dot{\omega}_y + \omega_x \omega_z (I_{x2} - I_{z2})] \quad (D-888)$$

$$A_{93} = I_{z2} \omega_x \quad (D-889)$$

Equation D-875 for the Z-component of the moment remains as is.

Simultaneous Solutions of Pivot Forces

Equations D-876, D-880, D-884, and D-887 are now solved simultaneously for the pivot forces. Therefore

$$\begin{aligned} -F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} &= B_{21} \\ \mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} &= B_{22} \\ -\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} &= B_{24} \end{aligned} \quad (D-890)$$

where

$$B_{21} = A_{84FR}F_{23F} + A_{85FR}F_{12} + A_{86} \quad (D-891)$$

$$B_{22} = A_{87FR}F_{23F} + A_{88FR}F_{12} + A_{89} \quad (D-892)$$

$$B_{23} = A_{90} + A_{91}\phi_2 \quad (D-893)$$

$$B_{24} = A_{92} + A_{93}\phi_2 \quad (D-894)$$

Again, as before the B_{2i} do not reflect the mesh contact modes. The A's and C's account for these variations as needed.

To use the solutions of equation D-67, equation D-890 has to be changed to a form that has the same signs as this set of expressions. This may be accomplished by substituting

$$\mu^* = -\mu \quad (D-895)$$

(This replaces $A_{11} = \mu_1 s_5$ in equation D-67.) Equation D-890 then becomes

$$\left. \begin{aligned} -F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} &= B_{21} \\ -\mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} &= B_{22} \\ \mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} &= B_{24} \end{aligned} \right\} \quad (D-896)$$

With the above substitution, (i.e., equation D-895) the coefficient determinant of equation D-896 becomes according to equation D-75

$$D = [(L_u + L_L)(1 + \mu^2)]^2 \quad (D-897)$$

According to equation D-80, the determinant $D_{F_{x2u}}$ now becomes with the appropriate changes

$$D_{F_{x2u}} = (L_L + L_L)(1 + \mu^2)[-L_L B_{21} + \mu L_L B_{22} - \mu B_{23} - B_{24}] \quad (D-898)$$

Now substitute for the B_{2i} 's according to equation D-891 to D-894

$$\begin{aligned} D_{F_{x2u}} = & (L_u + L_L)(1 + \mu^2) \{-L_L [A_{84FR}F_{23F} + A_{85FR}F_{12} + A_{86}] \\ & + \mu L_L [A_{87FR}F_{23F} + A_{88FR}F_{12} + A_{89}] \\ & - \mu [A_{90} + A_{91}\dot{\phi}_2] - [A_{92} + A_{93}\dot{\phi}_2]\} \end{aligned} \quad (D-899)$$

After collecting of terms, the tilded force $\tilde{F}_{x2u}$ becomes

$$\tilde{F}_{x2u} = \frac{\tilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{57} + C_{58}\dot{\phi}_2 + C_{59FR}F_{23F} + C_{60FR}F_{12}] \quad (D-900)$$

where

$$C_{57} = |-L_L A_{86} + \mu (L_L A_{89} - A_{90}) - A_{92}| \quad (D-901)$$

$$C_{58} = |\mu A_{91} + A_{93}| \quad (D-902)$$

$$C_{59FR} = |L_L (\mu A_{87FR} - A_{84FR})| \quad (D-903)$$

$$C_{60FR} = |L_L (\mu A_{88FR} - A_{85FR})| \quad (D-904)$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes

$$D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2) [-\mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}] \quad (D-905)$$

Substitution of equations D-891 to D-894 gives

$$\begin{aligned} D_{F_{y2u}} = & (L_u + L_L)(1 + \mu^2) \{-\mu L_L [A_{84FR}F_{23F} + A_{85FR}F_{12} + A_{86}] \\ & - L_L [A_{87FR}F_{23F} + A_{88FR}F_{12} + A_{89}] \\ & + [A_{90} + A_{91}\dot{\phi}_2] - \mu [A_{92} + A_{93}\dot{\phi}_2]\} \end{aligned} \quad (D-906)$$

After appropriate collecting of terms, the tilded force $\tilde{F}_{y2u}$ becomes

$$\tilde{F}_{y2u} = \frac{\tilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{61} + C_{62}\dot{\phi}_2 + C_{63FR}F_{23F} + C_{64FR}F_{12}] \quad (D-907)$$

where

$$C_{61} = |-L_L A_{89} - \mu (L_L A_{86} + A_{92}) - A_{90}| \quad (D-908)$$

$$C_{62} = |A_{91} - \mu A_{93}| \quad (D-909)$$

$$C_{63FR} = |L_L (\mu A_{84FR} + A_{87FR})| \quad (D-910)$$

$$C_{64FR} = |L_L (\mu A_{85FR} + A_{88FR})| \quad (D-911)$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes

$$D_{F_{x2L}} = (L_U + L_L)(1 + \mu^2) [L_U B_{21} - \mu L_U B_{22} - \mu B_{23} - B_{24}] \quad (D-912)$$

Substitute equations D-891 to D-894

$$\begin{aligned} D_{F_{x2L}} = & (L_U + L_L)(1 + \mu^2) (L_U [A_{84FR} F_{23F} + A_{85FR} F_{12} + A_{86}] \\ & - \mu L_U [A_{87FR} F_{23F} + A_{88FR} F_{12} + A_{89}] \\ & - \mu [A_{90} + A_{91} \dot{\phi}_2] - [A_{92} + A_{93} \dot{\phi}_2]) \end{aligned} \quad (D-913)$$

After collecting of terms, the tilded force $\tilde{F}_{x2L}$ becomes

$$\tilde{F}_{x2L} = \frac{\tilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{65} + C_{66} \dot{\phi}_2 + C_{67FR} F_{23F} + C_{68FR} F_{12}] \quad (D-914)$$

where

$$C_{65} = |-\mu (L_U A_{89} + A_{90}) + L_U A_{86} - A_{92}| \quad (D-915)$$

$$C_{66} = |\mu A_{91} + A_{93}| \quad (D-916)$$

$$C_{67FR} = |L_U (A_{84FR} - \mu A_{87FR})| \quad (D-917)$$

$$C_{68FR} = |L_U (A_{85FR} - \mu A_{88FR})| \quad (D-918)$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicabe adaptation becomes

$$D_{F_{y2L}} = (L_U + L_L)(1 + \mu^2) [\mu L_U B_{21} - L_U B_{22} + B_{23} - \mu B_{24}] \quad (D-919)$$

Substitution of equations D-891 to D-894 leads to

$$\begin{aligned}
 D_{F_{y2L}} = & (L_u + L_L)(1 + \mu^2) \{ \mu L_L [A_{84FR} F_{23F} + A_{85FR} F_{12} + A_{86}] \\
 & + L_u [A_{87FR} F_{23F} + A_{88FR} F_{12} + A_{89}] \\
 & + [A_{90} + A_{91}\dot{\phi}_2] - \mu [A_{92} + A_{93}\dot{\phi}_2] \} \quad (D-920)
 \end{aligned}$$

Again, terms are collected and an expression for the tilded force $\tilde{F}_{y2L}$ is found. Therefore

$$\tilde{F}_{y2L} = \frac{\tilde{D}_{F_{y2L}}}{D} = \frac{1}{L_T(1 + \mu^2)} [C_{69} + C_{70}\dot{\phi}_2 + C_{71FR} F_{23F} + C_{72FR} F_{12}] \quad (D-921)$$

where

$$C_{69} = |L_u A_{89} + \mu (L_u A_{86} - A_{92}) + A_{90}| \quad (D-922)$$

$$C_{70} = |A_{91} - \mu A_{93}| \quad (D-923)$$

$$C_{71FR} = |L_u (\mu A_{84FR} + A_{87FR})| \quad (D-924)$$

$$C_{72FR} = |L_u (\mu A_{85FR} + A_{88FR})| \quad (D-925)$$

Determination of Contact Force F_{23F} in Terms of Contact Force F_{12} and Gear and Pinion Parameters. Mesh No. 2 is in Round-on-Flat Contact and Mesh No. 1 in Round-on-Round Contact

Substitution of equations D-870, D-900, D-907, D-914, and D-921 into the Z-moment equation D-875 is now required. First, let the tilded forces be added

$$\tilde{F}_{x2u} + \tilde{F}_{y2u} + \tilde{F}_{x2L} + \tilde{F}_{y2L} = A_{94} + A_{95}\dot{\phi} + A_{96FR} F_{23F} + A_{97FR} F_{12} \quad (D-926)$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T(1 + \mu^2)} \quad (D-927)$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T(1 + \mu^2)} \quad (D-928)$$

$$A_{96FR} = \frac{C_{59FR} + C_{63FR} + C_{67FR} + C_{71FR}}{L_T(1 + \mu^2)} \quad (D-929)$$

$$A_{97FR} = \frac{C_{60FR} + C_{64FR} + C_{68FR} + C_{72FR}}{L_T(1 + \mu^2)} \quad (D-930)$$

Further, let equation D-870 be expressed as

$$\tilde{F}_{z2} = A_{98} = |m_2 Q_z| \quad (D-931)$$

Equation D-875 then becomes

$$\begin{aligned} & F_{23F} \{ a_{G2} (-\cos(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}) \} \\ & + \mu s_{2F} p_{G2} \} + F_{12} \{ a_{P1} (-\sin(\phi_{2P} - \delta_{P1} - \lambda_1)) + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1) \} - \mu s_{1R} p_{P1} \} \\ & + \mu p_{12} A_{98} + \mu p_2 [A_{94} \pm A_{95} \dot{\phi}_2 + A_{96FR} F_{23F} + A_{97FR} F_{12}] = I_{z2} (\dot{\omega} + \ddot{\phi}_2) \end{aligned} \quad (D-932)$$

or

$$\begin{aligned} & F_{23F} \{ a_{G2} (-\cos(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}) \} \\ & + \mu s_{2F} p_{G2} + \mu p_2 A_{96FR} \} + F_{12} \{ a_{P1} (-\sin(\phi_{2P} - \delta_{P1} - \lambda_1)) + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1) \} \\ & - \mu s_{1R} p_{P1} + \mu p_2 A_{97FR} \} + \mu (p_{12} A_{98} + p_2 A_{94}) \pm \mu p_2 A_{95} \dot{\phi}_2 = A_{99} + A_{100} \ddot{\phi}_2 \end{aligned} \quad (D-933)$$

where again, as in equations D-682 and D-683

$$A_{99} = I_{z2} \dot{\omega}_z \quad (D-934)$$

$$A_{100} = I_{z2} \quad (D-935)$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction, and the following friction moments must be positive

$$\mu F_{23} p_2 A_{96FR} \quad (D-936)$$

$$F_{12} p_2 A_{97FR} \quad (D-937)$$

$$\mu [p_{12} A_{98} + p_2 A_{94}] (A_{94} \text{ and } A_{98} \text{ are absolute values}) \quad (D-938)$$

The moment represented by the term containing $\dot{\phi}_2$ must always act opposite to the direction of rotation of gear and pinion no. 2. Therefore, the term must have a negative sign and the absolute value of μ must be used

$$-|\mu| p_2 A_{95} \dot{\phi}_2 \quad (D-939)$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-933 becomes

$$\begin{aligned} & F_{23F} \{ a_{G2} (-\cos(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})) \\ & + \mu (s_{2F} p_{G2} + p_2 A_{95FR}) \} + F_{12} \{ a_{P1} (-\sin(\phi_{2P} - \delta_{2P} - \lambda_1) \\ & + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1) - \mu (s_{1R} p_{P1} - p_2 A_{97FR})) \} \\ & + \mu [p_{12} A_{98} + p_2 A_{94}] - |\mu| p_2 A_{95} \dot{\phi}_2 = A_{99} + A_{100} \ddot{\phi}_2 \end{aligned} \quad (D-940)$$

Finally, the above is solved for F_{23F}

$$F_{23F} = \frac{A_{102FR} F_{12} - A_{103} + A_{104} \dot{\phi}_2 + A_{99} + A_{100} \ddot{\phi}_2}{A_{101FR}} \quad (D-941)$$

where

$$A_{101FR} = a_{G2}(-\cos(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}) + \mu s_{2F} \sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2})) \\ + \mu(s_{2F} \rho_{G2} + \rho_2 A_{96FR}) \quad (D-942)$$

$$A_{102FR} = a_{P1}(\sin(\phi_{2P} - \delta_{P1} - \lambda_1) - \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) \\ + \mu(s_{1R} \rho_{P1} - \rho_2 A_{97FR}) \quad (D-943)$$

$$A_{103} = \mu(\rho_{12} A_{98} + \rho_2 A_{94}) \quad (D-944)$$

$$A_{104} = |\mu| \rho_2 A_{95} \quad (D-945)$$

**DYNAMICS OF COMBINED SYSTEM IN COUPLED MOTION WITH
MESHES 1 AND 2 IN ROUND-ON-ROUND CONTACT (RR)**
(Applicable to both configurations and entrance and exit conditions)

To develop a single differential equation for the total system in coupled motion and RR contact, equation D-537 for F_{12} is first substituted into equation D-689 for F_{23}

$$F_{23} A_{101RR} = \frac{A_{102RR}}{A_{79R}} [I_{1R} \ddot{\phi}_1 + A_{81} \dot{\phi}_1 + A_{80} + A_{60} + A_{82} \dot{\phi}_1^2 \\ - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] \\ - A_{103} + A_{104} \dot{\phi}_2 + A_{99} + A_{100} \ddot{\phi}_2 \quad (D-946a)$$

Equations F-117 and F-122 of appendix F are now used to substitute for $\dot{\phi}_2$ and $\ddot{\phi}_2$ respectively. Similarly, equations F-151 and F-152 serve for $\dot{\phi}_1$ and $\ddot{\phi}_1$. Thus

$$F_{23} = \frac{1}{A_{101RR}} \left\{ \frac{A_{102RR}}{A_{79R}} [I_{1R} [\ddot{\phi} Y_1 Y_5 + \dot{\phi}^2 [Y_1 Y_6 + Y_2 (DER2R)^2]] \right. \\ + A_{81} \dot{\phi} (DER1R) (DER2R) + A_{80} + A_{60} + A_{82} \dot{\phi}^2 (DER1R)^2 (DER2R)^2 \\ \left. - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right] \\ - A_{103} + A_{104} \dot{\phi} DER2R + A_{99} + A_{100} [\ddot{\phi} Y_5 + \dot{\phi}^2 Y_6] \} \quad (D-946b)$$

The above expression for F_{23} is now substituted into equation D-372, the combined escapement coupled motion equation with mesh no. 2 in round-on-round contact

$$\begin{aligned}
 & [A_{51} I_{PR} U - A_{29} I_{zs}] \ddot{\phi} + [A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}] \dot{\phi}^2 + A_{51} A_{31} U \dot{\phi} \\
 & = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_P r_{cp} (K_x \sin \beta - K_y \cos \beta) \\
 & + \frac{A_{29} A_{49R}}{A_{101RR}} \left\{ \frac{A_{102RR}}{A_{79R}} [I_{1R} [\ddot{\phi} Y_1 Y_5 + \dot{\phi}^2 [Y_1 Y_6 + Y_2 (DER2R)^2]] \right. \\
 & + A_{81} \dot{\phi} (DER1R) (DER2R) + A_{80} + A_{60} + A_{82} \dot{\phi}^2 (DER1R)^2 (DER2R)^2 \\
 & \left. - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right] - A_{103} + A_{104} \dot{\phi} DER2R \\
 & \left. + A_{99} + A_{100} [\ddot{\phi} Y_5 + \dot{\phi}^2 Y_6] \right\} \quad (D-947)
 \end{aligned}$$

Collecting of terms leads to

$$\begin{aligned}
 & \ddot{\phi} \left[A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{100} A_{29} A_{49R} Y_5}{A_{101RR}} - \frac{A_{29} A_{49R} A_{102RR} Y_1 Y_5 I_{1R}}{A_{101RR} A_{79R}} \right] \\
 & + \dot{\phi}^2 \left[A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{29} A_{49R} A_{102RR}}{A_{101RR} A_{79R}} I_{1R} [Y_1 Y_6 + Y_2 (DER2R)^2] \right. \\
 & \left. - \frac{A_{29} A_{49R} A_{102RR} A_{82}}{A_{101RR} A_{79R}} (DER1R)^2 (DER2R)^2 - \frac{A_{29} A_{49R} A_{100}}{A_{101RR}} Y_6 \right] \\
 & + \dot{\phi} \left[A_{51} A_{31} U - \frac{A_{29} A_{49R} A_{102RR} A_{81}}{A_{101RR} A_{79R}} (DER1R) (DER2R) - \frac{A_{29} A_{49R} A_{104}}{A_{101RR}} DER2R \right] \\
 & = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_P r_{cp} (K_x \sin \beta - K_y \cos \beta) \\
 & + \frac{A_{29} A_{49R}}{A_{101RR}} \left\{ \frac{A_{102RR}}{A_{79R}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{99} \right\} \quad (D-948)
 \end{aligned}$$

Finally, the above may be rewritten as⁴

$$A_{105} \ddot{\phi} + A_{106} \dot{\phi}^2 + A_{107} \dot{\phi} = A_{108} + A_{109} (O_x \sin \gamma - O_y \cos \gamma) + A_{110} (K_x \sin \beta - K_y \cos \beta) \quad (D-949)$$

where

$$A_{105} = A_{51} I_{PR} U - A_{29} I_{25} - \frac{A_{29} A_{49R} A_{100}}{A_{101RR}} Y_5 - \frac{A_{29} A_{49R} A_{102RR}}{A_{79R} A_{101RR}} I_{1R} Y_1 Y_5 \quad (D-950)$$

$$A_{106} = A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{29} A_{49R} A_{102RR}}{A_{79R} A_{101RR}} I_{1R} \times [Y_1 Y_6 + Y_2 (DER2R)^2] - \frac{A_{29} A_{49R} A_{82} A_{102RR}}{A_{79R} A_{101RR}} (DER1R)^2 (DER2R)^2 - \frac{A_{29} A_{49R} A_{100}}{A_{101RR}} Y_6 \quad (D-951)$$

$$A_{107} = A_{51} A_{31} U - \frac{A_{29} A_{49R} A_{81} A_{102RR}}{A_{79R} A_{101RR}} (DER1R) (DER2R) - \frac{A_{29} A_{49R} A_{104}}{A_{101RR}} DER2R \quad (D-952)$$

$$A_{108} = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + \frac{A_{29} A_{49R}}{A_{101RR}} \left\{ \frac{A_{102RR}}{A_{79R}} [A_{80} + A_{60}] - A_{103} + A_{99} \right\} \quad (D-953)$$

$$A_{109} = - \frac{A_{29} A_{49R} A_{102RR}}{A_{79R} A_{101RR}} m_1 r_{c1} \quad (D-954)$$

$$A_{110} = A_{51} m_P r_{cp} \quad (D-955)$$

⁴The value of the signum function s_γ , together with α_{en} or α_{ex} , decides whether entrance or exit-coupled motion is described by the differential equation D-949.

Contact Forces

The contact force F_{23RR} is given by equation D-946b [note new subscript for computational purposes]

$$F_{23RR} = \frac{A_{111} \ddot{\phi} + A_{112} \dot{\phi}^2 + A_{113} \dot{\phi} + A_{114}}{A_{101RR}} \quad (D-956)$$

where

$$A_{111} = \frac{A_{102RR}}{A_{79R}} I_{1R} Y_1 Y_5 + A_{100} Y_5 \quad (D-957)$$

$$A_{112} = \frac{A_{102RR}}{A_{79R}} \left[I_{1R} (Y_1 Y_6 + Y_2 (DER2R)^2) + A_{82} (DER1R)^2 (DER2R)^2 \right] + A_{100} Y_6 \quad (D-958)$$

$$A_{113} = \frac{A_{102RR}}{A_{79R}} A_{81} (DER1R) (DER2R) + A_{104} (DER2R) \quad (D-959)$$

$$A_{114} = \frac{A_{102RR}}{A_{79R}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{99} \quad (D-960)$$

The contact force F_{12RR} is found with the help of equations D-537, F-142, and F-143

$$F_{12RR} = \frac{1}{A_{79R}} \left\{ I_{1R} [\ddot{\phi} (Y_1 Y_5) + \dot{\phi}^2 (Y_1 Y_6 + Y_2 (DER2R)^2)] + A_{81} \dot{\phi} (DER1R) (DER2R) + A_{82} \dot{\phi}^2 ((DER1R)^2 (DER2R)^2) + A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right\} \quad (D-961)$$

or

$$F_{12RR} = \frac{A_{115} \ddot{\phi} + A_{116} \dot{\phi}^2 + A_{117} \dot{\phi} + A_{118}}{A_{79R}} \quad (D-962)$$

where

$$A_{115} = I_{1R} Y_1 Y_5 \quad (D-963)$$

$$A_{116} = I_{1R} [Y_1 Y_6 + Y_2 (DER2R)^2 + A_{82} (DER1R)^2 (DER2R)^2] \quad (D-964)$$

$$A_{117} = A_{81} (DER1R) (DER2R) \quad (D-965)$$

$$A_{118} = A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \quad (D-966)$$

The contact force P_n , between the verge and the escape wheel, may either be obtained in terms of the pallet variable ψ or the escape wheel variable ϕ .

According to equation D-137 or equation D-339, one obtains in terms of $\psi(t)$, using the appropriate value of A_{29} (eq D-400)

$$P_n = \frac{I_{PR} \ddot{\psi} + A_{31} \dot{\psi} + A_{32} \psi^2 + A_{119} - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta)}{A_{29}} \quad (D-967)$$

where

$$A_{119} = A_9 + A_{30} \quad (D-968)$$

[see ref 2 for $\ddot{\psi}$ and $\dot{\psi}$ in terms of $\ddot{\phi}$ and $\dot{\phi}$]

When the appropriate value for $A_{51} = A_{51R} = AA_{51R}$ (eq D-371b) is substituted into equation D-239 or D-364, together with $F_{23} = F_{23RR}$, according to equation D-956, one obtains P_n in terms of $\phi(t)$

$$P_n = \frac{I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + F_{23RR} A_{49R} + A_{50}}{A_{51}} \quad (D-969)$$

NOTE: It must be kept in mind that the $\ddot{\phi}$ and $\dot{\phi}$ terms for all the above contact forces must be those associated with the differential equation D-949.

DYNAMICS OF COMBINED SYSTEM IN COUPLED MOTION WITH MESHES NO. 1 AND NO. 2 IN ROUND-ON-FLAT CONTACT (FF)

Combined Differential Equation

To obtain a single differential equation for the total system in coupled motion and FF contact, equation D-593 for F_{12F} is first substituted into equation D-773 for F_{23F}

$$F_{23F} A_{101FF} = \frac{A_{102FF}}{A_{79F}} \left[I_{1R} \ddot{\phi}_1 + A_{81} \dot{\phi}_1 + A_{82} \dot{\phi}_1^2 + A_{80} \right. \\ \left. + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right] \\ - A_{103} + A_{104} \dot{\phi}_2 + A_{99} + A_{100} \ddot{\phi} \quad (D-970)$$

Equations F-126 and F-131 of appendix F are now substituted for $\dot{\phi}_2$ and $\ddot{\phi}_2$, respectively. Similarly, equations F-150 and F-151 serve for $\dot{\phi}_1$ and $\ddot{\phi}_1$, in turn. Then

$$F_{23F} = \frac{1}{A_{101FF}} \left\{ \frac{A_{102FF}}{A_{79F}} \left[I_{1R} [\ddot{\phi} Y_3 Y_7 + \dot{\phi}^2 [Y_3 Y_8 + Y_4 (DER2F)^2]] \right. \right. \\ \left. + A_{81} \dot{\phi} (DER1F) (DER2F) + A_{82} \dot{\phi}^2 (DER1F)^2 (DER2F)^2 \right. \\ \left. + A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right] \\ \left. - A_{103} + A_{104} \dot{\phi} DER2F + A_{99} + A_{100} [\ddot{\phi} Y_7 + \dot{\phi}^2 Y_8] \right\} \quad (D-971)$$

The above expression for F_{23F} is now substituted into equation D-403, the combined escapement coupled motion equation, with mesh no. 2 in round-on-flat contact

$$\begin{aligned}
 & [A_{51} I_{PR} U - A_{29} I_{zs}] \ddot{\phi} + [A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}] \dot{\phi}^2 + A_{51} A_{31} U \dot{\phi} \\
 & = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \\
 & + \frac{A_{29} A_{49F}}{A_{101FF}} \left\{ \frac{A_{102FF}}{A_{79F}} \left[I_{1R} [\ddot{\phi} Y_3 Y_7 + \dot{\phi}^2 (Y_3 Y_8 + Y_4 (DER2F)^2)] \right. \right. \\
 & + A_{81} \dot{\phi} (DER1F) (DER2F) + A_{82} \dot{\phi}^2 (DER1F)^2 (DER2F)^2 + A_{80} + A_{60} \\
 & \left. \left. - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right] - A_{103} + A_{104} \dot{\phi} DER2F \right. \\
 & \left. + A_{99} + A_{100} [\ddot{\phi} Y_7 + \dot{\phi}^2 Y_8] \right\} \quad (D-972)
 \end{aligned}$$

Now, the coefficients of like terms are collected

$$\begin{aligned}
 & \ddot{\phi} \left[A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{100} A_{29} A_{49F}}{A_{101FF}} Y_7 - \frac{A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} I_{1R} Y_3 Y_7 \right] \\
 & + \dot{\phi}^2 \left[A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{82} A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} (DER1F)^2 (DER2F)^2 \right. \\
 & \left. - \frac{A_{100} A_{29} A_{49F}}{A_{101FF}} Y_8 - \frac{A_{29} A_{49F} A_{102FF} I_{1R}}{A_{101FF} A_{79F}} [Y_3 Y_8 + Y_4 (DER2F)^2] \right] \\
 & + \dot{\phi} \left[A_{51} A_{31} U - \frac{A_{81} A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} (DER1F) (DER2F) - \frac{A_{104} A_{29} A_{49F}}{A_{101FF}} DER2F \right] \\
 & = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) + \frac{A_{29} A_{49F}}{A_{101FF}} \\
 & \left\{ \frac{A_{102FF}}{A_{79F}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{99} \right\} \quad (D-973)
 \end{aligned}$$

The above may now be rewritten as⁵

$$\begin{aligned} & A_{120} \ddot{\phi} + A_{121} \dot{\phi}^2 + A_{122} \dot{\phi} \\ &= A_{123} + A_{124}(O_x \sin \gamma - O_y \cos \gamma) + A_{125}(K_x \sin \beta - K_y \cos \beta) \end{aligned} \quad (D-974)$$

where

$$\begin{aligned} A_{120} &= A_{51} I_{Pr} U - A_{29} I_{zs} - \frac{A_{100} A_{29} A_{49F}}{A_{101FF}} Y_7 \\ &\quad - \frac{A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} I_{1R} Y_3 Y_7 \end{aligned} \quad (D-975)$$

$$\begin{aligned} A_{121} &= A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} \\ &\quad - \frac{A_{82} A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} (DER1F)^2 (DER2F)^2 - \frac{A_{100} A_{29} A_{49F}}{A_{101FF}} Y_8 \\ &\quad - \frac{A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} I_{1R} [Y_3 Y_8 + Y_4 (DER2F)^2] \end{aligned} \quad (D-976)$$

$$\begin{aligned} A_{122} &= A_{51} A_{31} U - \frac{A_{81} A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} (DER1F)(DER2F) \\ &\quad - \frac{A_{104} A_{29} A_{49F}}{A_{101FF}} DER2F \end{aligned} \quad (D-977)$$

$$\begin{aligned} A_{123} &= A_{29} A_{50} - A_{51} (A_9 + A_{30}) \\ &\quad + \frac{A_{29} A_{49F}}{A_{101FF}} \left\{ \frac{A_{102FF}}{A_{79F}} (A_{80} + A_{60}) - A_{103} + A_{99} \right\} \end{aligned} \quad (D-978)$$

$$A_{124} = - \frac{A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} m_1 r_{c1} \quad (D-979)$$

$$A_{125} = A_{51} m_p r_{cp} \quad (D-980)$$

⁵As in equation D-949, the signum function s_γ , as well as the appropriate choice of the angle α , determine whether entrance or exit coupled motion is described.

Contact Forces

The contact force F_{23FF} is given by equation D-971 (note new subscript)

$$F_{23FF} = \frac{A_{126} \ddot{\phi} + A_{127} \dot{\phi}^2 + A_{128} \dot{\phi} + A_{129}}{A_{101FF}} \quad (D-981)$$

where

$$A_{126} = \frac{A_{102FF} I_{1R} Y_3 \ddot{Y}_7}{A_{79F}} + A_{100} Y_7 \quad (D-982)$$

$$A_{127} = \frac{A_{102FF}}{A_{79F}} \left[I_{1R} [Y_3 Y_8 + Y_4 (DER2F)^2] + A_{82} (DER1F)^2 (DER2F)^2 \right] + A_{100} Y_8 \quad (D-983)$$

$$A_{128} = \frac{A_{102FF} A_{81}}{A_{79F}} (DER1F) (DER2F) + A_{104} DER2F \quad (D-984)$$

$$A_{129} = \frac{A_{102FF}}{A_{79F}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{99} \quad (D-985)$$

The contact force F_{12FF} is found with the help of equations D-593, F-150, and F-151

$$F_{12FF} = \frac{1}{A_{79F}} \left\{ I_{1R} [\ddot{\phi} (Y_3 Y_7) + \dot{\phi}^2 (Y_3 Y_8 + Y_4 (DER2F)^2)] + A_{81} \dot{\phi} (DER1F) (DER2F) + A_{82} \dot{\phi}^2 (DER1F)^2 (DER2F)^2 + A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right\} \quad (D-986)$$

or

$$F_{12FF} = \frac{A_{130} \ddot{\phi} + A_{131} \dot{\phi}^2 + A_{132} \dot{\phi} + A_{133}}{A_{79F}} \quad (D-987)$$

where

$$A_{130} = I_{1R} Y_3 Y_7 \quad (D-988)$$

$$A_{131} = I_{1R} [Y_3 Y_8 + Y_4 (DER2F)^2] + A_{82} (DER1F)^2 (DER2F)^2 \quad (D-989)$$

$$A_{132} = A_{81} (DER1F) (DER2F) \quad (D-990)$$

$$A_{133} = A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \quad (D-991)$$

The contact force P_n , between the verge and the escape wheel, may again be found in terms of $\psi(t)$ with the help of equation D-967. If it is desired to obtain P_n in terms of $\phi(t)$, as applicable to the FF contact mode, equation D-981 for F_{23FF} is substituted into equation D-322 or D-395, keeping in mind that the term $A_{51} = A_{51F} = AA_{51F}$ must contain the appropriate values s_7 . Then

$$P_n = \frac{I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + F_{23RR} A_{49R} + A_{50}}{A_{51}} \quad (D-992)$$

For the contact forces F_{23FF} , F_{12FF} and P_n (above), the values of $\ddot{\phi}$ and $\dot{\phi}$ must be those associated with the differential equation D-974, which deals with the FF contact mode.

DYNAMICS OF COMBINED SYSTEM IN COUPLED MOTION WITH MESH NO. 2 IN ROUND-ON-ROUND CONTACT AND MESH NO.1 IN ROUND-ON-FLAT CONTACT (RF)

Combined Differential Equations

To obtain a single differential equation for the total system in coupled motion and RF contact, equation D-593 for F_{12F} is first substituted into equation D-857 for F_{23}

$$\begin{aligned} F_{23} A_{101RF} = & \frac{A_{102RF}}{A_{79F}} [I_{1R} \ddot{\phi}_1 + A_{81} \dot{\phi}_1 + + A_{82} \dot{\phi}_1^2 + A_{80} + A_{60} \\ & - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] \\ & - A_{103} + A_{104} \dot{\phi}_2 + A_{99} + A_{100} \ddot{\phi}_2 \end{aligned} \quad (D-993)$$

Equations F-108 and F-113 of appendix F are now substituted for $\dot{\phi}_2$ and $\ddot{\phi}_2$, respectively. Similarly, equations F-146 and F-147 serve for $\dot{\phi}_1$ and $\ddot{\phi}_1$.

$$\begin{aligned}
 F_{23} = & \frac{1}{A_{101RF}} \left\{ \frac{A_{102RF}}{A_{79F}} \left[I_{1R} [\ddot{\phi} Y_3 Y_5 + \dot{\phi}^2 (Y_3 Y_6 + Y_4 (DER2R)^2)] \right. \right. \\
 & + A_{81} \dot{\phi} (DER2R) (DER1F) + A_{82} \dot{\phi}^2 (DER2R)^2 (DER1F)^2 \\
 & A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \left. \right] \\
 & - A_{103} + A_{104} \dot{\phi} DER2R + A_{99} + A_{100} [\ddot{\phi} Y_5 + \dot{\phi}^2 Y_6] \left. \right\} \quad (D-994)
 \end{aligned}$$

The above expression for F_{23} is now substituted into equation D-372, the combined escapement coupled motion equation with mesh no. 2 in round-on-round contact

$$\begin{aligned}
 & [A_{51} I_{PR} U - A_{29} I_{ZS}] \ddot{\phi} + [A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}] \dot{\phi}^2 + A_{51} A_{31} U \dot{\phi} \\
 & = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_P r_{cp} (K_x \sin \beta - K_y \cos \beta) \\
 & + \frac{A_{29} A_{49R}}{A_{101RF}} \left\{ \frac{A_{102RF}}{A_{79F}} \left[I_{1R} [\ddot{\phi} Y_3 Y_5 + \dot{\phi}^2 (Y_3 Y_6 + Y_4 (DER2R)^2)] \right. \right. \\
 & + A_{81} \dot{\phi} (DER2R) (DER1F) + A_{82} \dot{\phi}^2 (DER2R)^2 (DER1F)^2 + A_{80} + A_{60} \\
 & - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \left. \right] - A_{103} + A_{104} \dot{\phi} DER2R \\
 & + A_{99} + A_{100} [\ddot{\phi} Y_5 + \dot{\phi}^2 Y_6] \left. \right\} \quad (D-995)
 \end{aligned}$$

Now the coefficients of like terms are collected

$$\begin{aligned}
& \ddot{\phi} \left[A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49R} A_{102RF}}{A_{79F} A_{101RF}} I_{1R} Y_3 Y_5 - \frac{A_{29} A_{49R} A_{100}}{A_{101RF}} Y_5 \right] \\
& + \dot{\phi}^2 \left[A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{29} A_{49R} A_{102RF}}{A_{79F} A_{101RF}} I_{1R} (Y_3 Y_6 + Y_4 (DER2R)^2) \right. \\
& \left. - \frac{A_{29} A_{49R} A_{82} A_{102RF}}{A_{101RF} A_{79F}} (DER2R)^2 (DER1F)^2 - \frac{A_{29} A_{49R} A_{100}}{A_{101RF}} Y_6 \right] \\
& + \dot{\phi} \left[A_{51} A_{31} U - \frac{A_{29} A_{49R} A_{81} A_{102RF}}{A_{79F} A_{101RF}} (DER2R) (DER1F) - \frac{A_{29} A_{49R} A_{104}}{A_{101RF}} DER2R \right] \\
& = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_P r_{cp} (K_x \sin \beta - K_y \cos \beta) \\
& + \frac{A_{29} A_{49R}}{A_{101RF}} \left\{ \frac{A_{102RF}}{A_{79F}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{99} \right\} \quad (D-996)
\end{aligned}$$

The above is now rewritten as⁶

$$\begin{aligned}
A_{134} \ddot{\phi} + A_{135} \dot{\phi}^2 + A_{136} \dot{\phi} &= A_{137} + A_{138} (O_x \sin \gamma - O_y \cos \gamma) \\
&+ A_{139} (K_x \sin \beta - K_y \cos \beta) \quad (D-997)
\end{aligned}$$

where

$$\begin{aligned}
A_{134} &= A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49R} A_{102RF}}{A_{79F} A_{101RF}} I_{1R} Y_3 Y_5 \\
&- \frac{A_{29} A_{49R} A_{100}}{A_{101RF}} Y_5 \quad (D-998)
\end{aligned}$$

$$\begin{aligned}
A_{135} &= A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} \\
&- \frac{A_{29} A_{49R} A_{102RF}}{A_{79F} A_{101RF}} I_{1R} (Y_3 Y_6 + Y_4 (DER2R)^2) \\
&- \frac{A_{29} A_{49R} A_{82} A_{102RF}}{A_{79F} A_{101RF}} (DER2R)^2 (DER1F)^2 - \frac{A_{29} A_{49R} A_{100}}{A_{101RF}} Y_6 \quad (D-999)
\end{aligned}$$

⁶Again, the proper sign s_7 and the appropriate angle α , depending on entrance or exit coupled motion, must be chosen.

$$A_{136} = A_{51} A_{31} U - \frac{A_{29} A_{49R} A_{81} A_{102RF}}{A_{79F} A_{101RF}} (DER2R) (DER1F) - \frac{A_{29} A_{49R} A_{104}}{A_{101RF}} DER2R \quad (D-1000)$$

$$A_{137} = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + \frac{A_{29} A_{49R}}{A_{101RF}} \left\{ \frac{A_{102RF}}{A_{79R}} [A_{80} + A_{60}] - A_{103} + A_{99} \right\} \quad (D-1001)$$

$$A_{138} = - \frac{A_{29} A_{49R} A_{102RF}}{A_{101RF} A_{79F}} m_1 r_{c1} \quad (D-1002)$$

$$A_{139} = A_{51} m_P r_{cp} \quad (D-1003)$$

Contact Forces

The contact force F_{23RF} is given by equation D-994 [note new subscript]

$$F_{23RF} = \frac{A_{140} \ddot{\phi} + A_{141} \dot{\phi}^2 + A_{142} \dot{\phi} + A_{143}}{A_{101RF}} \quad (D-1004)$$

where

$$A_{140} = \frac{A_{102RF} I_{1R} Y_3 Y_5}{A_{79F}} + A_{100} Y_5 \quad (D-1005)$$

$$A_{141} = \frac{A_{102RF}}{A_{79F}} \left[I_{1R} [Y_3 Y_6 + Y_4 (DER2R)^2] + A_{82} (DER2R)^2 (DER1F)^2 \right] + A_{100} Y_6 \quad (D-1006)$$

$$A_{142} = \frac{A_{102RF} A_{81}}{A_{79F}} (DER2R) (DER1F) + A_{104} (DER2R) \quad (D-1007)$$

$$A_{143} = \frac{A_{102RF}}{A_{79F}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{99} \quad (D-1008)$$

The contact force $F_{12RF} = F_{12F}$, i.e., equation D-593, is now expressed in terms of the angular velocity $\dot{\phi}$ and the angular acceleration $\ddot{\phi}$, which correspond to the RF contact mode, according to equations F-146 and F-147, respectively

$$F_{12RF} = \frac{1}{A_{79F}} \left\{ I_{1R} [\ddot{\phi}(Y_3 Y_5) + \dot{\phi}^2 (Y_3 Y_6 + Y_4 (DER2R)^2)] \right. \\ \left. + A_{81} \dot{\phi} (DER1F) (DER2R) + A_{82} \dot{\phi}^2 ((DER1F)^2 (DER2R)^2) \right. \\ \left. + A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right\} \quad (D-1009)$$

or

$$F_{12RF} = \frac{A_{144} \ddot{\phi} + A_{145} \dot{\phi}^2 + A_{146} \dot{\phi} + A_{147}}{A_{79F}} \quad (D-1010)$$

where

$$A_{144} = I_{1R} Y_3 Y_5 \quad (D-1011)$$

$$A_{145} = I_{1R} [Y_3 Y_6 + Y_4 (DER2R)^2] + A_{82} (DER1F)^2 (DER2R)^2 \quad (D-1012)$$

$$A_{146} = A_{81} (DER1F) (DER2R) \quad (D-1013)$$

$$A_{147} = A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \quad (D-1014)$$

The contact force P_n , between the verge and the escape wheel, may be found in terms of $\psi(t)$ with the help of equation D-967 again.

If it is desired to obtain P_n in terms of the applicable $\phi(t)$, one substitutes equation D-1004 for $F_{23RF} = F_{23}$ into equation D-239 or equation D-364. Again, it must be kept in mind that $A_{51} = A_{51R} = A A_{51R}$. Then

$$P_n = \frac{I_{z5} \ddot{\phi} + A_{48} \dot{\phi}^2 + F_{23RF} A_{49R} + A_{50}}{A_{51}} \quad (D-1015)$$

For the contact forces F_{23RF} , F_{12RF} , and the above P_n , the values of $\ddot{\phi}$ and $\dot{\phi}$ must be those associated with the differential equation D-997, which deals with the RF contact mode.

**DYNAMICS OF COMBINED SYSTEM IN COUPLED MOTION WITH
MESH NO. 2 IN ROUND-ON-FLAT CONTACT AND MESH NO. 1
IN ROUND-ON-ROUND CONTACT (FR)**

Combined Differential Equations

To obtain a single differential equation for the total system in coupled motion and FR contact, equation D-537 for F_{12} is first substituted into equation D-941 for F_{23F}

$$F_{23F} A_{101FR} = \frac{A_{102FR}}{A_{79R}} [I_{1R} \ddot{\phi}_1 + A_{81} \dot{\phi}_1 + A_{82} \dot{\phi}_1^2 + A_{80} + A_{60} \\ - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] \\ - A_{103} + A_{104} \dot{\phi}_2 + A_{99} + A_{100} \ddot{\phi}_2 \quad (D-1016)$$

Equations F-126 and F-131 of appendix F are now substituted for $\dot{\phi}_2$ and $\ddot{\phi}_2$, respectively. Similarly, equations F-154 and F-155 serve for $\dot{\phi}_1$ and $\ddot{\phi}_1$ in turn.

$$F_{23F} = \frac{1}{A_{101FR}} \left\{ \frac{A_{102FR}}{A_{79R}} [I_{1R} [\ddot{\phi} Y_1 Y_7 + \dot{\phi}^2 (Y_1 Y_8 + Y_2 (DER2F)^2)] \right. \\ + A_{81} \dot{\phi} (DER1R) (DER2F) + A_{82} \dot{\phi}^2 (DER1R)^2 (DER2F)^2 \\ + A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] \\ \left. - A_{103} + A_{104} \dot{\phi} DER2F + A_{99} + A_{100} [\ddot{\phi} Y_7 + \dot{\phi}^2 Y_8] \right\} \quad (D-1017)$$

The above expression for F_{23F} is now substituted into equation D-403, the combined escapement coupled motion equation, with mesh no. 2 in round-on-flat contact

$$[A_{51} I_{PR} U - A_{29} I_{ZS}] \ddot{\phi} + [A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}] \dot{\phi}^2 + A_{51} A_{31} U \dot{\phi} \\ = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_P r_{cp} (K_x \sin \beta - K_y \cos \beta) \\ + \frac{A_{29} A_{49F}}{A_{101FR}} \left\{ \frac{A_{102FR}}{A_{79R}} [I_{1R} [\ddot{\phi} Y_1 Y_7 + \dot{\phi}^2 (Y_1 Y_8 + Y_2 (DER2F)^2)] \right. \\ + A_{81} \dot{\phi} (DER1R) (DER2F) + A_{82} \dot{\phi}^2 (DER1R)^2 (DER2F)^2 + A_{80} + A_{60} \\ \left. - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{104} \dot{\phi} DER2F \right. \\ \left. + A_{99} + A_{100} [\ddot{\phi} Y_7 + \dot{\phi}^2 Y_8] \right\} \quad (D-1018)$$

Again, the coefficients of like terms are collected

$$\begin{aligned}
& \ddot{\phi} \left[A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49F} A_{102FR}}{A_{101FR} A_{79R}} I_{1R} Y_1 Y_7 - \frac{A_{29} A_{49F} A_{100}}{A_{101FR}} Y_7 \right] \\
& + \dot{\phi}^2 \left[A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{29} A_{49F}}{A_{101FR}} \left\{ \frac{A_{102FR}}{A_{79F}} [I_{1R} [Y_1 Y_8 + Y_2 (DER2F)^2] \right. \right. \\
& \left. \left. + A_{82} (DER1R)^2 (DER2F)^2 \right] + A_{100} Y_8 \right\} \right] \\
& + \dot{\phi} \left[A_{51} A_{31} U - \frac{A_{29} A_{49F}}{A_{101FR}} \left\{ \frac{A_{102FR}}{A_{79R}} A_{81} (DER1R) (DER2F) + A_{104} DER2F \right\} \right] \\
& = A_{29} A_{50} - A_{51} (A_9 + A_{30}) + A_{51} m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \\
& + \frac{A_{29} A_{49F}}{A_{101FR}} \left\{ \frac{A_{102FR}}{A_{79R}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{99} \right\} \quad (D-1019)
\end{aligned}$$

The above is now rewritten as⁷

$$\begin{aligned}
A_{148} \ddot{\phi} + A_{149} \dot{\phi}^2 + A_{150} \dot{\phi} &= A_{151} + A_{152} (O_x \sin \gamma - O_y \cos \gamma) \\
&+ A_{153} (K_x \sin \beta - K_y \cos \beta) \quad (D-1020)
\end{aligned}$$

where

$$A_{148} = A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49F}}{A_{101FR}} \left\{ \frac{A_{102FR} I_{1R} Y_1 Y_7}{A_{79R}} + A_{100} Y_7 \right\} \quad (D-1021)$$

⁷As before, entrance or exit contact depends on s_7 and α .

$$A_{149} = A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}$$

$$- \frac{A_{29} A_{49F}}{A_{101FR}} \left\{ \frac{A_{102FR}}{A_{79R}} \left[I_{1R} [Y_1 Y_8 + Y_2 (DER2F)^2] \right. \right. \\ \left. \left. + A_{82} (DER1R)^2 (DER2F)^2 \right] + A_{100} Y_8 \right\} \quad (D-1022)$$

$$A_{150} = A_{51} A_{31} U - \frac{A_{29} A_{49F}}{A_{101FR}} \left\{ \frac{A_{102FR}}{A_{79R}} A_{81} (DER1R) (DER2F) \right. \\ \left. + A_{104} DER2F \right\} \quad (D-1023)$$

$$A_{151} = A_{29} A_{50} - A_{51} (A_9 + A_{30}) \\ + \frac{A_{29} A_{49F}}{A_{101FR}} \left\{ \frac{A_{102FR}}{A_{79R}} [A_{80} + A_{30}] - A_{103} + A_{99} \right\} \quad (D-1024)$$

$$A_{152} = - \frac{A_{29} A_{49F} A_{102FR}}{A_{101FR} A_{79R}} m_1 r_{c1} \quad (D-1025)$$

$$A_{153} = A_{51} m_P r_{cp} \quad (D-1026)$$

Contact Forces

The contact force F_{23FR} is given by equation D-1017 [note new subscript]

$$F_{23FR} = \frac{A_{154} \ddot{\phi} + A_{155} \dot{\phi}^2 + A_{156} \dot{\phi} + A_{157}}{A_{101FR}} \quad (D-1027)$$

where

$$A_{154} = \frac{A_{102FR}}{A_{79R}} I_{1R} Y_1 Y_7 + A_{100} Y_7 \quad (D-1028)$$

$$A_{155} = \frac{A_{102FR}}{A_{79R}} \left\{ I_{1R} (Y_1 Y_8 + Y_2 (DER2F)^2) + A_{82} (DER1R)^2 (DER2F)^2 \right\} + A_{100} Y_8 \quad (D-1029a)$$

$$A_{156} = \frac{A_{102FR}}{A_{79R}} A_{81} (DER1R) (DER2F) + A_{104} (DER2F) \quad (D-1029b)$$

$$A_{157} = \frac{A_{102FR}}{A_{79R}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma)] - A_{103} + A_{99} \quad (D-1030)$$

The contact force $F_{12FR} = F_{12}$, i.e., equation D-537, is now expressed in terms of the angular velocity $\dot{\phi}$ and the angular acceleration $\ddot{\phi}$ which correspond to the FR contact mode. Thus, with equations F-154 and F-155, one obtains

$$F_{12FR} = \frac{1}{A_{79R}} \left\{ I_{1R} [\ddot{\phi} (Y_1 Y_7) + \dot{\phi}^2 [Y_1 Y_8 + Y_2 (DER2F)^2]] + A_{81} \dot{\phi} (DER1R) (DER2F) + A_{82} \dot{\phi}^2 (DER1R)^2 (DER2F)^2 + A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \right\} \quad (D-1031)$$

or

$$F_{12FR} = \frac{A_{158} \ddot{\phi} + A_{159} \dot{\phi}^2 + A_{160} \dot{\phi} + A_{161}}{A_{79R}} \quad (D-1032)$$

where

$$A_{158} = I_{1R} Y_1 Y_7 \quad (D-1033)$$

$$A_{159} = I_{1R} [Y_1 Y_8 + Y_2 (DER2F)^2] + A_{82} (DER1R)^2 (DER2F)^2 \quad (D-1034)$$

$$A_{160} = A_{81} (DER1R) (DER2F) \quad (D-1035)$$

$$A_{161} = A_{80} + A_{60} - m_1 r_{c1} (O_x \sin \gamma - O_y \cos \gamma) \quad (D-1036)$$

The contact force P_n , between the verge and the escape wheel, may again be found in terms of $\psi(t)$ with the help of equation D-967.

If it is desired to obtain P_n in terms of the applicable $\phi(t)$, one substitutes equation D-1027 for $F_{23FR} = F_{23F}$ into equation D-322 or equation D-395 keeping in mind that $A_{51} = A_{51F} = AA_{51F}$. Then

$$P_n = \frac{I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + F_{23FR} A_{49F} + A_{50}}{A_{51}} \quad (D-1037)$$

For the contact forces F_{23FR} , F_{12FR} , and P_n (above), the values of $\ddot{\phi}$ and $\dot{\phi}$ must be those associated with the differential equation D-1020, which deals with the FR contact mode.

DYNAMICS OF FREE MOTION

Pallet Free Motion Differential Equation

Regardless of gear tooth contact condition, the free motion equation of the pallet is obtained by letting $P_n = 0$ in equation D-967. Then

$$I_{PR} \ddot{\psi} + A_{32} \dot{\psi}^2 + A_{31} \dot{\psi} = -A_{119} + m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \quad (D-1038)$$

Escape Wheel--Gear Train--Rotor Free Motion Conditions for RR Contact

Combined Differential Equation

To obtain the combined free motion differential equation for the RR contact, equation D-969 for P_n is first set equal to zero. Then

$$I_{zs} \ddot{\phi} + A_{48R} \dot{\phi}^2 + F_{23RR} A_{49R} + A_{50R} = 0 \quad (D-1039)$$

Note that this expression is not dependent on entrance or exit anymore.

Equation D-956 is now substituted for F_{23RR}

$$I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + \frac{A_{49R}}{A_{101RR}} [A_{111} \ddot{\phi} + A_{112} \dot{\phi}^2 + A_{113} \dot{\phi} + A_{114}] + A_{50} = 0$$

or

$$A_{162} \ddot{\phi} + A_{163} \dot{\phi}^2 + A_{164} \dot{\phi} + A_{165} = 0 \quad (D-1040)$$

where

$$A_{162} = I_{zs} + \frac{A_{49R} A_{111}}{A_{101RR}} \quad (D-1041)$$

$$A_{163} = A_{48} + \frac{A_{49R} A_{112}}{A_{101RR}} \quad (D-1042)$$

$$A_{164} = \frac{A_{49R} A_{113}}{A_{101RR}} \quad (D-1043)$$

$$A_{165} = A_{50} + \frac{A_{49R} A_{114}}{A_{101RR}} \quad (D-1044)$$

Contact Force T_{23RR}

In order to differentiate the contact forces during free motion from those during coupled motion the nomenclature T is now introduced.

While T_{23RR} will have the same form as F_{23RR} , it must be kept in mind that $\ddot{\phi}$ and $\dot{\phi}$ now correspond to the free motion values of differential equation D-1040. Thus, with equation D-1039

$$T_{23RR} = - \frac{(I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + A_{50})}{A_{49R}} \quad (D-1045)$$

Contact Force T_{12RR}

The form of contact force T_{12RR} is identical to that of contact force F_{12RR} of equation D-962, i.e.

$$T_{12RR} = \frac{A_{115} \ddot{\phi} + A_{116} \dot{\phi}^2 + A_{117} \dot{\phi} + A_{118}}{A_{78R}} \quad (D-1046)$$

Again, the values of $\ddot{\phi}$ and $\dot{\phi}$ must correspond to those obtained from the solution of equation D-1040.

Escape Wheel--Gear Train--Rotor Free Motion Conditions for FF Contact

Combined Differential Equation

To obtain the combined differential equation for the FF contact mode, equation D-992 for the applicable form of P_n is first set equal to zero. Then

$$I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + F_{23FF} A_{49F} + A_{50} = 0 \quad (D-1047)$$

Equation D-981 is then substituted for F_{23FF}

$$I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + \frac{A_{49F}}{A_{101FF}} [A_{126} \ddot{\phi} + A_{127} \dot{\phi} + A_{128} \dot{\phi} + A_{129}] + A_{50} = 0$$

or

$$A_{166} \ddot{\phi} + A_{167} \dot{\phi}^2 + A_{168} \dot{\phi} + A_{169} = 0 \quad (D-1048)$$

where

$$A_{166} = I_{zs} + \frac{A_{49F} A_{126}}{A_{101FF}} \quad (D-1049)$$

$$A_{167} = A_{48} + \frac{A_{49F} A_{127}}{A_{101FF}} \quad (D-1050)$$

$$A_{168} = \frac{A_{49F} A_{128}}{A_{101FF}} \quad (D-1051)$$

$$A_{169} = \frac{A_{49F} A_{129}}{A_{101FF}} + A_{50} \quad (D-1052)$$

Contact Force T_{23FF}

The force T_{23FF} has the same form as F_{23FF} , as obtained from equation D-1047, i.e.

$$T_{23FF} = - \frac{(I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + A_{50})}{A_{49F}} \quad (D-1053)$$

Note that $\ddot{\phi}$ and $\dot{\phi}$ must come from equation D-1048.

Contact Force T_{12FF}

The form of contact force T_{12FF} is identical to that of contact force F_{12FF} of equation D-987, i.e.

$$T_{12FF} = \frac{A_{130} \ddot{\phi} + A_{131} \dot{\phi}^2 + A_{132} \dot{\phi} + A_{133}}{A_{79F}} \quad (D-1054)$$

Again, $\ddot{\phi}$ and $\dot{\phi}$ must come from equation D-1048.

Escape Wheel–Gear Train–Rotor Free Motion Conditions for RF Contact

Combined Differential Equation

To obtain the combined differential equation for the RF contact mode, P_n in equation D-1015 is first set equal to zero. This results in

$$I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + F_{23RF} A_{49R} + A_{50} = 0 \quad (D-1055)$$

Equation D-1004 for F_{23RF} is then substituted into the above

$$I_{zs} \ddot{\phi} + A_{48F} \dot{\phi}^2 + \frac{A_{49R}}{A_{101RF}} [A_{140} \ddot{\phi} + A_{141} \dot{\phi}^2 + A_{142} \dot{\phi} + A_{143}] + A_{50} = 0$$

or

$$A_{170} \ddot{\phi} + A_{171} \dot{\phi}^2 + A_{172} \dot{\phi} + A_{173} = 0 \quad (D-1056)$$

where

$$A_{170} = I_{zs} + \frac{A_{49R} A_{140}}{A_{101RF}} \quad (D-1057)$$

$$A_{171} = A_{48} + \frac{A_{49R} A_{141}}{A_{101RF}} \quad (D-1058)$$

$$A_{172} = \frac{A_{49R} A_{142}}{A_{101RF}} \quad (D-1059)$$

$$A_{173} = \frac{A_{49R} A_{143}}{A_{101RF}} + A_{50} \quad (D-1060)$$

Contact Force T_{23RF}

The contact force T_{23RF} has the same form as F_{23RF} , as obtained from equation D-1055. Thus

$$T_{23RF} = - \frac{(I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + A_{50})}{A_{49R}} \quad (D-1061)$$

Note that $\ddot{\phi}$ and $\dot{\phi}$ must now come from equation D-1056.

Contact Force T_{12RF}

The form of contact force T_{12RF} is identical to that of contact force F_{12RF} of equation D-1010, i.e.

$$T_{12RF} = \frac{A_{144} \ddot{\phi} + A_{145} \dot{\phi}^2 + A_{146} \dot{\phi} + A_{147}}{A_{79F}} \quad (D-1062)$$

Again, $\ddot{\phi}$ and $\dot{\phi}$ must be obtained from equation D-1056.

Escape Wheel--Gear Train--Rotor Free Motion Conditions for FR Contact

Combined Differential Equation

To obtain the combined differential equation for the FR contact mode, P_n in equation D-1037 is first set equal to zero. This leads to

$$I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + F_{23FR} A_{49F} + A_{50} = 0 \quad (D-1063)$$

Equation D-1027 for F_{23FR} is subsequently substituted into the above

$$I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + \frac{A_{49F}}{A_{101FR}} [A_{154} \ddot{\phi} + A_{155} \dot{\phi}^2 + A_{156} \dot{\phi} + A_{157}] + A_{50} = 0$$

or

$$A_{174} \ddot{\phi} + A_{175} \dot{\phi}^2 + A_{176} \dot{\phi} + A_{177} = 0 \quad (D-1064)$$

where

$$A_{174} = I_{zs} + \frac{A_{49F} A_{154}}{A_{101FR}} \quad (D-1065)$$

$$A_{175} = A_{48} + \frac{A_{49F} A_{155}}{A_{101FR}} \quad (D-1066)$$

$$A_{176} = \frac{A_{49F} A_{156}}{A_{101FR}} \quad (D-1067)$$

$$A_{177} = \frac{A_{49F} A_{157}}{A_{101FR}} + A_{50} \quad (D-1068)$$

Contact Force T_{23FR}

The force T_{23FR} has the same form as F_{23FR} , if obtained from equation D-1063, i.e.

$$T_{23FR} = - \frac{(I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + A_{50})}{A_{49F}} \quad (D-1069)$$

Here, $\ddot{\phi}$ and $\dot{\phi}$ must come from equation D-1064.

Contact Force T_{12FR}

The form of contact force T_{12FR} is identical to that of contact force F_{12FR} of equation D-1032, i.e.

$$T_{12FR} = \frac{A_{158} \ddot{\phi} + A_{159} \dot{\phi}^2 + A_{160} \dot{\phi} + A_{161}}{A_{79R}} \quad (D-1070)$$

Again, $\ddot{\phi}$ and $\dot{\phi}$ must be obtained from solution of the differential equation D-1064.

IMPACT EQUATIONS

The basic impact formulation may be taken directly from references 1 and 2. It must be realized that, the pre-impact angular velocity $\dot{\phi}_i$ of the escape wheel must correspond to the governing gear contact regime of free motion.

As in the above references, angle α_{EN} must be used for entrance impact, while for exit impact the angle α_{EX} is applicable. With both entrance and exit impact having the same form, one uses

$$\dot{\phi}_f = \frac{\dot{\phi}_i (I_{STOT} D_1'^2 - e_r I_{\zeta\zeta P} A_1'^2) + \dot{\psi}_i I_{\zeta\zeta P} A_1' (1 + e_r) D_1'}{I_{\zeta\zeta P} A_1'^2 + I_{STOT} D_1'^2} \quad (D-1071)$$

and

$$\dot{\psi}_f = \frac{\dot{\phi}_f A_1' - e_r (\dot{\psi}_i D_1' - \dot{\phi}_i A_1')}{D_1'} \quad (D-1072)$$

where I_{STOT} , the free motion escape wheel--gear train--rotor moment of inertia as referred to the escape wheel, depends on the gear contact regime.

RR Contact

With equations F-108 and F-142 of appendix F

$$I_{STOT} = I_{zs} + I_{z2} DER2R^2 + I_{\zeta\zeta_1} (DER2R)^2 (DER1R)^2 \quad (D-1073)$$

FF Contact

With equations F-126 and F-150

$$I_{\text{STOT}} = I_{\text{zs}} + I_{\text{z2}} \text{DER2F}^2 + I_{\zeta\zeta_1} (\text{DER1F})^2 (\text{DER2F})^2 \quad (\text{D-1074})$$

RF Contact

With equations F-108 and F-146

$$I_{\text{STOT}} = I_{\text{zs}} + I_{\text{z2}} \text{DER2R}^2 + I_{\zeta\zeta_1} (\text{DER2R})^2 (\text{DER1F})^2 \quad (\text{D-1075})$$

FR Contact

With equations F-126 and F-154

$$I_{\text{STOT}} = I_{\text{zs}} + I_{\text{z2}} \text{DER2F}^2 + I_{\zeta\zeta_1} (\text{DER2F})^2 (\text{DER1R})^2 \quad (\text{D-1076})$$

REFERENCES

1. Lowen, G. G. and Tepper, F. R., "Computer Simulation of Artillery S&A Mechanisms (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-82013, ARRADCOM, Dover, NJ, November 1982.
2. Tepper, F. R. and Lowen, G. G., "Computer Simulation of Artillery Safing and Arming Mechanism in Aeroballistic Environment (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-83050, ARDC, Dover, NJ, July 1984.
3. Shames, I. H., Engineering Mechanics. Statics. and Dynamics, Third Edition, Prentice Hall, Inc., Englewood Cliffs, NJ, 1980.
4. Lowen, G. G. and Tepper, F. R., "Computer Simulations of Artillery S&A Mechanisms (Involute Gear Train and Pin Pallet Runaway Escapement)," Technical Report ARLCD-TR-81039, ARRADCOM, Dover, NJ, July 1982.
5. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

APPENDIX E
PROJECTILE KINEMATICS

Until the time when actual aeroballistic data can be incorporated into program AERCLOC, the following expressions for the projectile kinematics will be used*

Spin Simulation

Assuming a constant spin velocity, obtain for the spin kinematics:

$$\ddot{\phi}_E = 0 \quad (E-1)$$

$$\dot{\phi}_E = \text{DPHIE} = \frac{\text{RPM} \times 2\pi}{60} \quad (E-2)$$

and

$$\phi_E = \text{PHIE} = \dot{\phi}_E t \quad (E-3)$$

Precession Simulation

Assuming that the precession velocity is also constant, the following is obtained

$$\ddot{\psi}_E = 0 \quad (E-4)$$

where

$$\dot{\psi}_E = \text{DPSIE} = \frac{\text{DPHIE}}{KP} \quad (E-5)$$

$KP = K_p$, is a divisor to obtain the precession velocity as a fraction of the spin velocity

$$K_p \approx 100 \quad (E-6)$$

$$\psi_E = \text{PSIE} = \dot{\psi}_E t \quad (E-7)$$

Nutation Simulation

The nutation angle is assumed to vary sinusoidally about some initial angle. Then

$$\theta_E = \text{THET} = \text{THETIN} + \text{TVAR} \sin (K_n \dot{\psi}_E t) \quad (E-8)$$

*For nomenclature see appendix A.

where

$$\text{THETIN} \approx 8 \text{ degrees, the initial cone angle} \quad (\text{E-9})$$

$$\text{TVAR} \approx 2 \text{ degrees, the maximum change in cone angle} \quad (\text{E-10})$$

$$K_n \approx 6 \text{ to } 8, \text{ multiplier of precession angular velocity } \dot{\psi}_E \text{ to obtain} \quad (\text{E-11})$$

maximum nutation velocity $\dot{\theta}_{\text{EMAX}}$

With the above

$$\dot{\theta}_E = \text{TVAR} * K_n * \dot{\psi}_E \cos (K_n \dot{\psi}_E t) \quad (\text{E-12})$$

$$\ddot{\theta}_E = - \text{TVAR} * K_n^2 * \dot{\psi}_E^2 \sin (K_n \dot{\psi}_E t) \quad (\text{E-13})$$

Drag Deceleration

The deceleration $\ddot{z} = \ddot{z}k$ of the center of mass, due to drag and expressed in the projectile-fixed system, is given by

$$\ddot{z} = \text{DDZ} = -386.4 * 10 \quad (\text{E-14})$$

APPENDIX F

**FORWARD AND REVERSE KINEMATICS OF CLOCK GEAR
MESHES NO. 1 AND NO. 2**

The present appendix restates for, the sake of convenience, various expressions pertaining to the forward as well as the reverse kinematics of meshes 1 and 2, which were originally derived in references 1 and 2, respectively.

The angle between the escape wheel pinion tooth centerline and the x-axis is now called ϕ_s .

Subsequently, the angular velocities and accelerations of gear and pinion no. 2 and rotor gear no. 1 will be formulated in terms of the angular velocity and the angular acceleration of the escape wheel for all regime combinations.

Forward Kinematics of Mesh No. 1 (angle ϕ_1 is input, angle ϕ_{2P} is output)¹

Round-on-Round Phase of Motion (fig. F-1)

Angle ϕ_{2P} . The angle ϕ_{2P} may be obtained from

$$\phi_{2P} = 2 \tan^{-1} \frac{A_{1R} \pm \sqrt{A_{1R}^2 + B_{1R}^2 - C_{1R}^2}}{B_{1R} + C_{1R}} \quad (F-1)$$

where

$$A_{1R} = b_1 \sin (\beta_1 + \delta_{P1}) - a_{G1} \sin (\phi_1 - \delta_{G1} + \delta_{P1}) \quad (F-2)$$

$$B_{1R} = b_1 \cos (\beta_1 + \delta_{P1}) - a_{G1} \cos (\phi_1 - \delta_{G1} + \delta_{P1}) \quad (F-3)$$

$$C_{1R} = \frac{L_1^2 - b_1^2 - a_{G1}^2 - a_{P1}^2 + 2a_{G1} b_1 \cos (\phi_1 - \delta_{G1} - \beta_1)}{2a_{P1}} \quad (F-4)$$

The correct sign in equation F-1 must be determined by geometric considerations.

Angle λ_1

$$\lambda_1 = \cos^{-1} \left[\frac{b_1 \cos \beta_1 + a_{P1} \cos (\phi_{2P} - \delta_{P1}) - a_{G1} \cos (\phi_1 - \delta_{G1})}{L_1} \right] \quad (F-5)$$

¹The output angle of mesh 1 is called ϕ_{2P} (P= pinion), while the input angle of mesh 2 will be ϕ_{2G} (G = gear). Only the increments of these angles are equal.

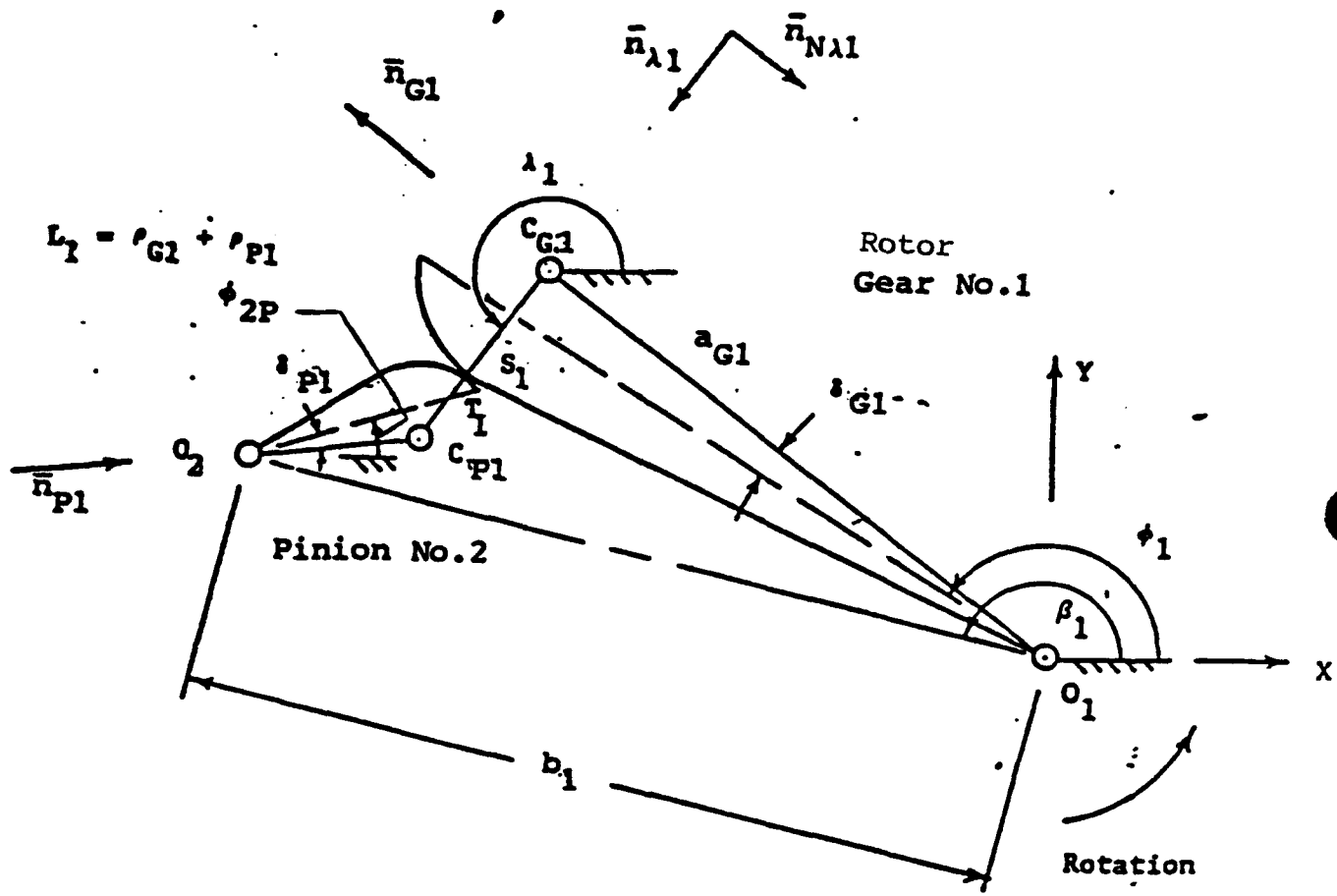


Figure F-1. Round-on-round phase of motion for mesh no. 1

$$\lambda_1 = \sin^{-1} \left[\frac{b_1 \sin \beta_1 + a_{P1} \sin (\phi_{2P} - \delta_{P1}) - a_{G1} \sin (\phi_1 - \delta_{G1})}{L_1} \right] \quad (F-6)$$

Output Angular Velocity² $\dot{\phi}_2 = \dot{\phi}_{2P} = \dot{\phi}_{2G}$

$$\dot{\phi}_2 = \dot{\phi}_1 \left[\frac{L_{1R}}{M_{1R}} \right] \quad (F-7)$$

where

$$L_{1R} = A_{1RD} \sin \phi_{2P} - B_{1RD} \cos \phi_{2P} - C_{1RD} \quad (F-8)$$

$$M_{1R} = A_{1R} \cos \phi_{2P} - B_{1R} \sin \phi_{2P} \quad (F-9)$$

with

$$A_{1RD} = a_{G1} \cos (\phi_1 - \delta_{G1} + \delta_{P1}) \quad (F-10)$$

$$B_{1RD} = a_{G1} \sin (\phi_1 - \delta_{G1} + \delta_{P1}) \quad (F-11)$$

$$C_{1RD} = \frac{a_{G1} b_1 \sin (\phi_1 - \delta_{G1} - \beta_1)}{a_{P1}} \quad (F-12)$$

Relative Velocity $V_{S1/T1R}$ at the Contact Point

$$\begin{aligned} \bar{V}_{S1/T1R} = \{ & \dot{\phi}_1 [a_{G1} \cos (\phi_1 - \delta_{G1} - \lambda_1) + \rho_{G1}] \\ & - \dot{\phi}_2 [a_{P1} \cos (\phi_{2P} - \delta_{P1} - \lambda_1) - \rho_{P1}] \} \bar{n}_{N\lambda 1} \end{aligned} \quad (F-13)$$

²Regarding the derivatives of the gear and pinion no. 2, there is no difference whether the gear or the pinion is involved. The difference is only needed for the angles, since the angles ϕ_{2P} and ϕ_{2G} are expressed with respect to different center lines.

Round-on Flat Phase of Motion (fig. F-2)

Angle ϕ_{2P}

$$\phi_{2P} = 2 \tan^{-1} \frac{A_{1F} \pm \sqrt{A_{1F}^2 + B_{1F}^2 - C_{1F}^2}}{B_{1F} + C_{1F}} \quad (F-14)$$

with appropriate choice of sign, and

$$A_{1F} = a_{G1} \cos (\phi_1 - \delta_{G1} - \alpha_{P1}) - b_1 \cos (\beta_1 - \alpha_{P1}) \quad (F-15)$$

$$B_{1F} = -a_{G1} \sin (\phi_1 - \delta_{G1} - \alpha_{P1}) + b_1 \sin (\beta_1 - \alpha_{P1}) \quad (F-16)$$

$$C_{1F} = -\rho_{G1} \quad (F-17)$$

Distance g_1

$$g_1 = \frac{a_{G1} \sin (\phi_1 - \delta_{G1}) - \rho_{G1} \cos (\phi_{2P} + \alpha_{P1}) - b_1 \sin \beta_1}{\sin (\phi_{2P} + \alpha_{P1})} \quad (F-18)$$

Output Angular Velocity $\dot{\phi}_2 = \dot{\phi}_{2P} = \dot{\phi}_{2G}$

$$\dot{\phi}_2 = \dot{\phi}_1 \frac{L_{1F}}{M_{1F}} \quad (F-19)$$

where

$$L_{1F} = A_{1FD} \sin \phi_{2P} + B_{1FD} \cos \phi_{2P} \quad (F-20)$$

$$M_{1F} = A_{1F} \cos \phi_{2P} - B_{1F} \sin \phi_{2P} \quad (F-21)$$

and

$$A_{1FD} = a_{G1} \sin (\phi_1 - \delta_{G1} - \alpha_{P1}) \quad (F-22)$$

$$B_{1FD} = a_{G1} \cos (\phi_1 - \delta_{G1} - \alpha_{P1}) \quad (F-23)$$

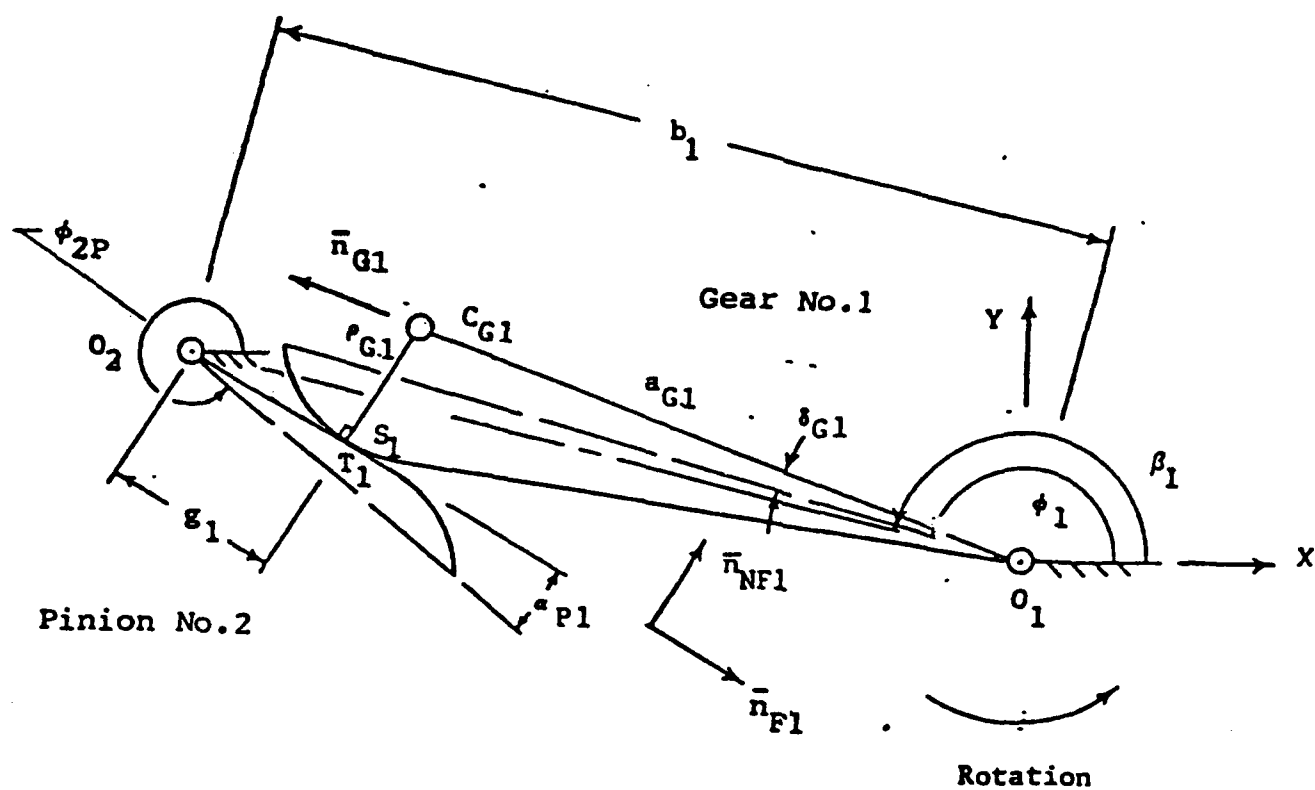


Figure F-2. Round-on-flat phase of motion of mesh no. 1

Relative Velocity $\bar{V}_{S1/T1_F}$ at Contact Point

$$\bar{V}_{S1/T1_F} = \dot{\phi}_1 \{ a_{G1} \sin (\phi_{2P} + \alpha_{P1} - \phi_1 + \delta_{G1}) + \rho_{G1} \} \bar{n}_{F1} \quad (F-24)$$

Transition Angles ϕ_{2PT} and ϕ_{1T}

$$\phi_{2PT} = 2 \tan^{-1} \frac{A_{1T} \pm \sqrt{A_{1T}^2 + B_{1T}^2 - C_{1T}^2}}{B_{1T} + C_{1T}} \quad (F-25)$$

with appropriate choice of sign, and

$$A_{1T} = -\rho_{G1} \cos (\beta_1 - \alpha_{P1}) + f_{P1} \sin (\beta_1 - \alpha_1) \quad (F-26)$$

$$B_{1T} = \rho_{G1} \sin (\beta_1 - \alpha_{P1}) + f_{P1} \cos (\beta_1 - \alpha_{P1}) \quad (F-27)$$

$$C_{1T} = \frac{a_{G1}^2 - \rho_{G1}^2 - b_1^2 - f_{P1}^2}{2b_1} \quad (F-28)$$

$$\phi_{1T} = \cos^{-1} \left[\frac{-\rho_{G1} \sin (\phi_{2PT} + \alpha_{P1}) + b_1 \cos \beta_1 + f_{P1} \cos (\phi_{2PT} + \alpha_{P1})}{a_{G1}} \right] + \delta_{G1} \quad (F-29)$$

$$\phi_{1T} = \sin^{-1} \left[\frac{\rho_{G1} \cos (\phi_{2PT} + \alpha_{P1}) + b_1 \sin \beta_1 + f_{P1} \sin (\phi_{2PT} + \alpha_{P1})}{a_{G1}} \right] + \delta_{G1} \quad (F-30)$$

Sensing Equations for the Determination of Contact of Subsequent Tooth Mesh

Contact will occur as soon as

$$\sqrt{L_{x1}^2 + L_{y1}^2} \leq \rho_{G1} + \rho_{P1} \quad (F-31)$$

where

$$L_{x1} = b_1 \cos \beta_1 + a_{P1} \cos (\phi_{2P} + \Delta\phi_{2P} - \delta_{P1}) - a_{G1} \cos (\phi_1 - \Delta\phi_1 - \delta_{G1}) \quad (F-32)$$

and

$$L_{y1} = b_1 \sin \beta_1 + a_{P1} \sin (\phi_{2P} + \Delta\phi_{2P} - \delta_{P1}) - a_{G1} \sin (\phi_1 - \Delta\phi_1 - \delta_{G1}) \quad (F-33)$$

The above requires the substitution of positive values for $\Delta\phi_{2P}$ and $\Delta\phi_1$, the tooth spacing angles.

Further, as in references 1 and 2, the angle ϕ_{2P} must be determined for the round-on-flat phase of motion, since the initial contact of the subsequent set of meshing teeth is preceded by this phase of motion. This means that equation F-14 is applicable.

FORWARD KINEMATICS OF MESH NO. 2

(Angle ϕ_{2G} is input, angle ϕ_S is output)

Round-on-Round Phase of Motion (fig. F-3)

Angle ϕ_S

$$\phi_S = 2 \tan^{-1} \frac{A_{2R} \pm \sqrt{A_{2R}^2 + B_{2R}^2 - C_{2R}^2}}{B_{2R} + C_{2R}} \quad (F-34)$$

with appropriate choice of sign, and

$$A_{2R} = a_{G2} \sin (\phi_{2G} + \delta_{G2} - \delta_{P2}) - b_2 \sin (\beta_2 - \delta_{P2}) \quad (F-35)$$

$$B_{2R} = a_{G2} \cos (\phi_{2G} + \delta_{G2} - \delta_{P2}) - b_2 \cos (\beta_2 - \delta_{P2}) \quad (F-36)$$

$$C_{2R} = \frac{a_{P2}^2 + a_{G2}^2 + b_2^2 - L_2^2 - 2a_{G2} b_2 \cos (\phi_{2G} + \delta_{G2} - \beta_2)}{2a_{P2}} \quad (F-37)$$

Angle λ_2

$$\lambda_2 = \cos^{-1} \left[\frac{b_2 \cos \beta_2 + a_{P2} \cos (\phi_S + \delta_{P2}) - a_{G2} \cos (\phi_{2G} + \delta_{G2})}{L_2} \right] \quad (F-38)$$

$$\lambda_2 = \sin^{-1} \left[\frac{b_2 \sin \beta_2 + a_{P2} \sin (\phi_S + \delta_{P2}) - a_{G2} \sin (\phi_{2G} + \delta_{G2})}{L_2} \right] \quad (F-39)$$

Escape Wheel and
Pinion No. 3

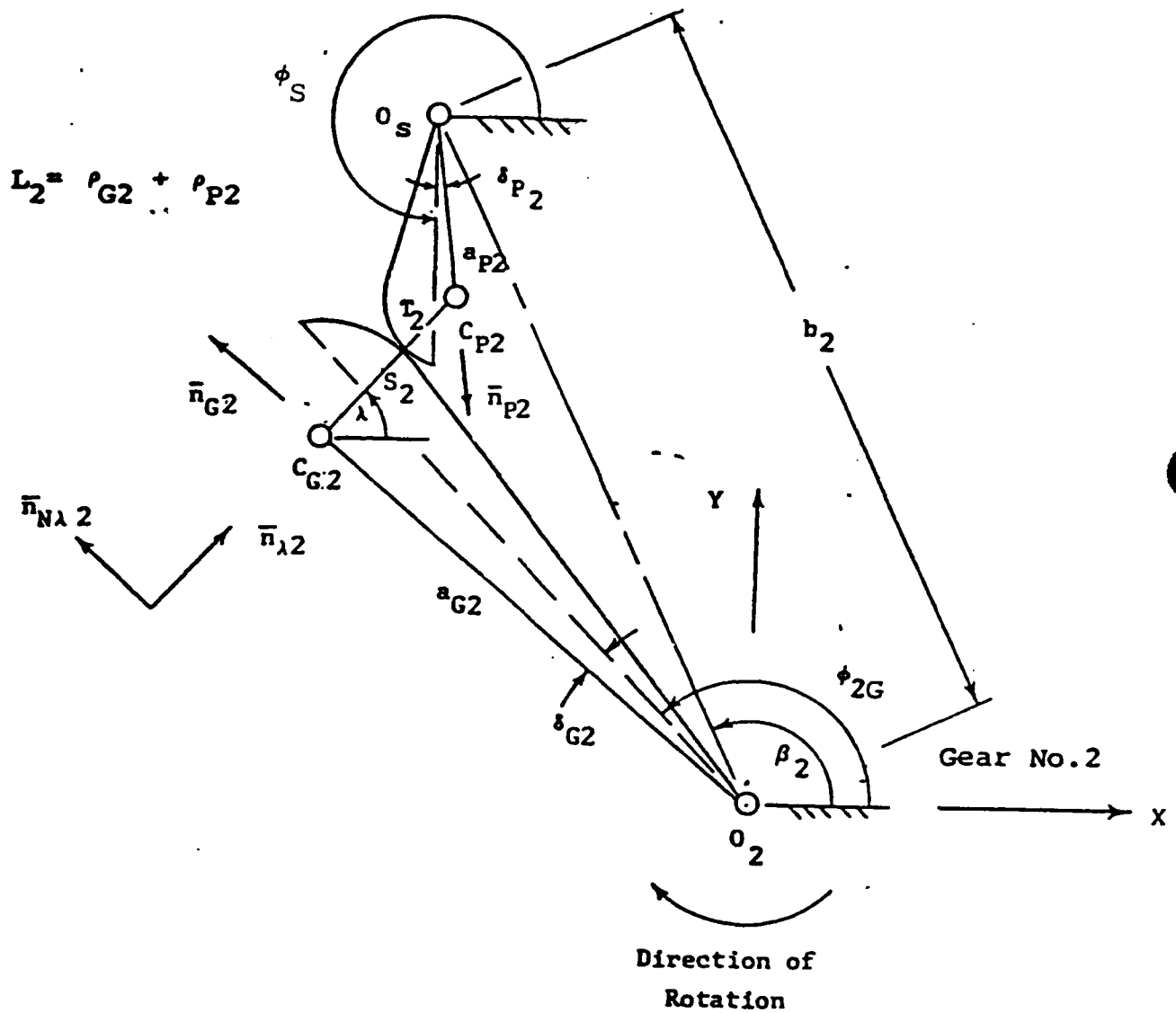


Figure F-3. Round-on-round phase of motion for mesh no. 2

Output Angular Velocity $\dot{\phi}^3$ of Escape Wheel

$$\dot{\phi} = \dot{\phi}_{2G} \frac{L_{2R}}{M_{2R}} \quad (F-40)$$

where

$$L_{2R} = B_{2RD} \cos \phi_S - A_{2RD} \sin \phi_S + C_{2RD} \quad (F-41)$$

$$M_{2R} = A_{2R} \cos \phi_S - B_{2R} \sin \phi_S \quad (F-42)$$

and

$$A_{2RD} = a_{G2} \cos (\phi_{2G} + \delta_{G2} - \delta_{P2}) \quad (F-43)$$

$$B_{2RD} = a_{G2} \sin (\phi_{2G} + \delta_{G2} - \delta_{P2}) \quad (F-44)$$

$$C_{2RD} = \frac{a_{G2} b_2 \sin (\phi_{2G} + \delta_{G2} - \beta_2)}{a_{P2}} \quad (F-45)$$

Note that in equation F-40

$$\dot{\phi}_{2G} = \dot{\phi}_{2P} = \dot{\phi}_2 \quad (F-46)$$

Relative Velocity $\bar{V}_{S2/T2R}$ at the Contact Point

$$\begin{aligned} \bar{V}_{S2/T2R} = & \left\{ \dot{\phi}_{2G} [a_{G2} \cos (\phi_{2G} + \delta_{G2} - \lambda_2) + \rho_{G2}] \right. \\ & \left. - \dot{\phi} [a_{P2} \cos (\phi_S + \delta_{P2} - \lambda_2) - \rho_{P2}] \right\} \bar{n}_{N\lambda_2} \end{aligned} \quad (F-47)$$

Round-on-Flat Phase of Motion (fig. F-4)

Angle ϕ_S

$$\phi_S = 2 \tan^{-1} \frac{A_{2F} \pm \sqrt{A_{2F}^2 + B_{2F}^2 - C_{2F}^2}}{B_{2F} + C_{2F}} \quad (F-48)$$

³The notation $\dot{\phi}$ is identical with $\dot{\phi}_S$. It is used, since the derivations in appendix D show this form of the escape wheel angular velocity.

The diagram illustrates the geometry and forces on a gear tooth. Key parameters and labels include:

- ϕ_S : Angle at the shaft center O_S .
- O_S : Shaft center.
- g_2 : Addendum.
- $\bar{n}_{G2}$: Normal force at the gear center C_{G2} .
- ρ_{G2} : Radius of curvature at the contact point T_2 .
- T_2 : Contact point between the tooth and the pitch circle.
- S_2 : Pitch circle radius.
- a_{G2} : Addendum.
- δ_{G2} : Angle between the tangent at T_2 and the line $C_{G2}T_2$.
- α_{P2} : Pressure angle.
- $\bar{n}_{NF2}$: Normal force at the tooth root.
- $\bar{n}_{F2}$: Tangential force at the tooth root.
- Y : Tooth root fillet radius.
- β_2 : Angle between the tangent at the root and the vertical.
- ϕ_{2G} : Angle between the tangent at the root and the line O_2T_2 .
- O_2 : Gear center.
- X : Horizontal axis.
- b_2 : Face width.
- Gear No.2**: Label for the gear.
- Direction of Rotation**: Indicated by a curved arrow at the bottom.

280

with appropriate choice of sign, and

$$A_{2F} = a_{G2} \cos (\phi_{2G} + \delta_{G2} + \alpha_{P2}) - b_2 \cos (\beta_2 + \alpha_{P2}) \quad (F-49)$$

$$B_{2F} = -a_{G2} \sin (\phi_{2G} + \delta_{G2} + \alpha_{P2}) + b_2 \sin (\beta_2 + \alpha_{P2}) \quad (F-50)$$

$$C_{2F} = \rho_{G2} \quad (F-51)$$

Distance g_2

$$g_2 = \frac{a_{G2} \sin (\phi_{2G} + \delta_{G2}) + \rho_{G2} \cos (\phi_S - \alpha_{P2}) - b_2 \sin \beta_2}{\sin (\phi_S - \alpha_{P2})} \quad (F-52)$$

Output Angular Velocity $\dot{\phi}$

$$\dot{\phi} = \dot{\phi}_{2G} \frac{L_{2F}}{M_{2F}} \quad (F-53)$$

where

$$L_{2F} = A_{2FD} \sin \phi_S + B_{2FD} \cos \phi_S \quad (F-54)$$

$$M_{2F} = A_{2F} \cos \phi_S - B_{2F} \sin \phi_S \quad (F-55)$$

and

$$A_{2FD} = a_{G2} \sin (\phi_{2G} + \delta_{G2} + \alpha_{P2}) \quad (F-56)$$

$$B_{2FD} = a_{G2} \cos (\phi_{2G} + \delta_{G2} + \alpha_{P2}) \quad (F-57)$$

Equation F-46 is also applicable to equation F-53.

Relative Velocity $\bar{V}_{S2/T2_F}$ at Contact Point

$$\bar{V}_{S2/T2_F} = \dot{\phi}_2 [a_{G2} \sin (\phi_S - \alpha_{P2} - \phi_{2G} - \delta_{G2}) - \rho_{G2}] \bar{n}_{F2} \quad (F-58)$$

Transition Angles ϕ_{ST} and ϕ_{2GT}

$$\phi_{ST} = 2 \tan^{-1} \frac{A_{2T} \pm \sqrt{A_{2T}^2 + B_{2T}^2 - C_{2T}^2}}{B_{2T} + C_{2T}} \quad (F-59)$$

with appropriate choice of sign, and

$$A_{2T} = \rho_{G2} \cos (\beta_2 + \alpha_{P2}) + f_{P2} \sin (\beta_2 + \alpha_{P2}) \quad (F-60)$$

$$B_{2T} = -\rho_{G2} \sin (\beta_2 + \alpha_{P2}) + f_{P2} \cos (\beta_2 + \alpha_{P2}) \quad (F-61)$$

$$C_{2T} = \frac{a_{G2}^2 - \rho_{G2}^2 - b_2^2 - f_{P2}^2}{2b_2} \quad (F-62)$$

$$\phi_{2GT} = \cos^{-1} \left[\frac{\rho_{G2} \sin (\phi_{ST} - \alpha_{P2}) + f_{P2} \cos (\phi_{ST} - \alpha_{P2}) + b_2 \cos \beta_2}{a_{G2}} \right] - \delta_{G2} \quad (F-63)$$

$$\phi_{2GT} = \sin^{-1} \left[\frac{-\rho_{G2} \cos (\phi_{ST} - \alpha_{P2}) + f_{P2} \sin (\phi_{ST} - \alpha_{P2}) + b_2 \sin \beta_2}{a_{G2}} \right] - \delta_{G2} \quad (F-64)$$

Sensing Equations for the Determination of Contact of Subsequent Tooth Mesh

Contact will occur as soon as

$$\sqrt{L_{x2}^2 + L_{y2}^2} \leq \rho_{G2} + \rho_{P2} \quad (F-65)$$

where

$$L_{x2} = b_2 \cos \beta_2 + a_{P2} \cos (\phi_S - \Delta\phi_S + \delta_{P2}) - a_{G2} \cos (\phi_{2G} + \Delta\phi_{2G} + \delta_{G2}) \quad (F-66)$$

$$L_{y2} = b_2 \sin \beta_2 + a_{P2} \sin (\phi_S - \Delta\phi_S + \delta_{P2}) - a_{G2} \sin (\phi_{2G} + \Delta\phi_{2G} + \delta_{G2}) \quad (F-67)$$

The above requires the substitution of positive values for $\Delta\phi_S$ and $\Delta\phi_{2G}$, the tooth spacing angles. The angle ϕ_S must be found according to equation F-48.

REVERSE KINEMATICS OF MESH NO. 1

(Angle ϕ_{2P} is input and angle ϕ_1 is output)

Round-on-Round Phase of Motion (fig. F-1)

Angle ϕ_1

$$\phi_1 = 2 \tan^{-1} \frac{D_{1R} \pm \sqrt{D_{1R}^2 + E_{1R}^2 - F_{1R}^2}}{E_{1R} + F_{1R}} \quad (F-68)$$

with appropriate choice of sign, and

$$D_{1R} = -2a_{G1} [a_{P1} \sin(\phi_{2P} + \delta_{G1} - \delta_{P1}) + b_1 \sin(\beta_1 + \delta_{G1})] \quad (F-69)$$

$$E_{1R} = -2a_{G1} [a_{P1} \cos(\phi_{2P} + \delta_{G1} - \delta_{P1}) + b_1 \cos(\beta_1 + \delta_{G1})] \quad (F-70)$$

$$F_{1R} = L_1^2 - a_{G1}^2 - a_{P1}^2 - b_1^2 - 2a_{P1} b_1 \cos(\phi_{2P} - \beta_1 - \delta_{P1}) \quad (F-71)$$

Angular Velocity $\dot{\phi}_1$

$$\dot{\phi}_1 = \dot{\phi}_{2P} \text{DER1R} \quad (F-72)$$

where

$$\text{DER1R} = \frac{F_{1RD} - D_{1RD} \sin \phi_1 - E_{1RD} \cos \phi_1}{D_{1R} \cos \phi_1 - E_{1R} \sin \phi_1} \quad (F-73)$$

and

$$D_{1RD} = -2a_{G1} a_{P1} \cos(\phi_{2P} + \delta_{G1} - \delta_{P1}) \quad (F-74)$$

$$E_{1RD} = 2a_{G1} a_{P1} \sin(\phi_{2P} + \delta_{G1} - \delta_{P1}) \quad (F-75)$$

$$F_{1RD} = 2a_{P1} b_1 \sin(\phi_{2P} - \beta_1 - \delta_{P1}) \quad (F-76)$$

Angular Acceleration $\ddot{\phi}_1$

$$\ddot{\phi}_1 = \ddot{\phi}_{2P} Y_1 + \dot{\phi}_{2P}^2 Y_2 \quad (F-77)$$

where

$$Y_1 = X_1 X_2 \quad (F-78)$$

$$Y_2 = X_1 X_3 \quad (F-79)$$

and

$$X_1 = \frac{1}{D_{1R} \cos \phi_1 - E_{1R} \sin \phi_1} \quad (F-80)$$

$$X_2 = F_{1RD} - D_{1RD} \sin \phi_1 - E_{1RD} \cos \phi_1 \quad (F-81)$$

$$\begin{aligned} X_3 = & F_{1RD} - D_{1RDD} \sin \phi_1 - E_{1RDD} \cos \phi_1 \\ & + DER1R [2 E_{1RD} \sin \phi_1 - 2 D_{1RD} \cos \phi_1] \\ & + DER1R^2 [D_{1R} \sin \phi_1 + E_{1R} \cos \phi_1] \end{aligned} \quad (F-82)$$

with

$$D_{1RDD} = 2a_{G1} a_{P1} \sin (\phi_{2P} + \delta_{G1} - \delta_{P1}) \quad (F-83)$$

$$E_{1RDD} = 2a_{G1} a_{P1} \cos (\phi_{2P} + \delta_{G1} - \delta_{P1}) \quad (F-84)$$

$$F_{1RDD} = 2a_{P1} b_1 \cos (\phi_{2P} - \beta_1 - \delta_{P1}) \quad (F-85)$$

Round-on-Flat Phase of Motion (fig. F-2)

Angle ϕ_1

$$\phi_1 = 2 \tan^{-1} \frac{D_{1F} \pm \sqrt{D_{1F}^2 + E_{1F}^2 - F_{1F}^2}}{E_{1F} + F_{1F}} \quad (F-86)$$

with appropriate choice of sign, and

$$D_{1F} = -a_{G1} \cos (\phi_{2P} + \alpha_{P1} + \delta_{G1}) \quad (F-87)$$

$$E_{1F} = a_{G1} \sin (\phi_{2P} + \alpha_{P1} + \delta_{G1}) \quad (F-88)$$

$$F_{1F} = -\rho_{G1} + b_1 \sin (\phi_{2P} + \alpha_{P1} - \beta_1) \quad (F-89)$$

Angular Velocity $\dot{\phi}_1$

$$\dot{\phi}_1 = \dot{\phi}_{2P} \text{ DER1F} \quad (\text{F-90})$$

where

$$\text{DER1F} = \frac{F_{1FD} - D_{1FD} \sin \phi_1 - E_{1FD} \cos \phi_1}{D_{1F} \cos \phi_1 - E_{1F} \sin \phi_1} \quad (\text{F-91})$$

and

$$D_{1FD} = a_{G1} \sin (\phi_{2P} + \alpha_{P1} + \delta_{G1}) \quad (\text{F-92})$$

$$E_{1FD} = a_{G1} \sin (\phi_{2P} + \alpha_{P1} + \delta_{G1}) \quad (\text{F-93})$$

$$F_{1FD} = b_1 \cos (\phi_{2P} + \alpha_{P1} - \beta_1) \quad (\text{F-94})$$

Angular Acceleration $\ddot{\phi}_1$

$$\ddot{\phi}_1 = \ddot{\phi}_{2P} Y_3 + \dot{\phi}_{2P}^2 Y_4 \quad (\text{F-95})$$

where

$$Y_3 = X_4 X_5 \quad (\text{F-96})$$

$$Y_4 = X_4 X_6 \quad (\text{F-97})$$

and

$$X_4 = \frac{1}{(D_{1F} \cos \phi_1 - E_{1F} \sin \phi_1)} \quad (\text{F-98})$$

$$X_5 = F_{1FD} - D_{1FD} \sin \phi_1 - E_{1FD} \cos \phi_1 \quad (\text{F-99})$$

$$\begin{aligned} X_6 = & F_{1FDD} - D_{1FDD} \sin \phi_1 - E_{1FDD} \cos \phi_1 \\ & + \text{DER1F} [-2 D_{1FD} \cos \phi_1 + 2 E_{1FD} \sin \phi_1] \\ & + \text{DER1F}^2 [D_{1F} \sin \phi_1 + E_{1F} \cos \phi_1] \end{aligned} \quad (\text{F-100})$$

and

$$D_{1FDD} = a_{G1} \cos (\phi_{2P} + \alpha_{P1} + \delta_{G1}) \quad (F-101)$$

$$E_{1FDD} = -a_{G1} \sin (\phi_{2P} + \alpha_{P1} + \delta_{G1}) \quad (F-102)$$

$$F_{1FDD} = -b_1 \sin (\phi_{2P} + \alpha_{P1} - \beta_1) \quad (F-103)$$

REVERSE KINEMATICS OF MESH NO. 2

(Angle ϕ_S is input and angle ϕ_{2G} is output)

Round-on-Round Phase of Motion (fig. F-3)

Angle ϕ_{2G}

$$\phi_{2G} = 2 \tan^{-1} \frac{D_{2R} \pm \sqrt{D_{2R}^2 + E_{2R}^2 - F_{2R}^2}}{E_{2R} + F_{2R}} \quad (F-104)$$

with appropriate choice of sign, and

$$D_{2R} = -2 a_{P2} a_{G2} \sin (\phi_S + \delta_{P2} - \delta_{G2}) - 2 a_{G2} b_2 \sin (\beta_2 - \delta_{G2}) \quad (F-105)$$

$$E_{2R} = -2 a_{P2} a_{G2} \cos (\phi_S + \delta_{P2} - \delta_{G2}) - 2 a_{G2} b_2 \cos (\beta_2 - \delta_{G2}) \quad (F-106)$$

$$F_{2R} = L_2^2 - a_{G2}^2 - a_{P2}^2 - b_2^2 - 2 a_{P2} b_2 \cos (\phi_S + \delta_{P2} - \beta_2) \quad (F-107)$$

Angular Velocity $\dot{\phi}_{2G}$

$$\dot{\phi}_{2G} = \dot{\phi} \text{ DER2R} \quad (F-108)$$

where

$$\text{DER2R} = \frac{F_{2RD} - D_{2RD} \sin \phi_{2G} - E_{2RD} \cos \phi_{2G}}{D_{2R} \cos \phi_{2G} - E_{2R} \sin \phi_{2G}} \quad (F-109)$$

and

$$D_{2RD} = -2 a_{P2} a_{G2} \cos (\phi_S + \delta_{P2} - \delta_{G2}) \quad (F-110)$$

$$E_{2RD} = 2 a_{P2} a_{G2} \sin (\phi_S + \delta_{P2} - \delta_{G2}) \quad (F-111)$$

$$F_{2RD} = 2 a_{P2} b_2 \sin (\phi_S + \delta_{P2} - \beta_2) \quad (F-112)$$

Angular Acceleration $\ddot{\phi}_{2G}$

$$\ddot{\phi}_{2G} = \ddot{\phi} Y_5 + \dot{\phi}^2 Y_6 \quad (F-113)$$

where

$$Y_5 = X_7 X_8 \quad (F-114)$$

$$Y_6 = X_7 X_9 \quad (F-115)$$

and

$$X_7 = \frac{1}{D_{2R} \cos \phi_{2G} - E_{2R} \sin \phi_{2G}} \quad (F-116)$$

$$X_8 = F_{2RD} - D_{2RD} \sin \phi_{2G} - E_{2RD} \cos \phi_{2G} \quad (F-117)$$

$$\begin{aligned} X_9 = & F_{2RDD} - D_{2RDD} \sin \phi_{2G} - E_{2RDD} \cos \phi_{2G} \\ & + DER2R [-2 D_{2RD} \cos \phi_{2G} + 2 E_{2RD} \sin \phi_{2G}] \\ & + DER2R^2 [D_{2R} \sin \phi_{2G} + E_{2R} \cos \phi_{2G}] \end{aligned} \quad (F-118)$$

$$D_{2RDD} = 2 a_{P2} a_{G2} \sin (\phi_S + \delta_{P2} - \delta_{G2}) \quad (F-119)$$

$$E_{2RDD} = 2 a_{P2} a_{G2} \cos (\phi_S + \delta_{P2} - \delta_{G2}) \quad (F-120)$$

$$F_{2RDD} = 2 a_{P2} b_2 \cos (\phi_S + \delta_{P2} - \beta_2) \quad (F-121)$$

Round-on-Flat Phase of Motion (fig. F-4)

Angle ϕ_{2G}

$$\phi_{2G} = 2 \tan^{-1} \frac{D_{2F} \pm \sqrt{D_{2F}^2 + E_{2F}^2 - F_{2F}^2}}{E_{2F} + F_{2F}} \quad (F-122)$$

with appropriate choice of sign, and

$$D_{2F} = -a_{G2} \cos (\phi_S - \alpha_{P2} - \delta_{G2}) \quad (F-123)$$

$$E_{2F} = a_{G2} \sin (\phi_S - \alpha_{P2} - \delta_{G2}) \quad (F-124)$$

$$F_{2F} = \rho_{G2} + b_2 \sin (\phi_S - \alpha_{P2} - \beta_2) \quad (F-125)$$

Angular Velocity $\dot{\phi}_2$

$$\dot{\phi}_{2G} = \dot{\phi} \text{ DER2F} \quad (F-126)$$

where

$$\text{DER2F} = \frac{F_{2FD} - D_{2FD} \sin \phi_{2G} - E_{2FD} \cos \phi_{2G}}{D_{2F} \cos \phi_{2G} - E_{2F} \sin \phi_{2G}} \quad (F-127)$$

and

$$D_{2FD} = a_{G2} \sin (\phi_S - \alpha_{P2} - \delta_{G2}) \quad (F-128)$$

$$E_{2FD} = a_{G2} \cos (\phi_S - \alpha_{P2} - \delta_{G2}) \quad (F-129)$$

$$F_{2FD} = b_2 \cos (\phi_S - \alpha_{P2} - \beta_2) \quad (F-130)$$

Angular Acceleration $\ddot{\phi}_2$

$$\ddot{\phi}_{2G} = \ddot{\phi} Y_7 + \dot{\phi}^2 Y_8 \quad (F-131)$$

where

$$Y_7 = X_{10} X_{11} \quad (F-132)$$

$$Y_8 = X_{10} X_{12} \quad (F-133)$$

and

$$X_{10} = \frac{1}{D_{2F} \cos \phi_{2G} - E_{2F} \sin \phi_{2G}} \quad (F-134)$$

$$X_{11} = F_{2FD} - D_{2FD} \sin \phi_{2G} - E_{2FD} \cos \phi_{2G} \quad (F-135)$$

$$\begin{aligned} X_{12} = & F_{2FDD} - D_{2FDD} \sin \phi_{2G} - E_{2FDD} \cos \phi_{2G} \\ & + DER2F [-2D_{2FD} \cos \phi_{2G} + 2E_{2FD} \sin \phi_{2G}] \\ & + DER2F^2 [D_{2F} \sin \phi_{2G} + E_{2F} \cos \phi_{2G}] \end{aligned} \quad (F-136)$$

and

$$D_{2FDD} = a_{G2} \cos (\phi_S - \alpha_{P2} - \delta_{G2}) \quad (F-137)$$

$$E_{2FDD} = -a_{G2} \sin (\phi_S - \alpha_{P2} - \delta_{G2}) \quad (F-138)$$

$$F_{2FDD} = -b_2 \sin (\phi_S - \alpha_{P2} - \beta_2) \quad (F-139)$$

ANGULAR VELOCITIES AND ACCELERATIONS OF GEAR AND PINION NO. 2 AND ROTOR GEAR NO. 1 IN TERMS OF THE ESCAPE WHEEL ANGULAR VELOCITY $\dot{\phi}$ AND ANGULAR ACCELERATION $\ddot{\phi}$ FOR VARIOUS MESH CONTACT MODES

Case No. 1: RR (Mesh 2: Round-on-Round; Mesh 1: Round-on-Round)

According to equations F-72 and F-77, the angular velocity and acceleration of the rotor gear of mesh 1 in the round-on-round phase are given, respectively by

$$\dot{\phi}_1 = \dot{\phi}_{2P} DER1R \quad (F-72)$$

$$\ddot{\phi}_1 = \ddot{\phi}_{2P} Y_1 + \dot{\phi}_{2P}^2 Y_2 \quad (F-77)$$

According to equations F-108 and F-113, the angular velocity and acceleration of gear no. 2 of mesh 2 in the round-on-round phase is given by

$$\dot{\phi}_{2G} = \dot{\phi} DER2R \quad (F-108)$$

$$\ddot{\phi}_{2G} = \ddot{\phi} Y_5 + \dot{\phi}^2 Y_6 \quad (F-113)$$

Since

$$\dot{\phi}_{2P} = \dot{\phi}_{2G} = \dot{\phi}_2 \quad (\text{F-140})$$

and

$$\ddot{\phi}_{2P} = \ddot{\phi}_{2G} = \ddot{\phi}_2 \quad (\text{F-141},$$

the angular velocity $\dot{\phi}_1$ of the rotor gear 1 becomes

$$\dot{\phi}_1 = \dot{\phi}(\text{DER1R})(\text{DER2R}) \quad (\text{F-142})$$

The angular acceleration $\ddot{\phi}_1$ of the rotor is also obtained by appropriate substitution, i.e.,

$$\ddot{\phi}_1 = \ddot{\phi}[Y_1 Y_5] + \dot{\phi}^2[Y_1 Y_6 + Y_2(\text{DER2R})^2] \quad (\text{F-143})$$

Case No. 2: RF (Mesh 2: Round-on-Round; Mesh 1: Round-on-Flat)

According to equations F-90 and F-95, the angular velocity and acceleration of the rotor gear of mesh 1 in the round-on-flat phase are given, respectively, by

$$\dot{\phi}_1 = \dot{\phi}_{2P} \text{DER1F} \quad (\text{F-90})$$

$$\ddot{\phi}_1 = \ddot{\phi}_{2P} Y_3 + \dot{\phi}_{2P}^2 Y_4 \quad (\text{F-95})$$

Equations F-117 and F-122 are again used to describe the angular velocity and acceleration of gear and pinion no. 2 of mesh 2 in the round-on-round phase. Since, again

$$\dot{\phi}_{2P} = \dot{\phi}_{2G} \quad (\text{F-144})$$

and

$$\ddot{\phi}_{2P} = \ddot{\phi}_{2G}, \quad (\text{F-145})$$

the angular velocity $\dot{\phi}_1$ of the rotor gear 1 becomes on substitution of equation F-108 into equation F-90

$$\dot{\phi}_1 = \dot{\phi}(\text{DER1F})(\text{DER2R}) \quad (\text{F-146})$$

Appropriate substitution of equation F-113 into equation F-95, yields for the angular acceleration $\ddot{\phi}_1$ of the rotor gear 1 the following

$$\ddot{\phi}_1 = \ddot{\phi}[Y_3 Y_5] + \dot{\phi}^2[Y_3 Y_6 + Y_4(\text{DER2R})^2] \quad (\text{F-147})$$

Case No. 3: FF (Mesh 2: Round-on-Flat; Mesh 1: Round-on-Flat)

As for case 2, equations F-90 and F-95 give the velocity and acceleration relationships for mesh 1 in the round-on-flat phase.

Equations F-126 and F-131 give the angular velocity and acceleration of gear and pinion no. 2 of mesh 2 in the round-on-flat phase as follows:

$$\dot{\phi}_{2G} = \dot{\phi} \text{DER2F} \quad (\text{F-126})$$

and

$$\ddot{\phi}_{2G} = \ddot{\phi} Y_7 + \dot{\phi}^2 Y_8 \quad (\text{F-131})$$

Again

$$\dot{\phi}_{2P} = \dot{\phi}_{2G} \quad (\text{F-148})$$

and

$$\ddot{\phi}_{2P} = \ddot{\phi}_{2G} \quad (\text{F-149})$$

Appropriate substitution of equation F-126 into F-90 furnishes the angular velocity $\dot{\phi}_1$ of the rotor gear 1 in terms of the escape wheel angular velocity $\dot{\phi}$ for the present FF case

$$\dot{\phi}_1 = \dot{\phi}(\text{DER1F})(\text{DER2F}) \quad (\text{F-150})$$

Similar substitution of equation F-131 into equation F-95 furnishes the angular acceleration $\ddot{\phi}_1$ of the rotor gear

$$\ddot{\phi}_1 = \ddot{\phi}[Y_3 Y_7] + \dot{\phi}^2[Y_3 Y_8 + Y_4(\text{DER2F})^2] \quad (\text{F-151})$$

Case No. 4: FR (Mesh 2: Round-on-Flat; Mesh 2: Round-on-Round)

To obtain the angular velocity $\dot{\phi}_1$, equation F-126 is substituted into equation F-72. In a similar procedure, the angular acceleration $\ddot{\phi}_1$ results from the substitution of equation F-131 into equation F-77. In either case, the following equalities must be observed:

$$\dot{\phi}_{2P} = \dot{\phi}_{2G} \quad (F-152)$$

and

$$\ddot{\phi}_{2P} = \ddot{\phi}_{2G} \quad (F-153)$$

Then,

$$\dot{\phi}_1 = \dot{\phi}(\text{DER1R})(\text{DER2F}) \quad (F-154)$$

and

$$\ddot{\phi}_1 = \ddot{\phi}[Y_1 Y_7] + \dot{\phi}^2[Y_1 Y_8 + Y_2 (\text{DER2F})^2] \quad (F-155)$$

REFERENCES

1. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.
2. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Efficiency," Technical Report ARLCD-TR-80024, ARRADCOM, Dover, NJ, November 1981.

APPENDIX G

PROJECTILE KINEMATICS IN TERMS OF COORDINATE SYSTEM FIXED
TO UNDERSIDE OF MECHANISM PLANE
(APPLICABLE TO M577 S&A)

The projectile in figure D-1 of appendix D, which shows the M577 S&A located on the underside of the mechanism plane, was rotated 180 degrees about the X_p axis, when compared to its original position in figure C-1 of appendix C. (Note that the relative position of the center of mass C_{PR} of the projectile remains undisturbed.

This rotation places the Y_p and Z_p axes in opposite directions to the Y and Z axes, respectively, of the newly introduced coordinate system which is attached to the underside of the mechanism plane.

It is therefore necessary to express the aeroballistic kinematics of appendix A in terms of this new X - Y - Z system. Figure G-1, which represents a revision of figure A-1, is used for this purpose. The original lower case x - y - z system is now labeled X_p - Y_p - Z_p .

When the angular velocity components of the projectile are now expressed in this new system (with additional subscript u), one obtains:

$$\omega_{xu} = \dot{\theta}_E \cos \phi_E + \dot{\psi}_E \sin \theta_E \sin \phi_E \quad (G-1)$$

$$\omega_{yu} = \dot{\theta}_E \sin \phi_E - \dot{\psi}_E \sin \theta_E \cos \phi_E \quad (G-2)$$

$$\omega_{zu} = -\dot{\phi}_E - \dot{\psi}_E \cos \theta_E \quad (G-3)$$

Differentiation of the above expressions furnishes the components of the angular acceleration of the projectile in this system

$$\begin{aligned} \dot{\omega}_{xu} = & \ddot{\theta}_E \cos \phi_E - \dot{\theta}_E \dot{\phi}_E \sin \phi_E + \ddot{\psi}_E \sin \theta_E \sin \phi_E \\ & + \dot{\psi}_E \dot{\theta}_E \cos \theta_E \sin \phi_E + \dot{\psi}_E \dot{\phi}_E \sin \theta_E \cos \phi_E \end{aligned} \quad (G-4)$$

$$\begin{aligned} \dot{\omega}_{yu} = & \ddot{\theta}_E \sin \phi_E + \dot{\theta}_E \dot{\phi}_E \cos \phi_E - \ddot{\psi}_E \sin \theta_E \cos \phi_E \\ & - \dot{\psi}_E \dot{\theta}_E \cos \theta_E \cos \phi_E + \dot{\psi}_E \dot{\phi}_E \sin \theta_E \sin \phi_E \end{aligned} \quad (G-5)$$

$$\dot{\omega}_{zu} = -\ddot{\phi}_E - \ddot{\psi}_E \cos \theta_E + \dot{\psi}_E \dot{\theta}_E \sin \theta_E \quad (G-6)$$

Comparison with equations A-2 to A-4 and A-6 to A-8, respectively, shows that the changing requirements can be satisfied by the following general notation

$$\omega_{xGEN} = \omega_x \quad (G-7)$$

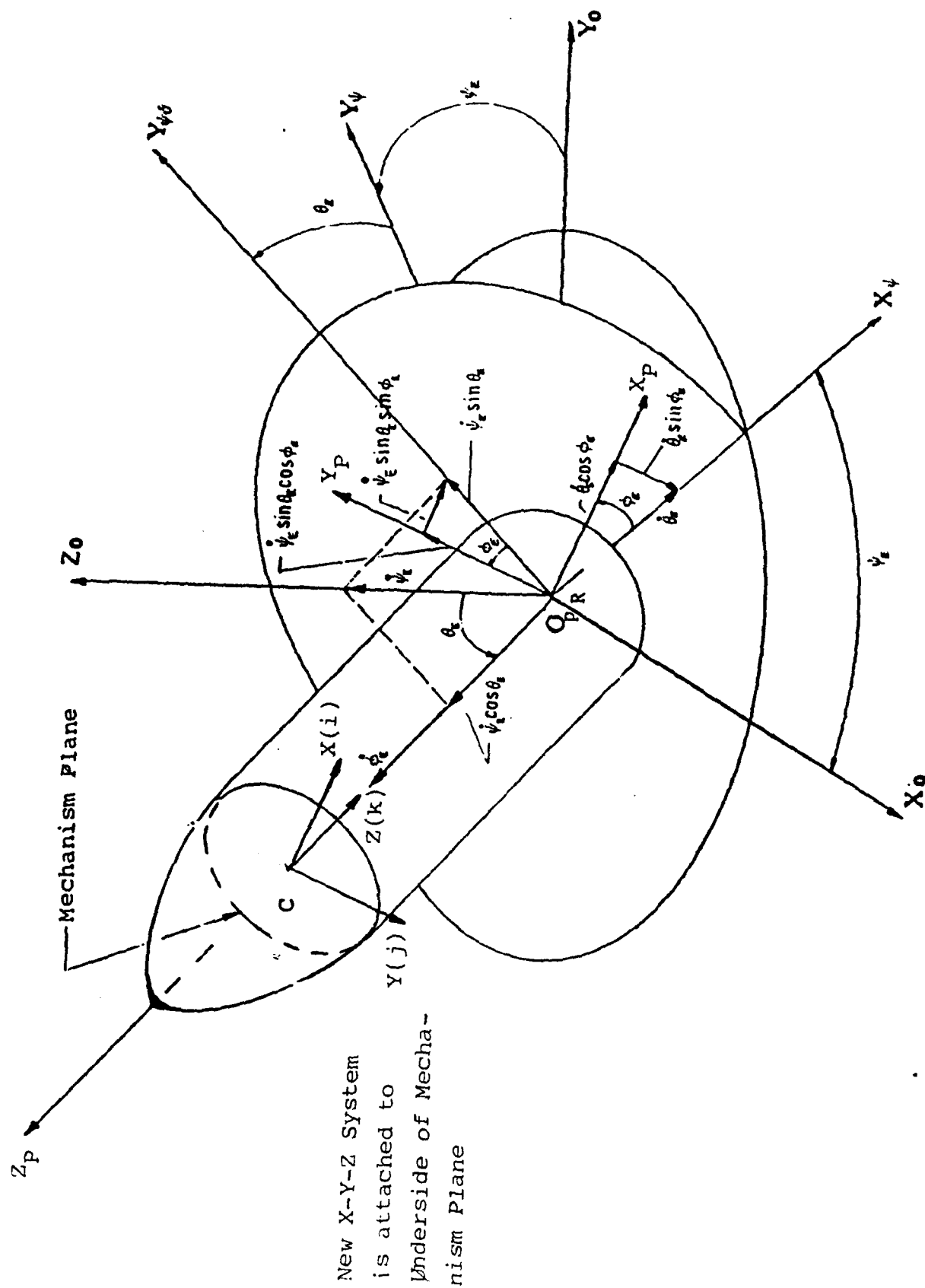


Figure G-1. Relationship of X-Y-Z coordinate system fixed to underside of mechanism plane to aeroballistic coordinate system

$$\omega_{yGEN} = S_8 \omega_y \quad (G-8)$$

$$\omega_{zGEN} = S_8 \omega_z \quad (G-9)$$

and

$$\dot{\omega}_{xGEN} = \dot{\omega}_x \quad (G-10)$$

$$\dot{\omega}_{yGEN} = S_8 \dot{\omega}_y \quad (G-11)$$

$$\dot{\omega}_{zGEN} = S_8 \dot{\omega}_z \quad (G-12)$$

In the above

$$S_8 = +1 \quad (G-13)$$

when equations A-2 to A-8 are applicable, and

$$S_8 = -1 \quad (G-14)$$

when equations G-1 to G-6 are needed.

In addition to the above, the sign of the drag deceleration (first used in equation E-14, ref 1 and given in appendix E of this report) must also be responsive to the location of the S&A with respect to the mechanism plane. Thus

$$\ddot{Z}_{GEN} = -S_8 |\ddot{Z}| \quad (G-15)$$

where $|\ddot{Z}|$ is the absolute value of the projectile drag deceleration. Further

$$S_8 = +1 \quad (G-16)$$

when the S&A is located as in figure C-1 of appendix C of this report, on top of the mechanism plane. When the S&A is located on the underside of the mechanism plane, as shown in figure D-1 of appendix D

$$S_8 = -1 \quad (G-17)$$

in equation G-15.

REFERENCES

1. Tepper, F. R. and Lowen, G. G., "Computer Simulation of Artillery Safing and Arming Mechanism in Aeroballistic Environment (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-83050, ARDC, Dover, NJ, July 1984.

APPENDIX H
PROGRAM AERCLOC

```

1  PROGRAM AERCLOC(INPUT,OUTPUT,TAPES=INPUT,TAPE6=OUTPUT)
2  COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,
3  +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RV,
4  +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,
5  +NP2,NP3,R1,R2,R3,R4,RH01,RH02,RH03,RHOP,J1,J2,GAMMA2,GAMA3P,
6  +GAMMA3,GAMA4P,GAMMA4,GAMMAP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,
7  +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,
8  +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,
9  +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2
10 +,RHOG1,RHOG2,RHOP1,RHOP2,DELPI,DELP2
11 +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FFMX,F23FFMX,
12 +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
13 +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F
14 COMMON /DATA/ RPM
15 COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8
16 COMMON /ZETA/ PSI,TIME,DPSI,GP,PHICUTD
17 COMMON/DATA5/LU,LL,MU,MU1
18 COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1F,LAMDA1,G1,PHIS,
19 +PHI2P,PHI1,PHI2,GAM
20 COMMON/DATA7/DER2F,DER1R,DER1F
21 COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DOONE,U,V,VST,G,P,Q,S
22 COMMON/DATA13/PHISI,PHISFF,PHIST,PH2PI,PH2PFF,PH2PT
23 COMMON/DATA12/X1,X2,X3,X4,X5,X6,X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4,
24 +Y5,Y6,Y7,Y8
25 DIMENSION AUX(8,2),AUX2(8,4),PRMT(5),PHI(2),DPHI(2),X(4),DX(
26 14)
27 REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS,OM0420
28 +,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,
29 +NP2,NP3,N,NT,LX1,LV1,LL1,LX2,LV2,LL2,L1,L2,J1,J2
30 EXTERNAL FCT,OUTP,FCTF,OUTPF
31
32 READ IN AND WRITE DATA
33
34 READ (5,27) A,B,C,ALPHEN,ALPHEX,NT,CONFIG
35 WRITE (6,28) A,B,C,ALPHEN,ALPHEX,NT,CONFIG
36 READ (5,29) EREST,LAMBDA,N
37 WRITE (6,30) EREST,LAMBDA,N
38 READ (5,35) NG1,NG2,NP2,NP3,CAPRP1,CAPRP2,RP2,RP3
39 WRITE (6,38) NG1,NG2,NP2,NP3,CAPRP1,CAPRP2,RP2,RP3
40 READ(5,36)CAPR01,CAPR02,R02,R03
41 WRITE(6,775)CAPR01,CAPR02,R02,R03
42 775 FORMAT(6X,*CAPR01 =*,F8.5,3X,*CAPR02 =*,F8.5,3X,*R02 =*,
43 +F8.5,3X,*R03 =*,F8.5/)
44 READ (5,31) M1,M2,M3,MP
45 WRITE (6,32) M1,M2,M3,MP
46 READ (5,17) IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1
47 WRITE (6,18) IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1
48 READ (5,19) IX2,IY2,IZ2
49 WRITE (6,20) IX2,IY2,IZ2
50 READ (5,19) IXS,IYS,IZS
51 WRITE (6,21) IXS,IYS,IZS
52 READ (5,17) IXXP,IEEP,IZZP,IXEP,IZXP,IEZP
53 WRITE (6,22) IXXP,IEEP,IZZP,IXEP,IZXP,IEZP
54 READ (5,33) RC1,RCP,RHOP,RPM,PHI1RCD,PSICD,PHID,PHICUTD,MU,MU1
55 WRITE (6,34) RC1,RCP,RHOP,RPM,PHI1RCD,PSICD,PHID,PHICUTD,MU,MU1
56 WRITE (5,23) LU,LL
57 WRITE (6,24) LU,LL

```

```

000730 READ (5,29) RHO1,RHO2,RHO3
000740 WRITE (6,40) RHO1,RHO2,RHO3
000750 READ (5,36) RHOF1,RHOF2,RHOF3,RHOF
000760 WRITE (6,25) RHOF1,RHOF2,RHOF3,RHOF
000770 READ(5,29)RHOP1,RHOG1,TCG1
000780 WRITE(6,700)RHOP1,RHOG1,TCG1
000790 READ(5,29)RHOP2,RHOG2,TCG2
000800 WRITE(6,701)RHOP2,RHOG2,TCG2
000810 READ (5,36) R1,R2,R3,R4
000820 WRITE (6,39) R1,R2,R3,R4
000830 CALL GEAR(CAPRP1,CAPRO1,RHOG1,TCG1,AG1,DELG1)
000840 CALL PINION(RP2,RO2,RHOP1,AP1,DELP1,ALPHP1,FP1)
000850 WRITE(6,41)AG1,AP1,ALPHP1,DELP1,DELG1,RHOP1,RHOG1,FP1
000860 41 FORMAT(6X,AG1=*,F6.4,3X,AP1=*,F6.4,3X,ALPHP1=*,
000870 +F7.3,3X,DELP1=*,F7.3,3X,DELG1=*,F7.3/6X, RHOP1=*,
000880 +F7.3,3X, RHOG1=*,F7.3,3X,FP1=*,F6.4/)
000890 CALL GEAR(CAPRP2,CAPRO2,RHOG2,TCG2,AG2,DELG2)
000900 CALL PINION(RP3,RO3,RHOP2,AP2,DELP2,ALPHP2,FP2)
000910 WRITE(6,42)AG2=*,F6.4,3X,AP2=*,F6.4,3X,ALPHP2=*,
000920 +F7.3,3X,DELP2=*,F7.3,3X,DELG2=*,F7.3/6X, RHOP2=*,
000930 +F7.3,3X, RHOG2=*,F7.3,3X,FP2=*,F6.4/)
000940 READ (5,37) J1,J2
000950 WRITE (6,43) J1,J2
000960 READ (5,36) RX,RV,RZ,S8
000970 WRITE (6,26) RX,RV,RZ,S8
000980
000990
001000
001010
001020
001030
001040
001050
001060
001070
001080
001090
001100
001110
001120
001130
001140
001150
001160
001170
001180
001190
001200
001210
001220
001230
001240
001250
001260
001270
001280
001290
001300
001310
001320
001330
001340
001350
001360
001370
001380
001390
001400
001410
001420
001430
001440
001450
001460
001470
001480
001490
001500
001510
001520
001530
001540
001550
001560
001570
001580
001590
001600
001610
001620
001630
001640
001650
001660
001670
001680
001690
001700
001710
001720
001730
001740
001750
001760
001770
001780
001790
001800
001810
001820
001830
001840
001850
001860
001870
001880
001890
001900
001910
001920
001930
001940
001950
001960
001970
001980
001990
002000
002010
002020
002030
002040
002050
002060
002070
002080
002090
002100
002110
002120
002130
002140
002150
002160
002170
002180
002190
002200
002210
002220
002230
002240
002250
002260
002270
002280
002290
002300
002310
002320
002330
002340
002350
002360
002370
002380
002390
002400
002410
002420
002430
002440
002450
002460
002470
002480
002490
002500
002510
002520
002530
002540
002550
002560
002570
002580
002590
002600
002610
002620
002630
002640
002650
002660
002670
002680
002690
002700
002710
002720
002730
002740
002750
002760
002770
002780
002790
002800
002810
002820
002830
002840
002850
002860
002870
002880
002890
002900
002910
002920
002930
002940
002950
002960
002970
002980
002990
003000
003010
003020
003030
003040
003050
003060
003070
003080
003090
003100
003110
003120
003130
003140
003150
003160
003170
003180
003190
003200
003210
003220
003230
003240
003250
003260
003270
003280
003290
003300
003310
003320
003330
003340
003350
003360
003370
003380
003390
003400
003410
003420
003430
003440
003450
003460
003470
003480
003490
003500
003510
003520
003530
003540
003550
003560
003570
003580
003590
003600
003610
003620
003630
003640
003650
003660
003670
003680
003690
003700
003710
003720
003730
003740
003750
003760
003770
003780
003790
003800
003810
003820
003830
003840
003850
003860
003870
003880
003890
003900
003910
003920
003930
003940
003950
003960
003970
003980
003990
004000
004010
004020
004030
004040
004050
004060
004070
004080
004090
004100
004110
004120
004130
004140
004150
004160
004170
004180
004190
004200
004210
004220
004230
004240
004250
004260
004270
004280
004290
004300
004310
004320
004330
004340
004350
004360
004370
004380
004390
004400
004410
004420
004430
004440
004450
004460
004470
004480
004490
004500
004510
004520
004530
004540
004550
004560
004570
004580
004590
004600
004610
004620
004630
004640
004650
004660
004670
004680
004690
004700
004710
004720
004730
004740
004750
004760
004770
004780
004790
004800
004810
004820
004830
004840
004850
004860
004870
004880
004890
004900
004910
004920
004930
004940
004950
004960
004970
004980
004990
005000
005010
005020
005030
005040
005050
005060
005070
005080
005090
005100
005110
005120
005130
005140
005150
005160
005170
005180
005190
005200
005210
005220
005230
005240
005250
005260
005270
005280
005290
005300
005310
005320
005330
005340
005350
005360
005370
005380
005390
005400
005410
005420
005430
005440
005450
005460
005470
005480
005490
005500
005510
005520
005530
005540
005550
005560
005570
005580
005590
005600
005610
005620
005630
005640
005650
005660
005670
005680
005690
005700
005710
005720
00573
```

115	X1=0	001300
	X2=0	001310
	X3=0	001320
	X4=0	001330
	X5=0	001340
120	X6=0	001350
	X7=0	001360
	X8=0	001370
	X9=0	001380
	X10=0	001390
125	X11=0	001400
	X12=0	001410
	Y1=0	001420
	Y2=0	001430
	Y3=0	001440
130	Y4=0	001450
	Y5=0	001460
	Y6=0	001470
	Y7=0	001480
	Y8=0	001490
135	DER1R=0	001500
	DER2R=0	001510
	DER1F=0	001520
	DER2F=0	001530
	S1R=0	001540
140	S1F=0	001550
	S2R=0	001560
	S2F=0	001570
	RY=S8*RY	001575
	RZ=S8*RZ	001576
145	PI=3.14159	001580
	ZZ=PI/180.	001590
	OMEGA=RPM*2.*PI/60.	001600
	OM2=OMEGA*OMEGA	001610
	PHI1RC=PHI1RCD+ZZ	001620
150	PSICC=PSICCD+ZZ	001630
	PSIC=PSICC	001640
	ALPHEN=ALPHEN+ZZ	001650
	ALPHEX=ALPHEX+ZZ	001660
	DELTA=360./N	001670
155	DPHI1=360.*ZZ/NG1	001680
	DPHI2P=360.*ZZ/NP2	001690
	DPHI2=360.*ZZ/NG2	001700
	DPHI5=360.*ZZ/NP3	001710
		001720
160	COMPUTATION OF MESH CURVATURE SUMMATION	001730
		001740
	L1=RHOG1+RHOP1	001750
	L2=RHOG2+RHOP2	001760
		001770
165	COMPUTATION OF MESH CENTER DISTANCES	001780
		001790
	B1=CAPRP1+RP2	001800
	B2=CAPRP2+RP3	001810
		001820
170	DETERMINATION OF SIGNUM FUNCTION S6	001830
		001840


```

175      IF (CONFIG.EQ.1.) S6=1.
      IF (CONFIG.EQ.2.) S6=-1.
      C
      C
      C      COMPUTATION OF GAMMAS AND BETAS
      GAMMA2=S6*ACOS((R1*R1+R2*R2-(CAPRP1*RP2)**2)/(2.*R1*R2))
      GAMA3P=ACOS((R2*R2+R3*R3-(CAPRP2*RP3)**2)/(2.*R2*R3))
      GAMMA3=GAMMA2+S6*GAMA3P
      GAMA4P=ACOS((R3*R3+R4*R4-A*A)/(2.*R3*R4))
      GAMMA4=GAMMA3+S6*GAMA4P
      GAMMA2D=GAMMA2/ZZ
      GAMMA3D=GAMMA3/ZZ
      GAMMA4D=GAMMA4/ZZ
      DELTA2=ACOS(((CAPRP1*RP2)**2+R1*R1-R2*R2)/(2.*R1*(CAPRP1+RP2)))
      DELTA3=ACOS(((CAPRP2*RP3)**2+R2*R2-R3*R3)/(2.*R2*(CAPRP2+RP3)))
      DELTA4=ACOS((A*A+R3*R3-R4*R4)/(2.*A*R3))
      BETA1=PI-S6*DELTA2
      BETA2=GAMMA2+PI-S6*DELTA3
      BETA3=GAMMA3+PI-S6*DELTA4
      IF (CONFIG.EQ.1.) GAMAPP=DELTA4+GAMA4P
      IF (CONFIG.EQ.2.) GAMAPP=2.*PI-DELTA4-GAMA4P
      BETA1D=BETA1/ZZ
      BETA2D=BETA2/ZZ
      BETA3D=BETA3/ZZ
      WRITE (6,44) BETA1D,BETA2D,BETA3D,GAMMA2D,GAMMA3D,GAMMA4D
      C
      C      PRELIMINARY COMPUTATIONS FOR MESH 1
      C
      C      DETERMINATION OF TRANSITION ANGLES FOR MESH 1
      C
      A1T=-RHOG1+COS(BETA1-ALPHP1)+FP1*SIN(BETA1-ALPHP1)
      B1T=RHOG1+SIN(BETA1-ALPHP1)+FP1*COS(BETA1-ALPHP1)
      C1T=(AG1**2-RHOG1**2-B1**2-FP1**2)/(2.*B1)
      ROOT1T=A1T**2+B1T**2-C1T**2
      Y1T1=A1T+SQRT(ROOT1T)
      Y1T2=A1T-SQRT(ROOT1T)
      X1T=B1T+C1T
      PH2PT1=2.*ATAN2(Y1T1,X1T)
      IF (PH2PT1.LT.O)PH2PT1=PH2PT1+2.*PI
      PH2PT2=2.*ATAN2(Y1T2,X1T)
      IF (PH2PT2.LT.O)PH2PT2=PH2PT2+2.*PI
      CALL TRANS1(RHOG1,ALPHP1,BETA1,FP1,AG1,B1,DELG1,ZZ,PH2PT1,PH1T1,
      +G11)
      IF (G11.GT.FP1)GO TO 51
      PH1T=PH1T1
      PH2PT=PH2PT1
      GO TO 53
51 CALL TRANS1(RHOG1,ALPHP1,BETA1,FP1,AG1,B1,DELG1,ZZ,PH2PT2,PH1T2,
      +G12)
      IF (G12.LT.FP1)GO TO 52
      WRITE(6,75)
      STOP
75 FORMAT(*SOMETHING IS WRONG WITH MESH 1*)
52 PH1T=PH1T2
      PH2PT=PH2PT2
53 PH1TD=PH1T/ZZ
      PH2PTD=PH2PT/ZZ

```

09/27/89 15.21.25

FTN 4.8+650

PROGRAM AERCLOC 74/860 OPT=1

```

230      WRITE(6, 76)PHI1TD,PH2PTD
        76 FORMAT(6X,*,PHI1TD=*,F7.3,5X,*,PH2PTD=*,F7.3)
        C
        C      DETERMINATION OF CORRECT SIGN FOR FORWARD ROUND-ON-FLAT
        C      REGIME OF MESH 1
        C
235      A1F=AG1+COS(PHI1T-DELG1-ALPHP1)-B1+COS(BETA1-ALPHP1)
        B1F=-AG1+SIN(PHI1T-DELG1-ALPHP1)+B1+SIN(BETA1-ALPHP1)
        C1F=-RHOG1
        ROOT1F=A1F**2+B1F**2-C1F**2
        Y1F=A1F+SQRT(ROOT1F)
        Y1F2=A1F-SQRT(ROOT1F)
        X1F=B1F+C1F
        PH2PF1=2.*ATAN2(Y1F1,X1F)
        PH2PF2=2.*ATAN2(Y1F2,X1F)
        IF(PH2PF1.LT.O)PH2PF1=PH2PF1+2.*PI
        IF(PH2PF2.LT.O)PH2PF2=PH2PF2+2.*PI
        IF(ABS(PH2PF1-PH2PT).LT.ABS(PH2PF2-PH2PT))GO TO 54
        SIGN1F=-1.
        GO TO 55
        54 SIGN1F=1.
        C
250      C      LATEST AND EARLIEST POSSIBLE VALUES OF PHI1 AND PHI2P FOR MESH 1
        C
        C
255      55 DO 56 I=1,2000
        PH1D1=PHI1TD+(I-1.)/100.
        PH11=PH1D1+ZZ
        A1F=AG1+COS(PHI1-DELG1-ALPHP1)-B1+COS(BETA1-ALPHP1)
        B1F=-AG1+SIN(PHI1-DELG1-ALPHP1)+B1+SIN(BETA1-ALPHP1)
        C1F=-RHOG1
        ROOT1F=A1F**2+B1F**2-C1F**2
        Y1F=A1F+SIGN1F*SQRT(ROOT1F)
        X1F=B1F+C1F
        PH2PF=2.*ATAN2(Y1F,X1F)
        LX1=B1+COS(BETA1)+AP1+COS(PH2PF+DPHI2P-DELP1)-AG1+COS(PHI1-DPHI1-
        1DELG1)
        LY1=B1+SIN(BETA1)+AP1+SIN(PH2PF+DPHI2P-DELP1)-AG1+SIN(PHI1-DPHI1-
        1DELG1)
        LL1=SQRT(LX1**2+LY1**2)
        DELEL1=LL1-L1
        IF(DELEL1.LE.O)GO TO 57
        56 CONTINUE
        57 PH11F=PHI1
        PH2PFF=PH2PF
        IF(PH2PFF-PH2PT.GT..001)PH2PFF=PH2PFF-2.*PI
        PH111=PH11F-DPHI1
        PH2P11=PH2PFF+DPHI2P
        PH11ID=PH111/ZZ
        PH2PID=PH2P11/ZZ
        PH11FD=PH11F/ZZ
        PH2PFD=PH2PFF/ZZ
        WRITE(6,77)PHI1ID,PH2PID,PH11FD,PH2PFD
280      77 FORMAT(6X,*,PHI1ID=*,F7.3,5X,*,PH2PID=*,F7.3,5X,*,PH11FD=*,
        +F7.3,5X,*,PH2PFD=*,F7.3)
        C
        C      DETERMINATION OF CORRECT SIGN FOR FORWARD ROUND-ON-ROUND REGIME
        C      OF MESH 1
285

```

```

C
290      A1R=B1*SIN(BETA1+DELP1)-AG1*SIN(PHI11-DELGI+DELP1)
        B1R=B1*COS(BETA1+DELP1)-AG1*COS(PHI11-DELGI+DELP1)
        C1R=(L1**2-B1**2-AG1**2-AP1**2+2.*AG1*B1*COS(PHI11-DELGI-BETA1))/
        +(2.*AP1)
        ROOT1R=A1R**2+B1R**2-C1R**2
        Y1R1=A1R*SORT(ROOT1R)
        Y1R2=A1R-SORT(ROOT1R)
        X1R=B1R+C1R
        PH2PR1=2.*ATAN2(Y1R1,X1R)
        PH2PR2=2.*ATAN2(Y1R2,X1R)
        IF(PH2PR1.LT.O)PH2PR1=PH2PR1+2.*PI
        IF(PH2PR2.LT.O)PH2PR2=PH2PR2+2.*PI
        IF(ABS(PH2PI-PH2PR1).LT.ABS(PH2PI-PH2PR2))GO TO 58
        SIGN1R=-1.
        GO TO 59
58      SIGN1R=1.
C
305      REVERSE KINEMATICS OF MESH 1
C
        DETERMINATION OF CORRECT SIGN FOR REVERSE ROUND-ON-ROUND REGIME
        FOR MESH 1
C
310      D1R=-2.*AG1*(AP1+SIN(PH2PI+DELGI-DELP1)+B1*SIN(BETA1+DELGI))
        E1R=-2.*AG1*(AP1+COS(PH2PI+DELGI-DELP1)+B1*COS(BETA1+DELGI))
        F1R=L1**2-AG1**2-AP1**2-B1**2-2.*AP1*B1*COS(PH2PI-BETA1-DELP1)
        ROOT1R=D1R**2+E1R**2-F1R**2
        Y1R1=D1R*SORT(ROOT1R)
        Y1R2=D1R-SORT(ROOT1R)
        X1R=E1R+F1R
        PHI1R1=2.*ATAN2(Y1R1,X1R)
        PHI1R2=2.*ATAN2(Y1R2,X1R)
        IF(PHI1R1.LT.O)PHI1R1=PHI1R1+2.*PI
        IF(PHI1R2.LT.O)PHI1R2=PHI1R2+2.*PI
        IF(ABS(PHI11-PHI1R1).LT.ABS(PHI11-PHI1R2))GO TO 60
        RSGN1R=-1.
        GO TO 61
60      RSGN1R=1.
C
325      DETERMINATION OF CORRECT SIGN FOR REVERSE ROUND-ON-FLAT REGIME
        FOR MESH 1
C
330      D1F=-AG1*COS(PH2PFF+ALPHP1+DELGI)
        E1F=AG1*SIN(PH2PFF+ALPHP1+DELGI)
        F1F=-RHOG1+B1*SIN(PH2PFF+ALPHP1-BETA1)
        ROOT1F=D1F**2+E1F**2-F1F**2
        Y1F1=D1F*SORT(ROOT1F)
        Y1F2=D1F-SORT(ROOT1F)
        X1F=E1F+F1F
        PHI1F1=2.*ATAN2(Y1F1,X1F)
        PHI1F2=2.*ATAN2(Y1F2,X1F)
        IF(PHI1F1.LT.O)PHI1F1=PHI1F1+2.*PI
        IF(PHI1F2.LT.O)PHI1F2=PHI1F2+2.*PI
        IF(ABS(PHI1F1-PHI1F) .LT.ABS(PHI1F2-PHI1F))GO TO 62
        RSGN1F=-1.
        GO TO 63
62      RSGN1F=1.

```

09/27/89 15.21.25

FTN 4.8+650

PROGRAM AERCLOC 74/860 OPT=1

```

345 C      PRELIMINARY COMPUTATIONS FOR MESH 2
345 C
345 C      DETERMINATION OF TRANSITION ANGLES FOR MESH 2
345 C
350 63 A2T=RHOG2*COS(BETA2+ALPHP2)+FP2*SIN(BETA2+ALPHP2)
350 B2T=-RHOG2*SIN(BETA2+ALPHP2)+FP2*COS(BETA2+ALPHP2)
350 C2T=(AG2**2-RHOG2**2-B2**2-FP2**2)/(2.*B2)
350 ROOT2T=A2T**2+B2T**2-C2T**2
350 Y2T1=A2T+SORT(ROOT2T)
350 Y2T2=A2T-SORT(ROOT2T)
350 X2T=B2T+C2T
355 PHIST1=2.*ATAN2(Y2T1,X2T)
355 PHIST2=2.*ATAN2(Y2T2,X2T)
355 IF(PHIST1.LT.O)PHIST1=PHIST1+2.*PI
355 IF(PHIST2.LT.O)PHIST2=PHIST2+2.*PI
355 CALL TRANS2(RHOG2,ALPHP2,BETA2,FP2,AG2,B2,DELG2,ZZ,PHIST1,PHIST2,
360 +G21)
360 IF(G21.GT.FP2)GO TO 64
360 PHIST=PHIST1
360 PHIST=PHIST1
360 GO TO 66
365 64 CALL TRANS2(RHOG2,ALPHP2,BETA2,FP2,AG2,B2,DELG2,ZZ,PHIST2,PHIST2,
365 +G22)
365 IF(G22.LT.FP2)GO TO 65
365 WRITE(6,72)
365 STOP
370 72 FORMAT(*SOMETHING IS WRONG WITH MESH 2*)
370 65 PHIST=PHIST2
370 PHIST=PHIST2
370 PHISTD=PHIST/ZZ
370 WRITE(6,73)PHISTD,PHISTD
370 73 FORMAT(6X,PHISTD=*,F7.3,5X,PHISTD=*,F7.3)
370 C
370 C      DETERMINATION OF CORRECT SIGN FOR FORWARD ROUND-ON-FLAT REGIME
370 C      FOR MESH 2
370 C
380 A2F=AG2*COS(PHIST2+DELG2+ALPHP2)-B2*COS(BETA2+ALPHP2)
380 B2F=-AG2*SIN(PHIST2+DELG2+ALPHP2)+B2*SIN(BETA2+ALPHP2)
380 C2F=RHOG2
380 ROOT2F=A2F**2+B2F**2-C2F**2
380 Y2F1=A2F+SORT(ROOT2F)
380 Y2F2=A2F-SORT(ROOT2F)
380 X2F=B2F+C2F
380 PHISF1=2.*ATAN2(Y2F1,X2F)
380 PHISF2=2.*ATAN2(Y2F2,X2F)
380 IF(PHISF1.LT.O)PHISF1=PHISF1+2.*PI
380 IF(PHISF2.LT.O)PHISF2=PHISF2+2.*PI
380 IF(ABS(PHISF1-PHIST).LT.ABS(PHISF2-PHIST))GO TO 67
380 SIGN2F=-1.
380 GO TO 68
380 67 SIGN2F=1.
380 C
380 C      LATEST AND EARLIEST POSSIBLE VALUES OF PHIST AND PHIS FOR MESH 2
380 C
380 C      68 DO 69 I=1,2000
380 C

```

400	PHI2D=PHI2D-(I-1.)/100. PHI2=PHI2+Z A2F=AG2+COS(PHI2+DELG2+ALPHP2)-B2+COS(BETA2+ALPHP2) B2F=-AG2+SIN(PHI2+DELG2+ALPHP2)+B2+SIN(BETA2+ALPHP2) C2F=RHOG2 ROOT2F=A2F**2+B2F**2-C2F**2 Y2F=A2F+SIGN2F*SQRT(ROOT2F) X2F=B2F+C2F PHISF=2.*ATAN2(Y2F,X2F) LX2=B2+COS(BETA2)+AP2+COS(PHISF-DPHIS*DELP2)-AG2+COS(PHI2+DPHI2+DELG2) LY2=B2+SIN(BETA2)+AP2+SIN(PHISF-DPHIS*DELP2)-AG2+SIN(PHI2+DPHI2+DELG2) LL2=SQRT(LX2**2+LY2**2) DELEL2=LL2-L2 IF(DELEL2.LE.O)GO TO 70 69 CONTINUE 70 PHI2F=PHI2 PHISFF=PHISF IF(PHISF-PHISFF.GT..001)PHISFF=PHISF+.2.*PI PHI2I=PHI2F+DPHI2 PHISI=PHISFF-DPHIS PHI2ID=PHI2I/ZZ PHISID=PHISI/ZZ PHI2FD=PHI2F/ZZ PHISFD=PHISF/ZZ WRITE(6,74)PHI2ID,PHISID,PHI2FD,PHISFD 74 FORMAT(6X,'PHI2ID =*,F7.3,5X,'PHISID =*,F7.3,5X, +PHI2FD =*,F7.3,5X,'PHISFD =*,F7.3)	004130 004140 004150 004160 004170 004180 004190 004200 004210 004220 004230 004240 004250 004260 004270 004280 004290 004300 004310 004320 004330 004340 004350 004360 004370 004380 004390 004400 004410 004420 004430 004440 004450 004460 004470 004480 004490 004500 004510 004520 004530 004540 004550 004560 004570 004580 004590 004600 004610 004620 004630 004640 004650 004660 004670
405		
410		
415		
420		
425		
430	DETERMINATION OF CORRECT SIGN FOR FORWARD ROUND-ON-ROUND REGIME OF MESH 2	004430 004440 004450 004460 004470 004480 004490 004500 004510 004520 004530 004540 004550 004560 004570 004580 004590 004600 004610 004620 004630 004640 004650 004660 004670
435	A2R=AG2+SIN(PHI21+DELG2-DELP2)-B2*SIN(BETA2-DELP2) B2R=AG2+COS(PHI21+DELG2-DELP2)-B2*COS(BETA2-DELP2) C2R=(AP2**2+AG2**2+B2**2-L2**2-.2.*AG2*B2+COS(PHI21+DELG2-BETA2))/ (2.*AP2) ROOT2R=A2R**2+B2R**2-C2R**2 Y2R1=A2R+SQRT(ROOT2R) Y2R2=A2R-SQRT(ROOT2R) X2R=B2R+C2R PHISR1=2.*ATAN2(Y2R1,X2R) PHISR2=2.*ATAN2(Y2R2,X2R) IF(PHISR1.LT.O)PHISR1=PHISR1+2.*PI IF(PHISR2.LT.O)PHISR2=PHISR2+2.*PI IF(ABS(PHIS1-PHISR1).LT.ABS(PHIS1-PHISR2))GO TO 71 SIGN2R=-1. GO TO 82 71 SIGN2R=1.	004430 004440 004450 004460 004470 004480 004490 004500 004510 004520 004530 004540 004550 004560 004570 004580 004590 004600 004610 004620 004630 004640 004650 004660 004670
440	REVERSE KINEMATICS OF MESH 2	004620 004630 004640 004650 004660 004670
445	DETERMINATION OF CORRECT SIGN FOR REVERSE ROUND-ON-ROUND REGIME FOR MESH 2	004650 004660 004670
450		
455	D2R=-2.*AP2+AG2+SIN(PHI21+DELG2-DELP2)-2.*AG2*B2+SIN(BETA2-DELP2) E2R=-2.*AP2+AG2+COS(PHI21+DELG2-DELP2)-2.*B2+COS(BETA2-DELP2)	004680 004690

09/27/89 15.21.25

FTN 4.8+650

PROGRAM AERCLOC 74/860 OPT=1

```

460      F2R=L2**2-AG2**2-AP2**2-B2**2-2.*AP2*B2+COS(PHIS1+DELP2-BETA2)
      ROOT2R=D2R**2+E2R**2-F2R**2
      Y2R1=D2R+SQRT(ROOT2R)
      Y2R2=D2R-SQRT(ROOT2R)
      X2R=E2R+F2R
      PHI2R1=2.*ATAN2(Y2R1,X2R)
      PHI2R2=2.*ATAN2(Y2R2,X2R)
      IF(PHI2R1.LT.O)PHI2R1=PHI2R1+2.*PI
      IF(PHI2R2.LT.O)PHI2R2=PHI2R2+2.*PI
      WRITE(6,666)PHI21,PHI2R1,PHI2R2
666      FORMAT(*,PHI21=*,E12.4,3X,PHI2R1=*,E12.4,3X,PHI2R2=*,E12.4)
      IF(ABS(PHI21-PHI2R1).LT.(PHI21-PHI2R2))GO TO 83
      RSGN2R=-1.
      GO TO 84
83      RSGN2R=1.
      C
      C
      C
      C
475      DETERMINATION OF CORRECT SIGN FOR REVERSE ROUND-ON-FLAT REGIME
      FOR MESH 2
      C
      C
      C
480      84 D2F=-AG2+COS(PHISFF-ALPHP2-DELG2)
      E2F=AG2*SIN(PHISFF-ALPHP2-DELG2)
      F2F=RHOG2+B2*SIN(PHISFF-ALPHP2-BETA2)
      ROOT2F=D2F**2+E2F**2-F2F**2
      Y2F1=D2F+SQRT(ROOT2F)
      Y2F2=D2F-SQRT(ROOT2F)
      X2F=E2F+F2F
      PHI2F1=2.*ATAN2(Y2F1,X2F)
      PHI2F2=2.*ATAN2(Y2F2,X2F)
      IF(PHI2F1.LT.O)PHI2F1=PHI2F1+2.*PI
      IF(PHI2F2.LT.O)PHI2F2=PHI2F2+2.*PI
      IF(ABS(PHI2F1-PHI2F).LT.ABS(PHI2F2-PHI2F))GO TO 85
      RSGN2F=-1.
      GO TO 86
85      RSGN2F=1.
      C
      C
      C
      C
495      DATA FOR RUNGE KUTTA
      86 DIFF1=PH2PFF-PH2P1
      PHI2P=J1*DIFF1+PH2P1
      DIFF2=PHISFF-PHIS1
      PHIS=J2*DIFF2+PHIS1
      ALPHR=ALPHEN
      PRMT(2)=3.
      PRMT(4)=.01
      NDIM=2
      NDIM2=4
      PHI(1)=PHID*ZZ
      PHI(2)=O
      C
      C
      C
      C
505      COUPLED MOTION
      C
      C
      C
      C
510      1 PRMT(1)=TIME
      PRMT(3)=.00001
      DPHI(1)=.5
      DPHI(2)=.5
      IF(PHITOT.GT.30..AND.PHITOT.LT.1450.)GO TO 2
      WRITE(6,45)

```

```

515      2 CALL RKGS(PRMT,PHI,DPHI,NDIM,IHLF,FCT,OUTP,AUX)
      IF (PHITOT.GT.PHICUTD)GO TO 16
      C
      C
      C
      TEST FOR ENTRANCE OR EXIT ACTION
      IF (PN.LE.O)GO TO 5
      PHID=PHI(1)/ZZ
      IF (PHID.GE.130..AND.PHID.LE.160.)GO TO 3
      GO TO 4
      3 PHI(1)=PHI(1)+DELTA*ZZ*NT
      PHIPR=PHI(1)/ZZ
      PSI=PSI+2.*PI-LAMBDA*ZZ
      PSIC=PSICC+LAMBDA*ZZ
      ALPHR=ALPHEX
      GO TO 5
      4 PHI(1)=PHI(1)-DELTA*ZZ*(NT+1.)
      PHIPR=PHI(1)/ZZ
      PSI=PSI-2.*PI+LAMBDA*ZZ
      ALPHR=ALPHEN
      PSIC=PSICC
      C
      C
      C
      FREE MOTION
      5 PRMT(1)=TIME
      X(1)=PHI(1)
      X(2)=PHI(2)
      X(3)=PSI
      X(4)=DPSI
      DX(1)=.25
      DX(2)=.25
      DX(3)=.25
      DX(4)=.25
      PRMT(3)=.00001
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 6
      WRITE (6,46)
      6 CALL RKGS (PRMT,X,DX,NDIM2,IHLF,FCTF,OUTPF,AUX2)
      IF (PHITOT.GT.PHICUTD) GO TO 16
      PHI(1)=X(1)
      PHI(2)=X(2)
      PSI=X(3)
      DPSI=X(4)
      G=(8*SIN(PHI(1))-C*SIN(PSI))/SIN(PSI+ALPHR)
      PHID=PHI(1)/ZZ
      IF (PHID.LT.160..AND.GP.GT.O.) GO TO 10
      IF (PHID.GT.160..AND.GP.LT.O.) GO TO 8
      IF (PHID.LT.160.) GO TO 7
      PHI(1)=PHI(1)-DELTA*ZZ*(NT+1.)
      PHIPR=PHI(1)/ZZ
      PSI=PSI-2.*PI+LAMBDA*ZZ
      PSIC=PSICC
      GO TO 5
      7 PHI(1)=PHI(1)+DELTA*ZZ*NT
      PHIPR=PHI(1)/ZZ
      PSI=PSI+2.*PI-LAMBDA*ZZ
      PSIC=PSICC+LAMBDA*ZZ
      GO TO 5
      C
      C
      C

```

```

575      C      EXIT ACTION
      C      COMPUTATION OF VELOCITIES VP AND VS FOR EXIT ACTION
      C
      8 VP=DPSI*(C*COS(ALPHR))+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 9
      WRITE (6,47) VP,VS
      C
580      C      EXIT ACTION TESTS
      C
      9 IF (PHI(2).GE.O..AND.DPSI.GE.O.) GO TO 12
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 12
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.LE.O.) GO TO 5
      C
590      C      COMPUTATION OF VELOCITIES VP AND VS FOR ENTRANCE ACTION
      C
      10 VP=DPSI*(C*COS(ALPHR))+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 11
      WRITE (6,47) VP,VS
      C
600      C      ENTRANCE ACTION
      C
      11 IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.GE.O.) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.LE.O.) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      C
605      C      IMPACT
      C
      12 CALL IMPACT (PHI(1),PHI(2),PSI,DPSI)
      IF (TIME.GT.5.0) GO TO 16
      C
610      C      TEST FOR EXIT ACTION
      C
      PHID=PHI(1)/ZZ
      IF (PHID.LE.160.0) GO TO 14
      C
615      C      EXIT ACTION
      C
      COMPUTATION OF VELOCITIES VP AND VS FOR EXIT ACTION
      VP=DPSI*(C*COS(ALPHR))+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 13
      WRITE (6,47) VP,VS
      C
620      C      13 IF (ABS(ABS(VP)-ABS(VS)).LT.2.0) GO TO 1
      C
625      C

```



```

C
C
630      EXIT ACTION TESTS
        IF (PHI(2).GE.O..AND.DPSI.GE.O.) GO TO 1
        IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
        IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 1
        IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
        IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
        IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).GT.ABS(VS)) GO TO 1
        IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
        IF (PHI(2).LE.O..AND.DPSI.LE.O.) GO TO 5
        006410
        006420
        006430
        006440
        006450
        006460
        006470
        006480
        006490
        006500
        006510
        006520
        006530
        006540
        006550
        006560
        006570
        006580
        006590
        006600
        006610
        006620
        006630
        006640
        006650
        006660
        006670
        006680
        006690
        006700
        006710
        006720
        006730
        006740
        006750
        006760
        006770
        006780
        006790
        006800
        006810
        006820
        006830
        006840
        006850
        006860
        006870
        006880
        006890
        006900
        006910
        006920
        006930
        006940
        006950
        006960

C
C
640      COMPUTATION OF VELOCITIES VP AND VS FOR ENTRANCE ACTION
        14 VP=DPSI*(C+COS(ALPHR))+G)
        VS=PHI(2)*B+COS(PHI(1)-PSI-ALPHR)
        IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 15
        WRITE (6,47) VP,VS
        15 IF (ABS(ABS(VP)-ABS(VS)).LT.2.O) GO TO 1
        006410
        006420
        006430
        006440
        006450
        006460
        006470
        006480
        006490
        006500
        006510
        006520
        006530
        006540
        006550
        006560
        006570
        006580
        006590
        006600
        006610
        006620
        006630
        006640
        006650
        006660
        006670
        006680
        006690
        006700
        006710
        006720
        006730
        006740
        006750
        006760
        006770
        006780
        006790
        006800
        006810
        006820
        006830
        006840
        006850
        006860
        006870
        006880
        006890
        006900
        006910
        006920
        006930
        006940
        006950
        006960

C
C
650      ENTRANCE ACTION TESTS
        IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
        IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 1
        IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
        IF (PHI(2).LE.O..AND.DPSI.GE.O.) GO TO 5
        IF (PHI(2).LE.O..AND.DPSI.LE.O.) GO TO 1
        IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 1
        IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
        IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
        16 TURNS=RPM*TIME/60.
        WRITE(6,48)F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,
        +F12FRMX,F23FFMX,F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
        +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PNMAX,TURNS
        STOP
        006410
        006420
        006430
        006440
        006450
        006460
        006470
        006480
        006490
        006500
        006510
        006520
        006530
        006540
        006550
        006560
        006570
        006580
        006590
        006600
        006610
        006620
        006630
        006640
        006650
        006660
        006670
        006680
        006690
        006700
        006710
        006720
        006730
        006740
        006750
        006760
        006770
        006780
        006790
        006800
        006810
        006820
        006830
        006840
        006850
        006860
        006870
        006880
        006890
        006900
        006910
        006920
        006930
        006940
        006950
        006960

C
C
660      17 FORMAT (6E12.4)
        18 FORMAT (1H,5X,6H1XX1 =,E13.4,3X,6H1EE1 =,E13.4,3X,6H1ZZ1 =,E13.4,
        13X,6H1XE1 =,E13.4,3X,6H1ZX1 =,E13.4,3X,6H1EZ1 =,E13.4/)
        19 FORMAT (3E12.4)
        20 FORMAT (1H,5X,5H1X2 =,E13.4,3X,5H1Y2 =,E13.4,3X,5H1Z2 =,E13.4/)
        21 FORMAT (1H,5X,5H1XS =,E13.4,3X,5H1YS =,E13.4,3X,5H1ZS =,E13.4/)
        22 FORMAT (1H,5X,6H1XXP =,E13.4,3X,6H1EHP =,E13.4,3X,6H1ZZP =,E13.4,
        13X,6H1XEP =,E13.4,3X,6H1ZXP =,E13.4,3X,6H1EZX =,E13.4/)
        23 FORMAT (2F10.5)
        24 FORMAT (6X,4H1U =,F5.3,3X,4H1L =,F5.3/)
        25 FORMAT (6X,7HRHOF1 =,F6.4,3X,7HRHOF2 =,F6.4,3X,7HRHOF3 =,F6.4,3X,6O6880
        1HRHOF =,F6.4/)
        26 FORMAT(6X,4HRX =,F8.3,3X,4HRY =,F8.3,3X,4HRZ =,F8.3,3X,
        +4HS8 =,F4.O/)
        27 FORMAT (7F10.5)
        28 FORMAT (1H,5X,2HA =,F13.5,5X,2HB =,F13.5,5X,2HC =,F13.5,5X,7HALPHEN=006920
        1,F9.4,5X,7HALPHEX =,F9.4//6X,3HNT =,F3.O,5X,8HCONFIG =,F3.O/)
        29 FORMAT (4F10.5)
        30 FORMAT (1H,5X,6HEREST =,F5.2,3X,7HLAMBDA =,F8.3,3X,3HN =,F4.O/)
        31 FORMAT (4E12.5)
        006410
        006420
        006430
        006440
        006450
        006460
        006470
        006480
        006490
        006500
        006510
        006520
        006530
        006540
        006550
        006560
        006570
        006580
        006590
        006600
        006610
        006620
        006630
        006640
        006650
        006660
        006670
        006680
        006690
        006700
        006710
        006720
        006730
        006740
        006750
        006760
        006770
        006780
        006790
        006800
        006810
        006820
        006830
        006840
        006850
        006860
        006870
        006880
        006890
        006900
        006910
        006920
        006930
        006940
        006950
        006960

```

```

685 32 FORMAT (1H, 5X, 4HM1 =, E15.5, 3X, 4HM2 =, E15.5, 3X, 4HM3 =, E15.5, 3X, 4HMO06970
    1P =, E15.5/)
    33 FORMAT (7F10.4/3F10.4)
    34 FORMAT (6X, 5HRC1 =, F7.4, 3X, 5HRCP =, F7.4, 3X, 6HRHDP =, F7.4, 3X, 5HRPM 007000
    +, F6.0, 3X, 9PHI1RCD =, F9.4, 3X, 8HPSICCD =, F9.4, 3X, 6HPHID =, F9.4//6X007010
    2, 9PHICUTD =, F6.0//6X, 4HMU =, F4.2, 3X, 5HMU1 =, F4.2/)
    35 FORMAT(4F10.4/4F10.4)
    36 FORMAT(4F10.4)
    37 FORMAT(2F10.2)
    38 FORMAT(1H, 5X, *NG1 =*, F4.0
    1, 3X, 5HNG2 =, F4.0, 3X, 5HNP2 =, F4.0, 3X, 5HNP3 =, F4.0//6X, 8HCAPRP1 =, F8.007070
    +, 5, 3X, *CAPRP2 =*, F8.5//6X, *RP2 =*, F8.5, 3X, *RP3 =*, F8.5/)
    39 FORMAT (6X, 4HR1 =, F7.5, 3X, 4HR2 =, F7.5, 3X, 4HR3 =, F7.5, 3X, 4HR4 =, F7.007090
    15/)
    40 FORMAT (6X, 6HRH01 =, F7.5, 3X, 6HRH02 =, F7.5, 3X, 6HRH03 =, F7.5/)
    43 FORMAT (1H, 5X, 4HJ1 =, F4.2, 3X, 4HJ2 =, F4.2/)
    44 FORMAT (6X, 8HBETA1D =, F7.2, 3X, 8HBETA2D =, F7.2, 3X, 8HBETA3D =, F7.2/6007130
    1X, 9HGAMMA2D =, F7.2, 3X, 9HGAMMA3D =, F7.2, 3X, 9HGAMMA4D =, F7.2)
    45 FORMAT (1H, 5X, 14HCOUPLED MOTION)
    46 FORMAT (1H, 5X, 11HFREE MOTION//)
    47 FORMAT (4H0VP=, F8.3, 3X, 3HVS=, F8.3)
    48 FORMAT(1H, 6X, *F23RRMX =*, F6.2, 3X, *F12RRMX =*, F6.2/1H, 6X,
    +*F23RFMX =*, F6.2, 3X, *F12RFMX =*, F6.2/1H, 6X, *F23FRMX =*, F6.2,
    +3X, *F12FRMX =*, F6.2/1H, 6X, *F23FFMX =*, F6.2, 3X, *F12FFMX =*,
    +F6.2/1H, 6X, *T23RRMX =*, F6.2, 3X, *T12RRMX =*, F6.2/1H, 6X,
    +*T23RFMX =*, F6.2, 3X, *T12RFMX =*, F6.2/1H, 6X, *T23FRMX =*,
    +F6.2, 3X, *T12FRMX =*, F6.2/1H, 6X, *T23FFMX =*, F6.2, 3X,
    +*T12FFMX =*, F6.2/1H, 6X, *PNMAX =*, F6.2//1H, 6X,
    +*NUMBER OF TURNS TO ARM =*, F8.3)
    END
700 710
705

```

```

1  SUBROUTINE ACCEL (RX,RY,RZ,GAMMA2,GAMMA3,GAMAPP,R1,R2,R3,R4,BETA3,007270
    IGX,GY,GZ,HX,HY,HZ,KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ,0X,OY,OZ,PX,007280
    +PY,PZ,QX,QY,QZ,T,DDZ)
    COMMON /DATA/ RPM
5  COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8
    REAL KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ
    CALL AERO(RPM,T,DDZ)
    GX=(OMY*RY+OMZ*RZ)*OMX-(OMY**2+OMZ**2)*RX+(DOMY*RZ-DOMZ*RY)
    GY=(OMX*RX+OMZ*RZ)*OMY-(OMX**2+OMZ**2)*RY+(DOMZ*RX-DOMY*RZ)
10  GZ=(OMX*RX+OMY*RY)*OMZ-(OMX**2+OMY**2)*RZ+(DOMX*RY-DOMY*RX)+DDZ
    R4X=-R4+COS(GAMAPP+BETA3)
    R4Y=-R4+SIN(GAMAPP+BETA3)
    HX=OMY*OMX*R4Y-(OMY**2+OMZ**2)*R4X-DOMZ*R4Y
    HY=OMX*OMY*R4X-(OMX**2+OMZ**2)*R4Y+DOMZ*R4X
15  HZ=(OMX*R4X+OMY*R4Y)*OMZ+(DOMX*R4Y-DOMY*R4X)
    KX=-(GX+HX)*COS(BETA3)-(GY+HY)*SIN(BETA3)
    KY=(GX+HX)*SIN(BETA3)-(GY+HY)*COS(BETA3)
    KZ=GZ+HZ
    R3X=R3+COS(GAMMA3)
    R3Y=R3+SIN(GAMMA3)
20  JX=OMX*OMY*R3Y-(OMY**2+OMZ**2)*R3X-DOMZ*R3Y
    JY=OMX*OMY*R3X-(OMX**2+OMZ**2)*R3Y+DOMZ*R3X
    JZ=(OMX*R3X+OMY*R3Y)*OMZ+DOMX*R3Y-DOMY*R3X
    NX=GX+JX
    NY=GY+JY
25  NZ=GZ+JZ
    LX=-(OMY**2+OMZ**2)*R1
    LY=(OMX*OMY+DOMZ)*R1
    LZ=(OMX*OMZ-DOMY)*R1
    OX=GX+LX
    OY=GY+LY
30  OZ=GZ+LZ
    R2X=R2+COS(GAMMA2)
    R2Y=R2+SIN(GAMMA2)
    PX=OMX*OMY*R2Y-(OMY**2+OMZ**2)*R2X-DOMZ*R2Y
    PY=OMX*OMY*R2X-(OMX**2+OMZ**2)*R2Y+DOMZ*R2X
35  PZ=(OMX*R2X+OMY*R2Y)*OMZ+DOMX*R2Y-DOMY*R2X
    OX=GX+PX
    OY=GY+PY
40  OZ=GZ+PZ
    RETURN
    END
    007290
    007300
    007310
    007320
    007330
    007340
    007350
    007360
    007370
    007380
    007390
    007400
    007410
    007420
    007430
    007440
    007450
    007460
    007470
    007480
    007490
    007500
    007510
    007520
    007530
    007540
    007550
    007560
    007570
    007580
    007590
    007600
    007610
    007620
    007630
    007640
    007650
    007660
    007670
    007680

```



```
1 SUBROUTINE CWDN (LU,LL,MU1,S5,MP,RCP,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA19,AA20,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20)
5 REAL LU,LL,MP,MU1,KX,KY,KZ
  BETA=PSI+PSIC
  SB=SIN(BETA)
  CB=COS(BETA)
10 CC1=ABS(-LL*AA12+MU1*S5*(AA1-LL*AA17)-AA5*MP+RCP*KZ*(MU1*S5+SB*CB))
  CC2=ABS(-LL*AA13+MU1*S5*(AA2-LL*AA18)-AA6)
  CC3=ABS(-LL*AA14+MU1*S5*(AA3-LL*AA19)-AA7)
  CC4=ABS(-LL*AA15+MU1*S5*(AA4-LL*AA20)-AA8)
  CC5=ABS(-LL*AA16-MU1*S5+LL*AA21)
  CC6=ABS(AA1-LL*AA17+MU1*S5*(LL*AA12+AA5)+MP+RCP*KZ*(SB-MU1*S5+CB))
  CC7=ABS(AA2-LL*AA18+MU1*S5*(AA6+LL*AA13))
  CC8=ABS(AA3-LL*AA19+MU1*S5*(AA7+LL*AA14))
  CC9=ABS(AA4-LL*AA20+MU1*S5*(AA8+LL*AA15)-AA8)
  CC10=ABS(MU1*S5+LL*AA16-LL*AA21)
  CC11=ABS(LU*AA12-AA5+MU1*S5*(LU*AA17+AA1)+MP+RCP*KZ*(MU1*S5+SB*CB))
  CC12=ABS(LU*AA13-AA6+MU1*S5*(LU*AA18+AA2))
  CC13=ABS(LU*AA14-AA7+MU1*S5*(LU*AA19+AA3))
  CC14=ABS(LU*AA15-AA8+MU1*S5*(LU*AA20+AA4))
  CC15=ABS(LU*AA16+MU1*S5+LU*AA21)
  CC16=ABS(LU*AA17+AA1+MU1*S5*(AA5-LU*AA12)+MP+RCP*KZ*(SB-MU1*S5+CB))
  CC17=ABS(LU*AA18+AA2+MU1*S5*(AA6-LU*AA13))
  CC18=ABS(LU*AA19+AA3+MU1*S5*(AA7-LU*AA14))
  CC19=ABS(LU*AA20+AA4+MU1*S5*(AA8-LU*AA15))
  CC20=ABS(LU*AA21-MU1*S5+LU*AA16)
  RETURN
  END
```

```

1  SUBROUTINE ATWO(S7,CONE,DONE,DPSI,PSI,
   INX,NY,NZ,AA16,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,
   CC10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,
   AA26,AA27,AA28,AA29,AA30,AA31,AA32,AA33,AA34R,AA34F,AA35,AA36,
   AA37R,AA37F,AA38,AA39,AA40,AA41,AA42,IPR)
5  COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXP,IEEP,I2ZP,IXEP,I2XP,
   +IEZP,IXS,IYS,IZS,IXX1,IEE1,I7Z1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,
   RX,RY,
   +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,
   +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,
   +GAMMA3,GAMA4P,GAMMA4,GAMMAP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,
10  +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,
   +RHOF,RHOF1,RHOF2,RHOF3,S6,DFHI1,DPHI2P,DPHI2,DPHIS,AG1,
   +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2
   +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2
   +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,
   +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
   +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,
15  +RSGN2F
   COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,SR
   COMMON/DATA5/LU,LL,MU,MU1
   COMMON/F,ITAG/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,
20  +PHI2P,PHI1,PHI2,GAM
   REAL LU,LL,LT,MU,MU1,IPR,I2ZP,NX,NY,NZ,M3,IXS,IYS,IZS,LAMDA2
   X=(LL+LU)*(1+MU1*2)
   AA24=(CC1+CC6+CC11+CC16)/X
   AF25=(CC2+CC7+CC12+CC17)/X
25  AA26=(CC3+CC8+CC13+CC18)/X
   AA27=(CC4+CC9+CC14+CC19)/X
   AA28=(CC5+CC10+CC15+CC20)/X
   AA29=S7*DONE-CONE+MU1+S4-MU1+RHOP+S5+AA28
30  AA30=MU1+S5*(RHOF+AA22+RHOP+AA24)
   AA31=MU1*(RHOF+AA23+RHOP+AA25)
   AA32=MU1+S5+RHOP+AA26
   AA33=MU1+RHOP+AA27
   IF (DPSI+DPSI2.GE.O) IPR=I2ZP+AA333
35  IF (DPSI+DPSI2.LT.O) IPR=I2ZP-AA333
   IF (IPR.LT.O) IPR=O
   AA33=MU1+S4+COS(PSI+ALPHR+BETA3)-S7*SIN(PSI+ALPHR+BETA3)
   AA34R=COS(LAMDA2)-MU+S2R+SIN(LAMDA2)
   AA34F=-SIN(PHIS-ALPHP2)+MU+S2F+COS(PHIS-ALPHP2)
40  AA35=-NX+M3
   AA36=S7*COS(PSI+ALPHR+BETA3)+MU1+S4*SIN(PSI+ALPHR+BETA3)
   AA37R=SIN(LAMDA2)+MU+S2R+COS(LAMDA2)
   AA37F=COS(PHIS-ALPHP2)+MU+S2F*SIN(PHIS-ALPHP2)
   AA38=-NY+M3
45  AA39=IXS+DOMX+OMY+OMZ*(IZS-IYS)
   AA40=IZS+OMY
   AA41=IYS+DOMY+OMY+OMZ*(IXS-IZS)
   AA42=-IZS+OMX
   RETURN
50  END

```

```

. 1 SUBROUTINE CTWO(LU,LL,MU,S6,AA33,AA34R,AA34F,AA35,AA36,AA37R,
+AA37F,AA38,AA39,AA40,AA41,AA42,CC21,CC22,CC23R,CC23F,
+CC24,CC25,CC26,CC27R,CC27F,CC28,CC29,CC30,CC31R,CC31F,
+CC32,CC33,CC34,CC35R,CC35F,CC36)
5 REAL LL,LU,MU
10 CC21=ABS(LL*AA35-AA41+MU*(LL*AA38+AA39))
CC22=ABS(LL*(AA33+MU*AA36))
CC23R=ABS(LL*(AA34R+MU*AA37R))
CC23F=ABS(LL*(AA34F+MU*AA37F))
CC24=ABS(MU*AA40-AA42)
10 CC25=ABS(LL*AA38+AA39+MU*(AA41-LL*AA35))
CC26=ABS(LL*(AA36-MU*AA33))
CC27R=ABS(LL*(AA37R-MU*AA34R))
CC27F=ABS(LL*(AA37F-MU*AA34F))
15 CC28=ABS(AA40+MU*AA42)
CC29=ABS(MU*(AA39-LU*AA38)-LU*AA35-AA41)
CC30=ABS(LU*(AA33+MU*AA36))
CC31R=ABS(LU*(AA34R+MU*AA37R))
CC31F=ABS(LU*(AA34F+MU*AA37F))
20 CC32=ABS(MU*AA40-AA42)
CC33=ABS(MU*(AA41+LU*AA35)+AA39-LU*AA38)
CC34=ABS(LU*(MU*AA33-AA36))
CC35R=ABS(LU*(MU*AA34R-AA37R))
CC35F=ABS(LU*(MU*AA34F-AA37F))
25 CC36=ABS(AA40+MU*AA42)
RETURN
END
009050
009060
009070
009080
009090
009100
009110
009120
009130
009140
009150
009160
009170
009180
009190
009200
009210
009220
009230
009240
009250
009260
009270
009280
009290
009300
009310

```

```

1  SUBROUTINE ATHREE(S7,DPHI,AONE,BONE,NZ
+ CC21,CC22,CC23R,CC24,CC25,CC26,CC27R,CC28,
+ CC29,CC30,CC31R,CC32,CC33,CC34,CC35R,CC36,AA43,AA44,
+ AA45R,AA46F,AA47,AA48,AA49F,AA50,AA51,AA52,AA53,AA54,
+ AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65
+ AA66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F)
COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXP,IEEP,IZZP,IXEP,IZXP,
+ IEZP,IXS,IVS,IZS,IXX1,IEE1,IZZ1,IXE1,IXZ1,IX2,IXZ2,IXZ3,RY,
+ RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,
+ NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMMA3P,
+ GAMMA3,GAMMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,
+ RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,
+ RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,
+ AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2
+ RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2
+ F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,
+ F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
+ T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F
COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8
COMMON/DATA5/LU,LL,MU,MU1
COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,
+ PHI2P,PHI12,GAM
REAL LU,LL,MU,M3,NX,NY,NZ,IZS,MU1,IXX1,IZZ1,IEE1,IXE1,IXZ1,IEZ
11,M1,M2,LAMDA1,LAMDA2
XX=(LU+LL)*(1.+MU**2)
AA43=(CC21+CC25+CC29+CC33)/XX
AA44=(CC32+CC26+CC30+CC34)/XX
AA45R=(CC23R+CC27R+CC31R+CC35R)/XX
AA45F=(CC23F+CC27F+CC31F+CC35F)/XX
AA46=(CC24+CC28+CC32+CC36)/XX
AA47=ABS(NZ*M3)
IF (DPHI.EQ.O) GO TO 1
AA48=MU+RH03*AA46/ABS(DPHI)
GO TO 2
1 AA48=O
2 AA49R=MU*(S2R+RHOP2+RH03*AA45R)-AP2*(SIN(LAMDA2-PHIS-DELP2)+MU*S2R009680
1*CO5(LAMDA2-PHIS-DELP2))
AA49F=-G2
AA50=IZS*DOMZ+MU*(RHOF3*AA47+RH03*AA43)
AA51=-S7*AONE+BONE+MU1*S4-MU+RH03*AA44
CG=CO5(GAM)
SG=SIN(GAM)
AA52=CG*(IXX1*(DOMX*CG+DOMY*SG)+(IZZ1-IEE1)*OMZ*(-OMX*SG+OMY*CG)+IO9750
1XE1*(OMZ*(OMX*CG+OMY*SG)+(DOMX*SG-DOMY*CG))-IZX1*((OMX*CG+OMY*SG)*OO9760
2*(-OMX*SG+OMY*CG)+DOMZ)-IEZ1*((-OMX*SG+OMY*CG)**2-OMZ**2))-SG*(IEE1OO9770
3*(-DOMX*SG+DOMY*CG)+(IXX1-IZZ1)*OMZ*(OMX*CG+OMY*SG)+IEZ1*((OMX*CG+OO9780
4OMY*SG)*(-OMX*SG+OMY*CG)-DOMZ)-IXE1*((DOMX*CG+DOMY*SG)+OMZ*(-OMX*SOO9790
5G+OMY*CG))-IZX1*(OMZ**2-(OMX*CG+OMY*SG)**2))
AA53=(((-OMX*SG+OMY*CG)*((IXX1+IZZ1-IEE1)*CG+2.*IXE1*SG)+(OMX*C
1G+OMY*SG)*((IEE1-IXX1+IZZ1)*SG+2.*IXE1*CG)+2.*OMZ*(IXE1+CG+IZX1*SGOO9820
2))
AA54=(IXE1+CG+IZX1*SG)
AA55=(-IZX1*CG+IEZ1*SG)
AA56=SG*(IXX1*(DOMX*CG+DOMY*SG)+(IZZ1-IEE1)*(-OMX*SG+OMY*CG)+OMZ+IO9860
1XE1*(OMZ*(OMX*CG+OMY*SG)-(-DOMX*SG+DOMY*CG))-IZX1*((OMX*CG+OMY*SG)OO9870
2*(-OMX*SG+OMY*CG)+DOMZ)-IEZ1*((-OMX*SG+OMY*CG)**2-OMZ**2))+CG*(IEE1OO9880

```


31+(-DOMX*SG+DOMY*CG)+(IXX1-IZZ1)*(OMX*CG+OMY*SG)*OMZ+IEZ1*(-OMX*CG+OMY*SG)+(-OMX*SG+DOMY*CG)-DOMZ)-IXE1*(DOMX*CG+DOMY*SG+OMZ*(-OMX*SG+DOMY*CG))-IXX1*(OMZ**2-(OMX*CG+OMY*SG)**2))	009910
AA57=(((-OMX*SG+OMY*CG)+((IXX1+IZZ1-IEE1)*SG-2.*IXE1*CG)*(OMX*CG+OMY*SG))*(2.*IXE1*SG+(IXX1-IZZ1-IEE1)*CG)+2.*OMZ*(IEZ1*SG-IZZ1*CG+OMY*SG))	009920
AA58=(IEZ1*SG-IZZ1*CG)	009930
AA59=- (IZZ1*SG+IEZ1*CG)	009940
AA60=IZZ1*DOMZ+(IEE1-IXX1)*(OMX*CG+OMY*SG)*(-OMX*SG+OMY*CG)+IZZ1*(-OMX*SG+OMY*CG)-DOMZ*(DOMX*CG+DOMY*SG)+IEZ1*(DOMX*SG+DOMY*CG-OMZ*(DOMX*CG+OMY*SG))-IXE1*((OMX*CG+OMY*SG)**2-((-OMX*SG+OMY*CG)**2))	009950
AA61= IZZ1	009960
AA62=M1*RC1*(-OMY**2*CG+OMX*OMY*SG-OMZ**2*CG-DOMZ*SG)+M1*DX	009970
AA63=-2.*M1*RC1*OMZ* CG	009980
AA64=-M1*RC1* CG	009990
AA65=-M1*RC1* SG	010000
AA66R=COS(LAMDA1)-MU*S1R+SIN(LAMDA1)	010010
AA66F=SIN(PHI2P+ALPH11)+MU*S1F+COS(PHI2P+ALPH11)	010020
AA67=M1*RC1*(-OMX**2*SG+OMX*OMY*CG-OMZ**2*SG+DOMZ*CG)+M1*DY	010030
AA68=-2.*M1*RC1* OMZ*SG	010040
AA69=-M1*RC1* SG	010050
AA70=M1*RC1*CG	010060
AA71R=SIN(LAMDA1)+MU*S1R+COS(LAMDA1)	010070
AA71F=MU*S1F+SIN(PHI2P+ALPH11)-COS(PHI2P+ALPH11)	010080
RETURN	010090
END	010100
	010110
	010120
	010130
	010140

```

1  SUBROUTINE CTHREE (LU,LL,PHI1RC,PHITOT, M1,RC1,MU,OX,OY,OZ,AA52, O10150
    1AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65, AO10160
    +AA66,AA67,AA68,AA69,AA70,AA71F,CC37,CC38,CC39, O10170
    +CC40,CC41R,CC41F,CC42,CC43,CC44,CC45,CC46R,CC46F,CC47, O10180
    +CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,CC54,CC55,CC56R,CC56F) O10190
    COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS, O10200
    +PHI2P,PHI1,PHI2,GAM O10210
    REAL LU,LL, M1,MU O10220
    CG=COS(GAM) O10230
    SG=SIN(GAM) O10240
    CC37=ABS(-LL*AA62+MU*(AA52-LL*AA67)-AA56+M1*RC1+OZ*(MU*SG+CG)) O10250
    CC38=ABS(-LL*AA63+MU*(AA53-LL*AA68)-AA57) O10260
    CC39=ABS(-LL*AA64+MU*(AA54-LL*AA69)-AA58) O10270
    CC40=ABS(-LL*AA65+MU*(AA55-LL*AA70)-AA59) O10280
    CC41R=ABS(-LL*(AA66R+MU*AA71R)) O10290
    CC41F=ABS(-LL*(AA66F+MU*AA71F)) O10300
    CC42=ABS(-LL*AA67+MU*(AA56+LL*AA62)+AA52+M1*RC1+OZ*(SG-MU*CG)) O10310
    CC43=ABS(-LL*AA68+MU*(LL*AA63+AA57)+AA53) O10320
    CC44=ABS(-LL*AA69+MU*(LL*AA64+AA58)+AA54) O10330
    CC45=ABS(-LL*AA70+MU*(LL*AA65+AA59)+AA55) O10340
    CC46R=ABS(LL*(MU*AA66R-AA71R)) O10350
    CC46F=ABS(LL*(MU*AA66F-AA71F)) O10360
    CC47=ABS(LU*AA62+MU*(LU*AA67+AA52)-AA56+M1*RC1+OZ*(MU*SG+CG)) O10370
    CC48=ABS(LU*AA63+MU*(LU*AA68+AA53)-AA57) O10380
    CC49=ABS(LU*AA64+MU*(LU*AA69+AA54)-AA58) O10390
    CC50=ABS(LU*AA65+MU*(LU*AA70+AA55)-AA59) O10400
    CC51R=ABS(LU*(AA66R+MU*AA71R)) C10410
    CC51F=ABS(LU*(AA66F+MU*AA71F)) O10420
    CC52=ABS(LU*AA67+MU*(AA56-LU*AA62)+AA52+M1*RC1+OZ*(SG-MU*CG)) O10430
    CC53=ABS(LU*AA68+MU*(AA57-LU*AA63)+AA53) O10440
    CC54=ABS(LU*AA69+MU*(AA58-LU*AA64)+AA54) O10450
    CC55=ABS(LU*AA70+MU*(AA59-LU*AA65)+AA55) O10460
    CC56R=ABS(LU*(AA71R-MU*AA66R)) O10470
    CC56F=ABS(LU*(AA71F-MU*AA66F)) O10480
    RETURN O10490
    END O10500

```

```

1  SUBROUTINE AF0UR(PHI,DPHI,CC37,CC38,CC39,CC40,
   +CC41F,CC42,CC43,CC44,CC45,
   +CC46R,CC46F,CC47,CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,
   +CC54,CC55,CC56R,CC56F,AA61,AA72,AA73,AA74,AA75,AA76,AA77,
   +AA78R,AA78F,AA79R,AA79F,AA80,AA81,AA82,AA83,AA84RR,AA84FF,
   +AA84RF,AA84FR,AA85RR,AA85FF,AA85RF,AA85FR,AA86,AA87RR,AA87FF,
   +AA87RF,AA87FR,AA88RR,AA88FF,AA88RF,AA88FR,AA89,AA90,AA91,
   +AA92,AA93)
   COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZXP,IZXP,
   +IEZP,IXS,IVS,IZS,IX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IZ2,IXX,RY,
   +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHIRC,NG1,NG2,
   +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMMA3P,
   +GAMMA3,GAMMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,
   +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,
   +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,
   +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2
   +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2
   +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,
   +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
   +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSNG1R,RSNG2R,RSNG1F,RSNG2F
   COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8
   COMMON/DATA2/KX,KY,OX,OY,OZ,OX,OX,QY,QZ
   COMMON/DATA4/I1R
   COMMON/DATA5/LU,LL,MU,MU1
   COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,
   +PHI2P,PHI1,PHI2,GAM
   REAL M1,M2,LU,LL,I1R,IX2,IZ2,IZ2,MU,LAMDA1,LAMDA2
   CG=COS(GAM)
   SG=SIN(GAM)
   XX=(LU+LL)*(1+MU**2)
   AA72=ABS(M1*RC1*(OMZ*(OMX+CG+OMY*SG)+DOMX*SG+DOMY*CG)+M1*OZ)
   AA73=ABS(2*M1*RC1*(OMX*CG+OMY*SG))
   AA74=(CC37+CC42+CC47+CC52)/XX
   AA75=(CC38+CC43+CC48+CC53)/XX
   AA76=(CC39+CC44+CC49+CC54)/XX
   AA77=(CC40+CC45+CC50+CC55)/XX
   AA78R=(CC41R+CC46R+CC51R+CC56R)/XX
   AA78F=(CC41F+CC46F+CC51F+CC56F)/XX
   AA79R=AG1*(SIN(PHI1-DELG1-LAMDA1))-MU*S1R*COS(PHI1-DELG1-LAMDA1))
   AA79F=AG1*(COS(PHI1-DELG1-PHI2P-ALPHP1))+MU*S1F*SIN(PHI1-DELG1-
   PHI2P-ALPHP1))-MU*(S1F*RHOG1+RHO1*AA78F)
   AA80=MU*(RHOF1*AA72+RHO1*AA74)
   AA81=ABS(MU)*(RHOF1*AA73+RHO1*AA75)
   AA82=MU*RHO1*AA76
   AA83=ABS(MU)*RHO1*AA77
   IF (OPHI*DPHI2,GE.O) I1R=AA61+AA83
   IF (DPHI*DPHI2,LT.O) I1R=AA61-AA83
   IF (I1R,LT.O) I1R=O
   AA84RR=-(COS(LAMDA2))+MU*S2R*SIN(LAMDA2))
   AA84FF=SIN(PHIS-ALPHP2)-MU*S2F*COS(PHIS-ALPHP2)
   AA84RF=AA84RR
   AA84FR=AA84FF
   AA85RR=COS(LAMDA1)-MU*S1R*SIN(LAMDA1)
   AA85FF=SIN(PHI2P+ALPHP1)+MU*S1F*COS(PHI2P+ALPHP1)
   AA85RF=AA85FF
   AA85FR=AA85RR

```

```

60      AAB6=-M2*QX
        AAB7RR=- (SIN(LAMDA2)+MU+S2R+COS(LAMDA2))
        AAB7FF=- (COS(PHIS-ALPHP2)+MU+S2F*SIN(PHIS-ALPHP2))
        AAB7RF=AAB7RR
        AAB7FR=AAB7FF
        AAB8RR=SIN(LAMDA1)+MU+S1R+COS(LAMDA1)
        AAB8FF=-COS(PHI2P+ALPHP1)+MU+S1F*SIN(PHI2P+ALPHP1)
        AAB8RF=AAB8FF
        AAB8FR=AAB8RR
        AAB9=-M2*QY
        AAB90=- (IX2*DMX+OMY+OMZ*(IZ2-IV2))
        AAB91=-IZ2*OMY
        AAB92=- (IV2*DMY+OMX+OMZ*(IX2-IZ2))
        AAB93=IZ2*OMX
        RETURN
        END

```

```

011080
011090
011100
011110
011120
011130
011140
011150
011160
011170
011180
011190
011200
011210
011220
011230

```

```
1  -SUBROUTINE CF0UR(AA84RR,AA84FF,AA84RF,AA84FR,AA85RR,  
  +AA85FF,AA85RF,AA85FR,AA86,AA87RR,AA87FF,AA87RF,AA87FR,AA88RR,  
  +AA88FF,AA88RF,AA88FR,AA89,AA90,AA91,AA92,AA93,CC57,CC58,  
  +CC59RR,CC59FF,CC59RF,CC59FR,CC60RR,CC60FF,CC60RF,CC60FR,CC61,  
  +CC62,CC63RR,CC63FF,CC63RF,CC63FR,CC64RR,CC64FF,CC64RF,  
  +CC64FR,CC65,CC66,CC67RR,CC67FF,CC67RF,CC67FR,CC68RR,CC68FF,  
  +CC68RF,CC68FR,CC69,CC70,CC71RR,CC71FF,CC71RF,CC71FR,CC72RR,  
  +CC72FF,CC72FR)  
  COMMON/DATA5/LU,LL,MU,MU1  
  REAL MU,LL,LU  
  CC57=ABS(-LL*AA86+MU*(LL*AA89-AA90)-AA92)  
  CC58=ABS(MU*AA91+AA93)  
  CC59RR=ABS(LL*(MU*AA87RR-AA84RR))  
  CC59FF=ABS(LL*(MU*AA87FF-AA84FF))  
  CC59RF=ABS(LL*(MU*AA87RF-AA84RF))  
  CC59FR=ABS(LL*(MU*AA87FR-AA84FR))  
  CC60RR=ABS(LL*(MU*AA88RR-AA85RR))  
  CC60FF=ABS(LL*(MU*AA88FF-AA85FF))  
  CC60RF=ABS(LL*(MU*AA88RF-AA85RF))  
  CC60FR=ABS(LL*(MU*AA88FR-AA85FR))  
  CC61=ABS(-LL*AA89-MU*(LL*AA86+AA92)+AA90)  
  CC62=ABS(AA91-MU*AA93)  
  CC63RR=ABS(LL*(MU*AA84RR+AA87RR))  
  CC63FF=ABS(LL*(MU*AA84FF+AA87FF))  
  CC63RF=ABS(LL*(MU*AA84RF+AA87RF))  
  CC63FR=ABS(LL*(MU*AA84FR+AA87FR))  
  CC64RR=ABS(LL*(MU*AA85RR+AA88RR))  
  CC64FF=ABS(LL*(MU*AA85FF+AA88FF))  
  CC64RF=ABS(LL*(MU*AA85RF+AA88RF))  
  CC64FR=ABS(LL*(MU*AA85FR+AA88FR))  
  CC65=ABS(-MU*(LU*AA89+AA90)+LU*AA86-AA92)  
  CC66=ABS(MU*AA91+AA93)  
  CC67RR=ABS(LU*(AA84RR-MU*AA87RR))  
  CC67FF=ABS(LU*(AA84FF-MU*AA87FF))  
  CC67RF=ABS(LU*(AA84RF-MU*AA87RF))  
  CC67FR=ABS(LU*(AA84FR-MU*AA87FR))  
  CC68RR=ABS(LU*(AA85RR-MU*AA88RR))  
  CC68FF=ABS(LU*(AA85FF-MU*AA88FF))  
  CC68RF=ABS(LU*(AA85RF-MU*AA88RF))  
  CC68FR=ABS(LU*(AA85FR-MU*AA88FR))  
  CC69=ABS(LU*AA89+MU*(LU*AA86-AA92)+AA90)  
  CC70=ABS(AA91-MU*AA93)  
  CC71RR=ABS(LU*(MU*AA84RR+AA87RR))  
  CC71FF=ABS(LU*(MU*AA84FF+AA87FF))  
  CC71RF=ABS(LU*(MU*AA84RF+AA87RF))  
  CC71FR=ABS(LU*(MU*AA84FR+AA87FR))  
  CC72RR=ABS(LU*(MU*AA85RR+AA88RR))  
  CC72FF=ABS(LU*(MU*AA85FF+AA88FF))  
  CC72RF=ABS(LU*(MU*AA85RF+AA88RF))  
  CC72FR=ABS(LU*(MU*AA85FR+AA88FR))  
  RETURN  
  END
```

```

1  SUBROUTINE AFIVE(T, PHI, DPHI, PSI, DPSI, DELPHI, IPR) 011760
   REAL M1, M2, M3, MP, IXXU, IEE1, IZZ1, IXX1, IZZ1, IXX2, IY2, IZZ2, IXS, IYSO 011770
   1, IZS, IXXP, IEEP, IZXP, IXEP, IZXP, IZXP, MU, MU1, KX, KY, KZ, JX, JY, J 011780
   2Z, LX, LY, LZ, NX, NY, NZ, LU, LL, LAMBA, NG1, NG2, NP2, NP3, IPR, I1R. 011790
   +LAMD1, LAMD2 011800
5  COMMON A, B, C, ALPHR, PI, ZZ, M1, M2, M3, MP, IXXP, IEEP, IZXP, IXEP, IZXP, 011810
   +IEZP, IXS, IYS, IZS, IXX1, IEE1, IZZ1, IXX1, IZZ1, IXX2, IY2, IZZ2, RX, RY, 011820
   +RZ, EREST, LAMBA, DELTA, PHITOT, PHIPR, OMEGA, OM2, RC1, PHI1RC, NG1, NG2, 011830
   +NP2, NP3, R1, R2, R3, R4, RHO1, RHO2, RHO3, RHOP, J1, J2, GAMMA2, GAMMA3P, 011840
   +GAMMA3, GAMMA4P, GAMMA4, GAMMAP, DELTA2, DELTA3, DELTA4, BETA2, BETA3, 011850
   +RCP, PSIC, S1, S2, S4, S5, DDPHI, DPSI2, PNMAX, PN, ALPHEN, ALPHEX, BETA1, 011860
   +RHOF, RHOF1, RHOF2, RHOF3, S6, DPHI1, DPHI2P, DPHI2, DPHIS, AG1, 011870
   +AP1, AG2, AP2, ALPHP1, ALPHP2, DELG1, DELG2, FP1, FP2, B1, B2, L1, L2 011880
   +, RHOG1, RHOG2, RHOP1, RHOP2, DELP1, DELP2 011890
   +, F23RRMX, F12RRMX, F23RFMX, F12RFMX, F23FRMX, F12FRMX, F23FFMX, 011900
   +F12FFMX, T23RRMX, T12RRMX, T23RFMX, T12RFMX, 011910
   +T23FRMX, T12FRMX, T23FFMX, T12FFMX, PHI1R, RSGN1R, RSGN2R, RSGN1F, RSGN2F 011920
   COMMON/DATA2/KX, KY, OX, OY, OZ, QX, QY, QZ 011930
   COMMON/DATA3/OMX, OMY, OMZ, DOMX, DOMY, DOMZ, S8 011940
   COMMON/DATA4/I1R 011950
   COMMON/DATA5/LU, LL, MU, MU1 011960
   COMMON/DATA6/S2R, S2F, LAMDA2, G2, S1R, S1F, LAMDA1, G1, PHIS, 011970
   +PHI2P, PHI1, PHI2, GAM 011980
20  COMMON/DATA7/DER2R, DER2F, DER1R, DER1F 011990
   COMMON/DATA8/PHI1T, PHI2T, AONE, BONE, CONE, DONE, U, V, VST, G, P, Q, S 012000
   COMMON/DATA9/AA105, AA106, AA107, AA108, AA109, AA110, AA115, AA116, 012010
   +AA117, AA118, AA119, AA120, AA121, AA122, AA123, AA124, AA125, 012020
   +AA130, AA131, AA132 012030
   COMMON/DATA10/AA9, AA29, AA30, AA31, AA32, AA48, AA49R, AA49F, AA50, AA51, 012040
   +AA60, AA79R, AA79F, AA80, AA81, AA82, AA89, AA100, AA101R, AA101RR, 012050
   +AA101FF, AA101RF, AA102FR, AA102RR, AA102FF, AA102RF, AA103, AA104, 012060
   +AA111, AA112, AA113, AA114, AA126, AA127, AA128, AA129 012070
   COMMON/DATA11/AA133, AA134, AA135, AA136, AA137, AA138, AA139, AA140, 012080
   +AA141, AA142, AA143, AA144, AA145, AA146, AA147, AA148, AA149, AA150, 012090
   +AA151, AA152, AA153, AA154, AA155, AA156, AA157, AA158, AA159, AA160, 012100
   +AA161, AA162, AA163, AA164, AA165, AA166, AA167, AA168, AA169, AA170, 012110
   +AA171, AA172, AA173, AA174, AA175, AA176, AA177 012120
   COMMON/DATA12/X1, X2, X3, X4, X5, X6, X7, X8, X9, X10, X11, X12, Y1, Y2, Y3, Y4, 012130
   +Y5, Y6, Y7, Y8 012140
   CALL ACCEL (RX, RY, RZ, GAMMA2, GAMMA3, GAMMAP, R1, R2, R3, R4, BETA3, GX, GY, 012150
   1GZ, HX, HY, HZ, KX, KY, KZ, JX, JY, JZ, NX, NY, NZ, LX, LY, LZ, OX, OY, OZ, PX, PY, PZ, 012160
   2OX, OY, OZ, T, OMX, OMY, OMZ, DOMX, DOMY, DOMZ, DDZ) 012170
   IF (DPHI.EQ.O) GO TO 1 012180
   MU=ABS(MU)*DPHI/ABS(DPHI) 012190
45  1 CALL GKINEM(T, DPHI, PHDOT1, PHDOT2, X1, X2, X3, X4, X5, X6, 012200
   +X7, X8, X9, X10, X11, X12, Y1, Y2, Y3, Y4, Y5, Y6, Y7, Y8) 012210
   IF (VST.NE.O) GO TO 3 012220
   S4=1. 012230
   GO TO 4 012240
3  S4=VST/ABS(VST) 012250
4  IF (DPSI.NE.O) GO TO 5 012260
   S5=1. 012270
   GO TO 6 012280
5  S5=DPSI/ABS(DPSI) 012290
55  6 IF (ALPHR.EQ.ALPHEN) S7=1. 012300
   IF (ALPHR.EQ.ALPHEX) S7=-1. 012310
   CALL AWON (S6, S7, ALPHR, BETA3, RCP, MP, IXXP, IEEP, IZXP, IXEP, IZXP, IZXP, 012320

```

```
1MU1,S4,S5,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3      012330
2,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA19,AA20,AA21,AA22,AA23,PHITOT) 012340
3A18,AA19,AA20,AA21,AA22,AA23,PHITOT)          012350
CALL CWDN (LU,LL,MU1,S5,MP,RCP,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA19,AA20,AA21,AA22,AA23,PHITOT) 012360
1A5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA19,AA20,AA21,AA22,AA23,PHITOT) 012370
219,AA20,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20) 012380
311,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20) 012390
CALL ATWD(S7,CONE,DONE,DPSI,PSI,NX,NY,          012400
1N2,AA16,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,AA26,AA27,AA28,AA29,AA30,AA31,AA32,AA33,AA34,AA35,AA36,AA37,AA38,AA39,AA40,AA41,AA42,IPR) 012410
211,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,AA26,AA27,AA28,AA29,AA30,AA31,AA32,AA33,AA34,AA35,AA36,AA37,AA38,AA39,AA40,AA41,AA42,IPR) 012420
+7,AA28,AA29,AA30,AA31,AA32,AA33,AA34,AA35,AA36,AA37,AA38,AA39,AA40,AA41,AA42,IPR) 012430
+AA37R,AA37F,AA38,AA39,AA40,AA41,AA42,IPR)      012440
CALL CTWD(LU,LL,MU,S6,AA33,AA34R,AA34F,AA35,AA36,AA37R, 012450
+AA37F,AA38,AA39,AA40,AA41,AA42,CC21,CC22,CC23R,CC23F, 012460
+CC24,CC25,CC26,CC27R,CC27F,CC28,CC29,CC30,CC31R,CC31F, 012470
+CC32,CC33,CC34,CC35R,CC35F,CC36)              012480
CALL ATHREE (S7,DPIH,AONE,BONE,NZ              012490
+CC21,CC22,CC23R,CC23F,CC24,CC25,CC26,CC27R,CC27F,CC28, 012500
+CC29,CC30,CC31R,CC31F,CC32,CC33,CC34,CC35R,CC35F,CC36,AA43,AA44, 012510
+AA45R,AA45F,AA46,AA47,AA48,AA49R,AA49F,AA50,AA51,AA52,AA53,AA54, 012520
+AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65 012530
+AA66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F)   012540
CALL CTHREE (LU,LL,PHI1RC,PHITOT, M1,RC1,MU,DX,DY,DZ,AA52, 012550
1AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65,AA66,AA67,AA68,AA69,AA70,AA71R,AA71F,CC37,CC38,CC39, 012560
+CC40,CC41R,CC41F,CC42,CC43,CC44,CC45,CC46R,CC46F,CC47, 012570
+CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,CC54,CC55,CC56R,CC56F) 012580
CALL AFOUR (PHI,DPIH,                      012590
+CC37,CC38,CC39,CC40,CC41R,CC41F,CC42,CC43,CC44,CC45, 012600
+CC46R,CC46F,CC47,CC48,CC49,CC50,CC51R,CC51F,CC52,CC53, 012610
+CC54,CC55,CC56R,CC56F,AA61,AA62,AA63,AA64,AA65,AA66,AA67, 012620
+AA78R,AA78F,AA79R,AA79F,AA80,AA81,AA82,AA83,AA84R,AA84F, 012630
+AA84RF,AA84FR,AA85RR,AA85FF,AA86R,AA86F,AA87R,AA87F, 012640
+AA87RF,AA87FR,AA88RR,AA88FF,AA89R,AA89F,AA90R,AA90F, 012650
+AA92,AA93)                                     012660
CALL CFOUR(AA84RR,AA84FF,AA84FR,AA84FR,AA85RR, 012670
+AA85FF,AA85FR,AA86,AA87RR,AA87FF,AA87FR,AA88RR, 012680
+AA88FF,AA88FR,AA89,AA90,AA91,AA92,AA93,CC57,CC58, 012690
+CC59RR,CC59FF,CC59RF,CC59FR,CC60RR,CC60FF,CC60FR,CC61, 012700
+CC62,CC63RR,CC63FF,CC63RF,CC63FR,CC64RR,CC64FF,CC64RF, 012710
+CC64FR,CC65,CC66,CC67RR,CC67FF,CC67RF,CC67FR,CC68RR,CC68FF, 012720
+CC68RF,CC68FR,CC69,CC70,CC71RR,CC71FF,CC71RF,CC71FR,CC72RR, 012730
+CC72FF,CC72RF,CC72FR)                         012740
XX=(LU+LL)*(1.+MU**2)                          012750
SG=SIN(GAM)                                       012760
CG=COS(GAM)                                       012770
AA94=(CC57+CC61+CC65+CC69)/XX                   012780
AA95=(CC58+CC62+CC66+CC70)/XX                   012790
AA96RR=(CC59RR+CC63RR+CC67RR+CC71RR)/XX          012800
AA96FF=(CC59FF+CC63FF+CC67FF+CC71FF)/XX          012810
AA96RF=(CC59RF+CC63RF+CC67RF+CC71RF)/XX          012820
AA96FR=(CC59FR+CC63FR+CC67FR+CC71FR)/XX          012830
AA97RR=(CC60RR+CC64RR+CC68RR+CC72RR)/XX          012840
AA97FF=(CC60FF+CC64FF+CC68FF+CC72FF)/XX          012850
AA97RF=(CC60RF+CC64RF+CC68RF+CC72RF)/XX          012860
AA97FR=(CC60FR+CC64FR+CC68FR+CC72FR)/XX          012870
AA98=ABS(M2*QZ)                                  012880
AA99=ABS(M2*QZ)                                  012890
```

115 AA99=I22+DOMZ 012900
AA100=I22 012910
AA101R=AG2*(SIN(PHI2+DELG2-LAMDA2)-MU*S2R+COS(PHI2+DELG2-LAMDA2)) 012920
1-MU*(S2R+RHOG2-RH02+AA96RR) 012930
AA101FF=AG2*(-COS(PHI2+DELG2-PHIS+ALPHP2)+MU*S2F*SIN(PHI2+DELG2 012940
1-PHIS+ALPHP2))*MU*(RH02+AA96FF+S2F+RHOG2) 012950
AA101RF=AG2*(SIN(PHI2+DELG2-LAMDA2)-MU*S2R+COS(PHI2+DELG2-LAMDA2)) 012960
1-MU*(S2R+RHOG2-RH02+AA96RF) 012970
AA101FR=AG2*(-COS(PHI2+DELG2-PHIS+ALPHP2)+MU*S2F*SIN(PHI2+DELG2 012980
1-PHIS+ALPHP2))*MU*(S2F+RHOG2+RH02+AA96FR) 012990
AA102RR=AP1*(SIN(PHI2P-DELP1-LAMDA1)-MU*S1R+COS(PHI2P-DELP1-LAMDA1 013000
1)))+MU*(S1R+RHOP1-RH02+AA97RR) 013010
AA102FF=G1-MU*RH02+AA97FF 013020
AA102RF=G1-MU*RH02+AA97RF 013030
AA102FR=AP1*(SIN(PHI2P-DELP1-LAMDA1)-MU*S1R+COS(PHI2P-DELP1-LAMDA1 013040
+)))+MU*(S1R+RHOP1-RH02+AA97FR) 013050
AA103=MU*(RHOF2+AA98+RH02+AA94) 013060
AA104=ABS(MU)*RH02+AA95 013070
AA105=AA51+IPR-U-AA29+AA9R+AA100*Y5)/(AA29+AA49R+AA100*Y5)/(AA29+ 013080
1AA49R+AA102RR+I1R+Y1*Y5)/(AA79R+AA101RR) 013090
AA106=AA51*(AA32+U+Y2+IPR+V)-AA29+AA48-(AA29+AA49R+AA102RR+I1R)/(013100
1AA79R+AA101RR)*(Y1*Y6+Y2+DER2R+Y2)-(AA29+AA49R+AA82+AA102RR+DER1R 013110
2*DER1R+DER2R+Y2)/(AA79R+AA101RR)-(AA29+AA49R+AA100*Y6)/AA101RR 013120
AA107=AA51+U-(AA29+AA49R+AA81+AA102RR+DER1R+DER2R)/(AA79R+ 013130
1AA101RR)-(AA29+AA49R+AA104+DER2R)/AA101RR 013140
AA108=AA29+AA50-AA51*(AA9+AA30)+(AA29+AA49R)/AA101RR*(AA102RR+ 013150
1(AA80+AA60))/AA79R-AA103+AA99 013160
AA109=-(AA29+AA49R+AA102RR+M1*RC1)/(AA79R+AA101RR) 013170
AA110=AA51+MP+RCP 013180
AA111=AA102RR+I1R+Y1*Y5/AA79R+AA100*Y5 013190
AA112=AA102RR/AA79R*(I1R+(Y1*Y6+Y2+DER2R+Y2)+AA82+DER1R+Y2+DER2R+ 013200
1DER2R)+AA100*Y6 013210
AA113=AA102RR+AA81+DER1R+DER2R/AA79R+AA104+DER2R 013220
AA114=AA102RR/AA79R*(AA80+AA60-M1*RC1*(OX+SG-OY+CG))-AA103+AA99 013230
AA115=I1R+Y1*Y5 013240
AA116=I1R*(Y1*Y6+Y2+DER2R+Y2)+AA82+DER1R+Y2+DER2R+Y2 013250
AA117=AA81+DER1R+DER2R 013260
AA118=AA80+AA60-M1*RC1*(OX+SG-OY+CG) 013270
AA119=AA9+AA30 013280
AA120=AA51+IPR-U-AA29+AA9R+AA100*Y5/AA79R+AA101FF 013290
1-AA29+AA49F+AA102FF+I1R+Y3*Y7/(AA101FF+AA79F) 013300
AA121=AA51*(AA32+U+Y2+IPR+V)-AA29+AA48-AA82+AA29+AA49F+AA102FF 013310
1*DER1F+Y2+DER2F+Y2/(AA101FF+AA79F)-AA100+AA29+AA49F+Y8/AA101FF 013320
2-AA29+AA49F+AA102FF+I1R*(Y3*Y8+Y4+DER2F+Y2)/(AA101FF+AA79F) 013330
AA122=AA51+AA31+U-AA81+AA29+AA49F+DER2F/AA101FF 013340
1F+AA79F)-AA104+AA29+AA49F+DER2F/AA101FF 013350
AA123=AA29+AA50-AA51*(AA9+AA30)+AA29+AA49F*(AA102FF*(AA80+AA60))/ 013360
1AA79F-AA103+AA99)/AA101FF 013370
AA124=-AA29+AA49F+AA102FF+M1*RC1/(AA101FF+AA79F) 013380
AA125=AA51+MP+RCP 013390
AA126=AA102FF+I1R+Y3*Y7/AA79F+AA100*Y7 013400
AA127=AA102FF*(I1R+(Y3*Y8+Y4+DER2F+Y2)+AA82+DER1F+Y2+DER2F+Y2)/ 013410
1AA79F+AA100*Y8 013420
AA128=AA102FF+AA81+DER1F+DER2F/AA79F+AA104+DER2F 013430
AA129=AA102FF*(AA80+AA60-M1*RC1*(OX+SG-OY+CG))/AA79F-AA103+AA99 013440
AA130=I1R+Y3*Y7 013450
AA131=I1R*(Y3*Y8+Y4+DER2F+Y2)+AA82+DER1F+Y2+DER2F+Y2 013460

SUBROUTINE AFIVE

74/860 OPT=1

FTN 4.8+650

09/27/89 15.21.25

PAGE

4

AA132=AA81+DER1F+DER2F
RETURN
END

013470
013480
013490

```
1 SUBROUTINE ASIX(T,PHI,DPHI,PSI,DPSI,DELPHI,IPR) 013500
  REAL M1,M2,M3,MP,IXXU,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IV2,IZZ2,IXS,IVS 013510
  1,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU1,KX,KY,KZ,JX,JY,J 013520
  2Z,LX,LV,LZ,NX,NV,NZ,LU,LL,LAMBA,NG1,NG2,NP2,NP3,IPR,IR, 013530
  +LAMDA1,LAMDA2 013540
  COMMON A,B,C,ALPHR,P1,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP, 013550
  +IEZP,IXS,IVS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IV2,IZZ2,IXS,IVS, 013560
  +RZ,EREST,LAMBA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2, 013570
  +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMMA3P, 013580
  +GAMMA3,GAMMA4P,GAMMA4,GAMMA4P,DELTA2,DELTA3,DELTA4,BETA2,BETA3, 013590
  +RCP,PSIC,S1,S2,S4,S5,DOPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1, 013600
  +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2,DPHI2,DPHIS,AG1, 013610
  +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2 013620
  +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2 013630
  +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX, 013640
  +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX, 013650
  +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSNG1R,RSNG2R,RSNG1F,RSNG2F 013660
  COMMON/DATA2/KX,KY,OX,OY,OZ,OX,OY,OZ 013670
  COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8 013680
  COMMON/DATA4/I1R 013690
  COMMON/DATA5/LL,LL,MU,MU1 013700
  COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS, 013710
  +PHI2P,PHI1,PHI2,GAM 013720
  COMMON/DATA7/DER2R,DER2F,DER1R,DER1F 013730
  COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S 013740
  COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116, 013750
  +AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125, 013760
  +AA130,AA131,AA132 013770
  COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51, 013780
  +AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101R,AA101RR, 013790
  +AA101FF,AA101RF,AA102R,AA102RR,AA102FF,AA102RF,AA103,AA104, 013800
  +AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129 013810
  COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140, 013820
  +AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150, 013830
  +AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160, 013840
  +AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170, 013850
  +AA171,AA172,AA173,AA174,AA175,AA176,AA177 013860
  COMMON/DATA12/X1,X2,X3,X4,X5,X6,X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4, 013870
  +Y5,Y6,Y7,Y8 013880
  CALL ACCEL (RX,RV,RZ,GAMMA2,GAMMA3,GAMMA4,R1,R2,R3,R4,BETA3,GX,GY, 013890
  1GZ,HX,HY,HZ,KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LV,LZ,OX,OY,OZ,PX,PY,PZ, 013900
  2OX,OY,OZ,T,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DDZ) 013910
  IF (DPHI.EQ.O)GO TO 1 013920
  MU=ABS(MU)*DPHI/ABS(DPHI) 013930
  1 CALL GKINEM(T,DPHI,PHDOT1,PHDOT2,X1,X2,X3,X4,X5,X6, 013940
  +X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8) 013950
  IF (VST.NE.O)GO TO 3 013960
  S4=1. 013970
  GO TO 4 013980
  3 S4=VST/ABS(VST) 013990
  4 IF (DPSI.NE.O) GO TO 5 014000
  S5=1. 014010
  GO TO 6 014020
  5 S5=DPSI/ABS(DPSI) 014030
  6 IF (ALPHR.EQ.ALPHEN) S7=1. 014040
  IF (ALPHR.EQ.ALPHEX) S7=-1. 014050
  CALL AWON (S6,S7,ALPHR,BETA3,RCP,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP, 014060
```

60	1MU1,S4,S5,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3 2,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA19,AA20,AA21,AA22,AA23,PHITOT) 3A18,AA19,AA20,AA21,AA22,AA23,PHITOT) CALL CWON (LU,LL,MU1,S5,MP,RCP,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA19,AA20,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20) 311,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20) CALL ATWO(S7,CONE,DONE,DPSI,PSI,NX,NV, 1NZ,AA16,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,AA26,AA27,AA28,AA29,AA30,AA31,AA32,AA33,AA34,AA35,AA36, +AA37R,AA37F,AA38,AA39,AA40,AA41,AA42,IPR) CALL CTWO(LU,LL,MU,S6,AA33,AA34R,AA34F,AA35,AA36,AA37R, +AA37F,AA38,AA39,AA40,AA41,AA42,CC21,CC22,CC23R,CC23F, +CC24,CC25,CC26,CC27R,CC27F,CC28,CC29,CC30,CC31R,CC31F, +CC32,CC33,CC34,CC35R,CC35F,CC36) CALL ATHREE (S7,DPHI,AONE,BONE,NZ +CC21,CC22,CC23R,CC23F,CC24,CC25,CC26,CC27R,CC27F,CC28, +CC29,CC30,CC31R,CC31F,CC32,CC33,CC34,CC35R,CC35F,CC36,AA43,AA44, +AA45R,AA45F,AA46,AA47,AA48,AA49R,AA49F,AA50,AA51,AA52,AA53,AA54, +AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65 +,AA66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F) CALL CTHREE (LU,LL,PHI,IRC,PHITOT, M1,RC1,MU,OX,OY,OZ,AA52, 1AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65,AA66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F,CC37,CC38,CC39, +CC40,CC41R,CC41F,CC42,CC43,CC44,CC45,CC46R,CC46F,CC47, +CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,CC54,CC55,CC56R,CC56F) CALL AFOUR (PHI,DPHI, +CC37,CC38,CC39,CC40,CC41R,CC41F,CC42,CC43,CC44,CC45, +CC46R,CC46F,CC47,CC48,CC49,CC50,CC51R,CC51F,CC52,CC53, +CC54,CC55,CC56R,CC56F,AA61,AA72,AA73,AA74,AA75,AA76,AA77, +AA78R,AA78F,AA79R,AA79F,AA80,AA81,AA82,AA83,AA84R,AA84F, +AA84RF,AA84FR,AA85R,AA85RR,AA85FF,AA85FR,AA86,AA87R,AA87FF, +AA87RF,AA87FR,AA88R,AA88FF,AA88FR,AA89,AA90,AA91, +AA92,AA93) CALL CFOUR(AA84R,AA84F,AA84FR,AA84RF,AA85R, +AA85FF,AA85FR,AA86,AA87R,AA87FF,AA87FR,AA88R, +AA88FF,AA88FR,AA89,AA90,AA91,AA92,AA93,CC57,CC58, +CC59R,CC59FF,CC59RF,CC59FR,CC60R,CC60FF,CC60FR,CC61, +CC62,CC63R,CC63FF,CC63RF,CC63FR,CC64R,CC64FF,CC64FR, +CC64FR,CC65,CC66,CC67R,CC67FF,CC67FR,CC68R,CC68FF, +CC68FR,CC68FR,CC69,CC70,CC71R,CC71FF,CC71FR,CC72R, +CC72FF,CC72FR,CC72FR) XX=(LU+LL)*(1+MU**2) SG=SIN(GAM) CG=COS(GAM) AA133=AA80+AA60-M1*RC1*(OX*SG-OY*CG) AA134=AA51+1PR*U-AA29+1ZS-AA29+AA49R+AA102RF+11R*Y3+Y5/(AA79F+ 1AA101RF)-AA29+AA49R+AA100*Y5/AA101RF AA135=AA51*(AA32*U+1PR*V)-AA29+AA48-AA29+AA49R+AA102RF+11R* 1(Y3+Y6+Y4*DER2R**2)/(AA79F+AA101RF)-AA29+AA49R+AA100*Y6/AA101RF 2DER2R**2+DER1F**2/(AA79F+AA101RF)-AA29+AA49R+AA100*Y6/AA101RF AA136=AA51*AA31*U-AA29+AA49R+AA81*AA102RF+DER2R*DER1F/(AA79F+ 1AA101RF)-AA29+AA49R+AA104*DER2R/AA101RF AA137=AA29+AA50-AA51*(AA9+AA30)+AA29+AA49R*(AA102RF*(AA80+AA60))/ 1AA79F-AA103+AA99/AA101RF AA138=-AA29+AA49R+AA102RF*M1*RC1/(AA101+AA79F) 014070 014080 014090 014100 014110 014120 014130 014140 014150 014160 014170 014180 014190 014200 014210 014220 014230 014240 014250 014260 014270 014280 014290 014300 014310 014320 014330 014340 014350 014360 014370 014380 014390 014400 014410 014420 014430 014440 014450 014460 014470 014480 014490 014500 014510 014520 014530 014540 014550 014560 014570 014580 014590 014600 014610 014620 014630
65	
70	
75	
80	
85	
90	
95	
100	
105	
110	

```
115 AA129=AA51*MP*RCP
AA140=AA102RF*(I1R*Y3*Y5/AA79F+AA100*Y5
AA141=AA102RF*(I1R*(Y3*Y6+Y4*DER2R**2)+AA82*DER2R**2*DER1F**2)/
1AA79F+AA100*Y6
AA142=AA102RF*AA81*DER2R*DER1F/AA79F+AA104*DER2R
AA143=AA102RF*(AA80+AA60-M1*RC1*(OX*SG-OY*CG))/AA79F-AA103+AA99
AA144=I1R*Y3*Y5
AA145=I1R*(Y3*Y6+Y4*DER2R**2)+AA82*DER1F**2*DER2R**2
AA146=AA81*DER1F*DER2R
AA147=AA80+AA60-M1*RC1*(OX*SG-OY*CG)
AA148=AA51*IPR*U-AA29*IZS-(AA29*AA49F*(AA102FR+I1R*Y1*Y7/AA79R+
1AA100*Y7))/AA101FR
AA149=AA51*(AA32*U+U1PR*V)-AA29*AA48-(AA29*AA49F*(AA102FR*(I1R*
1(Y1*Y8+Y2*DER2F**2)+AA82*DER1R**2*DER2F**2)/AA79R+AA100*Y8))/
1AA101FR
AA150=AA51*AA31*U-(AA29*AA49F*(AA102FR+AA81*DER1R*DER2F/AA79R+
1AA104*DER2F))/AA101FR
AA151=AA2*AA50-AA51*(AA9+AA30)+(AA29*AA49F*(AA102FR*(AA80+AA60))/
1AA79R-AA103+AA39))/AA101FR
AA152=-AA29*AA49F+AA102FR*M1*RC1/(AA101FR*AA79R)
AA153=AA51*MP*RCP
AA154=AA102FR*I1R*Y1*Y7/AA79R+AA100*Y7
AA155=AA102FR*(I1R*(Y1*Y8+Y2*DER2F**2)+AA82*DER1R**2*DER2F**2)/
1AA79R+AA100*Y8
AA156=AA102FR*AA81*DER1R*DER2F/AA79R+AA104*DER2F
AA157=AA102FR*(AA80+AA60-M1*RC1*(OX*SG-OY*CG))/AA79R-AA103+AA99
AA158=I1R*Y1*Y7
AA159=I1R*(Y1*Y8+Y2*DER2F**2)+AA82*DER1R**2*DER2F**2)
AA160=AA81*DER1R*DER2F
AA161=AA80+AA60-M1*RC1*(OX*SG-OY*CG)
AA162=IZS+AA49R*AA111/AA101RR
AA163=AA48+AA49R*AA112/AA101RR
AA164=AA49R*AA113/AA101RR
AA165=AA50+AA49R*AA114/AA101RR
AA166=IZS+AA49F*AA126/AA101FF
AA167=AA48+AA49F*AA127/AA101FF
AA168=AA49F*AA128/AA101FF
AA169=AA49F*AA129/AA101FF+AA50
AA170=IZS+AA49R*AA140/AA101RF
AA171=AA48+AA49R*AA141/AA101RF
AA172=AA49R*AA142/AA101RF
AA173=AA49R*AA143/AA101RF+AA50
AA174=IZS+AA49F*AA154/AA101FR
AA175=AA48+AA49F*AA155/AA101FR
AA176=AA49F*AA156/AA101FR
AA177=AA49F*AA157/AA101FR+AA50
RETURN
END
```

```

1  SUBROUTINE AERO(RPM,T,DDZ)
COMMON/ DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8
REAL KP,KN
KP=100.
KN=20.
PI=3.14159
Z=PI/180.
THETIN=15.*Z
DPHIE=RPM*2.*PI/60.
PHIE=DPHIE*T
DPSIE=DPHIE/KP
PSIE=DPSIE*T
TV=5.*Z
THET=THETIN+TV*SIN(KN*DPSIE*T)
DTHET=TV*KN*DPSIE*COS(KN*DPSIE*T)
DDZ=-386.*10.*S8
DTHET2=-TV*KN**2*DPSIE**2*SIN(KN*DPSIE*T)
OMX=DTHET*COS(PHIE)+DPSIE*SIN(THET)*SIN(PHIE)
OMY=-DTHET*SIN(PHIE)+DPSIE*SIN(THET)*COS(PHIE)
OMZ=OMY*S8
OMZ=DPHIE*DPSIE*COS(THET)
OMZ=OMZ*S8
DOMX=DTHET2*COS(PHIE)-DTHET*DPHIE*SIN(PHIE)+DPSIE*DTHET*COS(THET)*SIN(PHIE)+DPSIE*DPHIE*SIN(THET)*COS(PHIE)
DOMY=-DTHET2*SIN(PHIE)-DTHET*DPHIE*COS(PHIE)+DPSIE*DTHET*COS(THET)*SIN(PHIE)-DPSIE*DPHIE*SIN(THET)*COS(PHIE)
DOMY=DOMY*S8
DOMZ=-DPSIE*DTHET*SIN(THET)
DOMZ=DOMZ*S8
RETURN
END

```

```

1  SUBROUTINE KINEM(A,B,ALPHR,PHI,C,PSI,DPSI)
   COMMON/DAT8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S
   DIMENSION PHI(2)
   PI=3.14159
5  CAPA=A*COS(ALPHR)+B*COS(PHI(1)-ALPHR)
   CAPB=A*SIN(ALPHR)-B*SIN(PHI(1)-ALPHR)
   CAPC=C*SIN(ALPHR)
   PSI=2.*ATAN2((CAPA-SORT(CAPA**2+CAPB**2-CAPC**2)).(CAPB+CAPC))
10  IF (PSI.LT.O.) PSI=2.*PI+PSI
   G=(B*SIN(PHI(1))-C*SIN(PSI))/SIN(PSI+ALPHR)
   P=B*COS(PHI(1)-ALPHR-PSI)
   Q=A*COS(PSI+ALPHR)+B*COS(PHI(1)-ALPHR-PSI)
   U=P/Q
15  V=1./Q**3*(A*P**2*SIN(PSI+ALPHR)-B*(P-Q)**2*SIN(PHI(1)-ALPHR-PSI))
   AONE=B*COS(PHI(1)-PSI-ALPHR)
   BONE=B*SIN(PHI(1)-PSI-ALPHR)
   CONE=-C*SIN(ALPHR)
   DONE=C*COS(ALPHR)+G
   DPSI=U*PHI(2)
20  VST=-PHI(2)*B*SIN(PHI(1)-PSI-ALPHR)-DPSI+C*SIN(ALPHR)
   RETURN
   END

```

```

1  SUBROUTINE GKINEM(T,DPHI,PHDOT1,PHDOT2,X1,X2,X3,X4,X5,X6,
   *X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8)
COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZXP,IZXP,
+IEZP,IXS,IVS,I2S,IXI1,IEE1,IZI1,IXE1,IZX1,IEZ1,IXZ1,I2Z,IZ2,RX,RV,
+RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,
+NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMMA3P,
+GAMMA3,GAMMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,
+RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,
+RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,
+AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2
+RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2
+*F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,
+*F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
+*T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F
COMMON/DATA5/LU,LL,MU,MU1
COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,
+PHI2P,PHI1,PHI2,GAM
COMMON/DATA7/DER2R,DER2F,DER1R,DER1F
COMMON/DATA13/PHIS1,PHISFF,PHIST,PH2PI,PH2PFF,PH2PT
REAL LAMDA1,LAMDA2,L1,L2

20  C
21  C
22  C
23  MESH 2
24  IF (PHIS.GE.PHISFF)PHIS=PHIS1
25  IF (PHIS.GE.PHIST)GO TO 35
D2R=-2.*AP2*AG2*SIN(PHIS+DELP2-DELG2)-2.*AG2*B2*SIN(BETA2-DELG2)
E2R=-2.*AP2*AG2*COS(PHIS+DELP2-DELG2)-2.*AG2*B2*COS(BETA2-DELG2)
F2R=L2+2-AG2+2-AP2+2-B2+2-2.*AP2*B2*COS(PHIS+DELP2-BETA2)
ROOT2R=D2R**2+E2R**2-F2R**2
Y2R=D2R+RSGN2R*SQRT(ROOT2R)
X2R=E2R+F2R
PHI2=2.*ATAN2(Y2R,X2R)
IF (PHI2.LT.O)PHI2=PHI2+2.*PI
PHI2D=PHI2/ZZ
SLAM2=(B2*SIN(BETA2)+AP2*SIN(PHIS+DELP2)-AG2*SIN(PHI2+DELG2))/L2
CLAM2=(B2*COS(BETA2)+AP2*COS(PHIS+DELP2)-AG2*COS(PHI2+DELG2))/L2
LAMDA2=ATAN2(SLAM2,CLAM2)
D2RD=-2.*AP2*AG2*COS(PHIS+DELP2-DELG2)
E2RD=2.*AP2*AG2*SIN(PHIS+DELP2-DELG2)
F2RD=2.*AP2*B2*SIN(PHIS+DELP2-BETA2)
DER2R=(F2RD-D2RD*SIN(PHI2)-E2RD*COS(PHI2))/(D2R+COS(PHI2)-E2R*
1SIN(PHI2))
PHDOT2=DPHI+DER2R
VST2R=PHDOT2*(AG2+COS(PHI2+DELG2-LAMDA2)+RHOG2)-DPHI*(AP2+
1COS(PHIS+DELP2-LAMDA2)-RHOP2)
IF (VST2R.NE.O)GO TO 100
S2R=1.
GO TO 101
100 S2R=VST2R/ABS(VST2R)
101 D2RDD=2.*AP2*AG2*SIN(PHIS+DELP2-DELG2)
E2RDD=2.*AP2*AG2*COS(PHIS+DELP2-DELG2)
F2RDD=2.*AP2*B2*COS(PHIS+DELP2-BETA2)
X7=1./(D2R+COS(PHI2)-E2R*SIN(PHI2))
X8=F2RD-D2RD*SIN(PHI2)-E2RD*COS(PHI2)
X9=F2RDD-D2RDD*SIN(PHI2)-E2RDD*COS(PHI2)+DER2R*(-2.*D2RD+COS(PHI2)+O16150
1+2.*E2RD*SIN(PHI2))+DER2R**2*(D2R+SIN(PHI2)+E2R+COS(PHI2))
Y5=X7*X8
O15610
O15620
O15630
O15640
O15650
O15660
O15670
O15680
O15690
O15700
O15710
O15720
O15730
O15740
O15750
O15760
O15770
O15780
O15790
O15800
O15810
O15820
O15830
O15840
O15850
O15860
O15870
O15880
O15890
O15900
O15910
O15920
O15930
O15940
O15950
O15960
O15970
O15980
O15990
O16000
O16010
O16020
O16030
O16040
O16050
O16060
O16070
O16080
O16090
O16100
O16110
O16120
O16130
O16140
O16150
O16160
O16170

```

```
60      V6=X7*X9
      GO TO 36
35      D2F=-AG2*COS(PHIS-ALPHP2-DELG2)
      E2F=AG2*SIN(PHIS-ALPHP2-DELG2)
      F2F=RHOG2*B2*SIN(PHIS-ALPHP2-BETA2)
      ROOT2F=D2F**2+E2F**2-F2F**2
      V2F=D2F+RSGN2F*SORT(ROOT2F)
      X2F=E2F+F2F
      PHI2=2.*ATAN2(V2F,X2F)
      IF(PHI2.LT.O)PHI2=PHI2+2.*PI
      PHI2D=PHI2/ZZ
      G2=(AG2*SIN(PHI2+DELG2)+RHOG2*COS(PHIS-ALPHP2)-B2*SIN(BETA2))/
      1SIN(PHIS-ALPHP2)
      D2FD=AG2*SIN(PHIS-ALPHP2-DELG2)
      E2FD=AG2*COS(PHIS-ALPHP2-DELG2)
      F2FD=B2*COS(PHIS-ALPHP2-BETA2)
      DER2F=(F2FD-D2FD*SIN(PHI2)-E2FD*COS(PHI2))/(D2F*COS(PHI2)-E2F*
      1SIN(PHI2))
      PHDOT2=DPHI+DER2F
      VST2F=PHDOT2*(AG2*SIN(PHIS-ALPHP2-DELG2)-RHOG2)
      IF(VST2F.NE.O)GO TO 102
      S2F=1.
      GO TO 103
80      S2F=VST2F/ABS(VST2F)
      102 D2FDD=AG2*COS(PHIS-ALPHP2-DELG2)
      103 D2FDD=-AG2*SIN(PHIS-ALPHP2-DELG2)
      E2FDD=-AG2*SIN(PHIS-ALPHP2-BETA2)
      F2FDD=-B2*SIN(PHIS-ALPHP2-BETA2)
      X10=1./(D2F*COS(PHI2)-E2F*SIN(PHI2))
      X11=F2FD-D2FD*SIN(PHI2)-E2FD*COS(PHI2)
      X12=F2FDD-D2FDD*SIN(PHI2)-E2FDD*COS(PHI2)+DER2F*(-2.*D2FD*
      1COS(PHI2)+2.*E2FD*SIN(PHI2))+DER2F**2*(D2F*SIN(PHI2)+E2F*
      2COS(PHI2))
      Y7=X10*X11
      Y8=X10*X12
36      IF(T.EQ.O)PHI2PR=PHI2
      DDPHI2=PHI2-PHI2PR
      IF(DDPHI2.GT.O)DDPHI2=O
      PHI2PR=PHI2
      C
      C
      C
      MESH 1
      DDPHI2P=DDPHI2
      PHI2P=PHI2P+DDPHI2P
      IF(PHI2P.LE.PH2PFF)PHI2P=PH2PI
      IF(PHI2P.LE.PH2PT)GO TO 39
      DIR=-2.*AG1*(AP1*SIN(PHI2P+DELG1-DELP1)+B1*SIN(BETA1+DELG1))
      ER=-2.*AG1*(AP1*COS(PHI2P+DELG1-DELP1)+B1*COS(BETA1+DELG1))
      FIR=L1**2-AG1**2-AP1**2-B1**2-2.*AP1*B1*COS(PHI2P-BETA1-DELP1)
      ROOT1R=D1R**2+E1R**2-F1R**2
      Y1R=D1R+RSGN1R*SORT(ROOT1R)
      X1R=E1R+F1R
      PHI1=2.*ATAN2(Y1R,X1R)
      IF(PHI1.LT.O)PHI1=PHI1+2.*PI
      PHI1D=PHI1/ZZ
      SLAM1=(B1*SIN(BETA1)+AP1*SIN(PHI2P-DELP1)-AG1*SIN(PHI1-DELG1))/L1
      CLAM1=(B1*COS(BETA1)+AP1*COS(PHI2P-DELP1)-AG1*COS(PHI1-DELG1))/L1
      LAMDA1=ATAN2(SLAM1,CLAM1)
      O16180
      O16190
      O16200
      O16210
      O16220
      O16230
      O16240
      O16250
      O16260
      O16270
      O16280
      O16290
      O16300
      O16310
      O16320
      O16330
      O16340
      O16350
      O16360
      O16370
      O16380
      O16390
      O16400
      O16410
      O16420
      O16430
      O16440
      O16450
      O16460
      O16470
      O16480
      O16490
      O16500
      O16510
      O16520
      O16530
      O16540
      O16550
      O16560
      O16570
      O16580
      O16590
      O16600
      O16610
      O16620
      O16630
      O16640
      O16650
      O16660
      O16670
      O16680
      O16690
      O16700
      O16710
      O16720
      O16730
      O16740
```



```
115 P2PDDT=PHDDT2
    D1RD=-2.*AG1*AP1+COS(PHI2P+DELG1-DELP1)
    E1RD=2.*AG1*AP1+SIN(PHI2P+DELG1-DELP1)
    F1RD=2.*AP1*B1+SIN(PHI2P-BETA1-DELP1)
    DER1R=(F1RD-D1RD*SIN(PHI1)-E1RD*COS(PHI1))/(D1R+COS(PHI1)-E1R*
120 SIN(PHI1))
    PHDDT1=P2PDDT*DER1R
    VST1R=PHDDT1*(AG1+COS(PHI1-DELG1-LAMDA1)+RHOG1)-PHDDT2*(AP1+
    COS(PHI2P-DELP1-LAMDA1)-RHOP1)
    IF(VST1R.NE.O)GO TO 104
125 S1R=1.
    GO TO 105

104 S1R=VST1R/ABS(VST1R)
105 D1RDD=2.*AG1*AP1+SIN(PHI2P+DELG1-DELP1)
    E1RDO=2.*AG1*AP1+COS(PHI2P+DELG1-DELP1)
    F1RDD=2.*AP1*B1+COS(PHI2P-BETA1-DELP1)
    X1=1./(D1R+COS(PHI1)-E1R*SIN(PHI1))
    X2=F1RD-D1RD*SIN(PHI1)-E1RD*COS(PHI1)
    X3=F1RD-D1RD*SIN(PHI1)-E1RDO*COS(PHI1)+DER1R*(2.*E1RD*SIN(PHI1)
130 1-2.*D1RD*COS(PHI1))+DER1R**2*(D1R+SIN(PHI1)+E1R+COS(PHI1))
    Y1=X1*X2
    Y2=X1*X3
    GO TO 40

39 D1F=-AG1+COS(PHI2P+ALPHP1+DELG1)
    E1F=AG1+SIN(PHI2P+ALPHP1+DELG1)
    F1F=-RHOG1+B1+SIN(PHI2P+ALPHP1-BETA1)
    ROOT1F=D1F**2+E1F**2-F1F**2
    Y1F=D1F+RSQRT(SQRT(ROOT1F))
    X1F=E1F+F1F
    PHI1=2.*ATAN2(Y1F,X1F)
    IF(PHI1.LT.O)PHI1=PHI1+2.*PI
    PHI1D=PHI1/ZZ
    G1=(AG1+SIN(PHI1-DELG1)-RHOG1+COS(PHI2P+ALPHP1)-B1*SIN(BETA1))
    +/SIN(PHI2P+ALPHP1)
    D1FD=AG1*SIN(PHI2P+ALPHP1+DELG1)
    E1FD=AG1+COS(PHI2P+ALPHP1+DELG1)
    F1FD=B1+COS(PHI2P+ALPHP1-BETA1)
    DER1F=(F1FD-D1FD*SIN(PHI1)-E1FD*COS(PHI1))/(D1F+COS(PHI1)-E1F*
150 SIN(PHI1))
    P2PDDT=PHDDT2
    PHDDT1=P2PDDT*DER1F
    VST1F=PHDDT1*(AG1+SIN(PHI2P+ALPHP1-PHI1+DELG1)+RHOG1)
    IF(VST1F.NE.O)GO TO 107
    S1F=0
    GO TO 108

107 S1F=VST1F/ABS(VST1F)
108 D1FDD=AG1+COS(PHI2P+ALPHP1+DELG1)
    E1FDD=-AG1+SIN(PHI2P+ALPHP1+DELG1)
    F1FDD=-B1+SIN(PHI2P+ALPHP1-BETA1)
    X4=1./(D1F+COS(PHI1)-E1F*SIN(PHI1))
    X5=F1FD-D1FD*SIN(PHI1)-E1FD*COS(PHI1)
    X6=F1FDD-D1FDD*SIN(PHI1)-E1FDD*COS(PHI1)+DER1F*(-2.*D1FD+
165 COS(PHI1)+2.*E1FD*SIN(PHI1))+DER1F**2*(D1F+SIN(PHI1)+E1F+
    COS(PHI1))
    Y3=X4*X5
    Y4=X4*X6
    40 IF(T.EQ.O)PHI1PR=PHI1
```

SUBROUTINE GKINEM

74/860 OPT=1

FTN 4.8+650

09/27/89 15.21.25

PAGE

4

DDPHI1=PHI1-PHI1PR
IF (DDPHI1.LT.O)DDPHI1=O
PHI1PR=PHI1
IF (T.EQ.O)PHI1TOT=O
PHI1TOT=PHI1TOT+DDPHI1
GAM=PHI1RC+PHI1TOT
RETURN
END

175

017320
017330
017340
017350
017360
017370
017380
017390

```

1  SUBROUTINE TRANS1(RHOG,ALPHP,BETA,FP,AG,B,DELG,Z,PH2PT,PHIT,G)
   PI=3.14159
   CT=(-RHOG*SIN(PH2PT+ALPHP)+B*COS(BETA)+FP*COS(PH2PT+ALPHP))/
   +AG
5  ST=(RHOG*COS(PH2PT+ALPHP)+B*SIN(BETA)+FP*SIN(PH2PT+ALPHP))/AG
   PHIT=ATAN2(ST,CT)+DELG
   IF(PHIT.LT.O)PHIT=PHIT+2.*PI
   PHINEX=PHIT+O.O1+Z
10  AF=AG+COS(PHINEX-DELG-ALPHP)-B*COS(BETA-ALPHP)
   BF=-AG+SIN(PHINEX-DELG-ALPHP)+B*SIN(BETA-ALPHP)
   CF=-RHOG
   ROOTF=AF**2+BF**2-CF**2
   Y1F=AF+SORT(ROOTF)
   Y2F=AF-SORT(ROOTF)
   XF=BF+CF
15  P2NEX1=2.*ATAN2(Y1F,XF)
   P2NEX2=2.*ATAN2(Y2F,XF)
   IF(P2NEX1.LT.O.)P2NEX1=P2NEX1+2.*PI
   IF(P2NEX2.LT.O.)P2NEX2=P2NEX2+2.*PI
20  IF(ABS(P2NEX1-PH2PT).LT.ABS(P2NEX2-PH2PT))GO TO 1
   P2NEX=P2NEX2
   GO TO 2
   1 P2NEX=P2NEX1
25  2 G=(AG+SIN(PHINEX-DELG)-RHOG+COS(P2NEX+ALPHP)-B*SIN(BETA))/SIN(P2NEO17630
   1X+ALPHP)
   RETURN
   END
O17400
O17410
O17420
O17430
O17440
O17450
O17460
O17470
O17480
O17490
O17500
O17510
O17520
O17530
O17540
O17550
O17560
O17570
O17580
O17590
O17600
O17610
O17620
O17630
O17640
O17650
O17660

```

```

1  SUBROUTINE TRANS2(RHOG,ALPHP,BETA,FP,AG,B,DELG,Z,PHIST,PHIT,G)
    PI=3.141592
    ST=(-RHOG*COS(PHIST-ALPHP))+FP*SIN(PHIST-ALPHP)+B*SIN(BETA))/AG
    CT=(RHOG*SIN(PHIST-ALPHP))+FP*COS(PHIST-ALPHP)+B*COS(BETA))/AG
    PHIT=ATAN2(ST,CT)-DELG
    IF(PHIT.LT.O)PHIT=PHIT+2.*PI
    PHINEX=PHIT-O.O1*Z
    AF=AG+COS(PHINEX+DELG+ALPHP)-B*COS(BETA+ALPHP)
    BF=-AG+SIN(PHINEX+DELG+ALPHP)+B*SIN(BETA+ALPHP)
    CF=RHOG
    ROOTF=AF**2+BF**2-CF**2
    Y1F=AF+SORT(ROOTF)
    Y2F=AF-SORT(ROOTF)
    XF=BF+CF
    PSNEX1=2.*ATAN2(Y1F,XF)
    PSNEX2=2.*ATAN2(Y2F,XF)
    IF(PSNEX1.LT.O)PSNEX1=PSNEX1+2.*PI
    IF(PSNEX2.LT.O)PSNEX2=PSNEX2+2.*PI
    IF(ABS(PSNEX1-PHIST).LT.ABS(PSNEX2-PHIST))GO TO 1
    PSINEX=PSNEX2
    GO TO 2
1  PSINEX=PSNEX1
2  G=(AG*SIN(PHINEX+DELG)+RHOG+COS(PSINEX-ALPHP)-B*SIN(BETA))/SIN(
    +PSINEX-ALPHP)
    RETURN
    END
25

```

017670
017680
017690
017700
017710
017720
017730
017740
017750
017760
017770
017780
017790
017800
017810
017820
017830
017840
017850
017860
017870
017880
017890
017900
017910
017920

```

1  SUBROUTINE FCT(T,PHI,DPHI)
   DIMENSION PHI(2),DPHI(2)
   COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,
+IEZP,IXS,IVS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IV2,IZ2,RX,RV,
+RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHIRC,NG1,NG2,
+NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,
+GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA3,DELTA4,BETA2,BETA3,
+RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,
+RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,
+AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2
+ ,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2
+ ,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,
+F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
+T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F
15  COMMON/DATA2/KX,KY,OX,OY,OZ,OX,OY,OZ
   COMMON/DATA5/LU,LL,MU,MU1
   COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,
+PHI2P,PHI1,PHI2,GAM
20  COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DOONE,U,V,VST,G,P,Q,S
   COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,
+AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,
+AA130,AA131,AA132
   COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49,AA50,AA51,
+AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101R,AA101RR,
+AA101FF,AA101RF,AA102RR,AA102RF,AA102FF,AA102RF,AA103,AA104,
+AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129
   COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,
+AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,
+AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,
+AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,
+AA171,AA172,AA173,AA174,AA175,AA176,AA177
30  REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IV2,IZ2,IXS,IVS,
+IZS,IXXP,IEEP,IZXP,IXEP,IZXP,IEZP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,
+NP2,NP3,N,NT,LX1,LX2,LX2,LY2,LY2,LY2,LY2,LX1,LX2,KX,KY
35  CALL KINEM(A,B,ALPHR,PHI,C,PSI,DPSI)
   CALL AFIVE(T,PHI(1),PHI(2),PSI,DPSI,DELPHI,IPR)
   CALL ASIX(T,PHI(1),PHI(2),PSI,DPSI,DELPHI,IPR)
   BETA=PSI+PSIC
40  SB=SIN(BETA)
   CB=COS(BETA)
   CG=COS(GAM)
   SG=SIN(GAM)
45  IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 1
   IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 2
   IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 3
   IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 4
1  W1=AA105
   W2=AA106
   W3=AA107
   W4=AA108
   W5=AA109
   W6=AA110
   GO TO 5
2  W1=AA120
   W2=AA121
   W3=AA122
   W4=AA123
55

```

09/27/89 15.21.25

FTN 4.8+650

SUBROUTINE FCT 74/860 OPT=1

```

60      W5=AA124
        W6=AA125
        GO TO 5
3      W1=AA134
        W2=AA135
        W3=AA136
        W4=AA137
        W5=AA138
        W6=AA139
        GO TO 5
4      W1=AA148
        W2=AA149
        W3=AA150
        W4=AA151
        W5=AA152
        W6=AA153
5      DPHI(1)=PHI(2)
        DPHI(2)=1./W1+(-W2*PHI(2))+2-W3*PHI(2)+W4+W5*(OX+SG-OY+CG)+W6+
1      (KX+SB-KY+CB))
        RETURN
        END
75      018500
          018510
          018520
          018530
          018540
          018550
          018560
          018570
          018580
          018590
          018600
          018610
          018620
          018630
          018640
          018650
          018660
          018670
          018680
          018690
          018700

```

```

SUBROUTINE OUTP(T,PHI,DPHI,IHLF,NDIM,PRMT)
DIMENSION PHI(2),DPHI(2),PRMT(5)
COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,
+IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RV,
+RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,
+NM2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,
+GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,
+RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,
+RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,
+AP1,AG2,AP2,ALPHP1,ALPHP2,DELG2,DELG2,FP1,FP2,B1,B2,L1,L2
+ ,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2
+,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,
+F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
+T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F
COMMON/ZETA/PSI,TIME,DPSI,GP,PHICUTD
COMMON/DATA2/KX,KY,OX,OY,OZ,OX,QY,QZ
COMMON/DATA5/LU,LL,MU,MU1
COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,
+PHI2P,PHI1,PHI2,GAM
COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DOONE,U,V,VST,G,P,Q,S
COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,
+AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,
+AA130,AA131,AA132
COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51,
+AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101FR,AA101RR,
+AA101FF,AA101RF,AA102FR,AA102RR,AA102FF,AA102RF,AA103,AA104,
+AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129
COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,
+AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,
+AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,
+AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,
+AA171,AA172,AA173,AA174,AA175,AA176,AA177
REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS,IYSO19030
+,IZS,IXXP,IEEP,IZXP,IXEP,IZXP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,
+NP2,NP3,N,NT,LX1,LX1,LY1,LY1,LL1,LX2,LY2,LL2,L1,L2,KX,KY,IPR
PHID=PHI(1)/ZZ
DELPHI=PHID-PHIPR
PHIPR=PHID
PHITOT=PHITOT+DELPHI
PHIT=PHITOT*ZZ
DDPHSD=DELPHI
DDPHIS=DDPHSD*ZZ
PHIS=PHIS+DDPHIS
PHISD=PHIS/ZZ
PHI2D=PHI2/ZZ
PHI1D=PHI1/ZZ
CALL KINEM(A,B,ALPHR,PHI,C,PS,DPSI)
PSID=PSI/ZZ
CALL AFIVE(T,PHI(1),PHI(2),PSI,DPSI,DELPHI,IPR)
CALL ASIX(T,PHI(1),PHI(2),PSI,DPSI,DELPHI,IPR)
BETA=PSI+PSIC
SB=SIN(BETA)
CB=COS(BETA)
SG=SIN(GAM)
CG=COS(GAM)
COMPUTATION OF CONTACT FORCES

```

C

```
60      IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 1
      IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 2
      IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 3
      IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 4
      1 DDPHI=(-AA106*PHI(2)**2-AA107*PHI(2)+AA108+AA109*(OX*SG-OY*CG)
      1+AA110*(KX*SB-KY*CB))/AA105
      DPSI2=U*DDPHI+V*PHI(2)**2
      F23RR=(AA111*DDPHI+AA112*PHI(2)**2+AA113*PHI(2)+AA114)/AA101RR
      F12RR=(AA115*DDPHI+AA116*PHI(2)**2+AA117*PHI(2)+AA118)/AA79R
      PN=(I2S*DDPHI+AA48*PHI(2)**2+F23RR*AA49R+AA50)/AA51
      IF(F23RR.GT.F23RRMX)F23RRMX=F23RR
      IF(F12RR.GT.F12RRMX)F12RRMX=F12RR
      IF(PN.GT.PNMAX)PNMAX=PN
      PNPSI=(IPR*DPSI2+AA32*DPSI**2+AA31*DPSI+AA119-MP*RCP*(KX*SB-KY*CB)
      1)/AA29
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5
      WRITE(6,101)T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23RR,F12RR,PN,PNPSI,
      1DDPHI
      GO TO 5
      2 DDPHI=(-AA121*PHI(2)**2-AA122*PHI(2)+AA123+AA124*(OX*SG-OY*CG)
      1+AA125*(KX*SB-KY*CB))/AA120
      DPSI2=U*DDPHI+V*PHI(2)**2
      F23FF=(AA126*DDPHI+AA127*PHI(2)**2+AA128*PHI(2)+AA129)/AA101FF
      F12FF=(AA130*DDPHI+AA131*PHI(2)**2+AA132*PHI(2)+AA133)/AA79F
      PN=(I2S*DDPHI+AA48*PHI(2)**2+F23FF*AA49F+AA50)/AA51
      IF(F23FF.GT.F23FFMX)F23FFMX=F23FF
      IF(F12FF.GT.F12FFMX)F12FFMX=F12FF
      IF(PN.GT.PNMAX)PNMAX=PN
      PNPSI=(IPR*DPSI2+AA32*DPSI**2+AA31*DPSI+AA119-MP*RCP*(KX*SB-KY*CB)
      1)/AA29
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5
      WRITE(6,102)T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23FF,F12FF,PN,PNPSI,
      1DDPHI
      GO TO 5
      3 DDPHI=(-AA135*PHI(2)**2-AA136*PHI(2)+AA137+AA138*(OX*SG-OY*CG)
      1+AA139*(KX*SB-KY*CB))/AA134
      DPSI2=U*DDPHI+V*PHI(2)**2
      F23RF=(AA140*DDPHI+AA141*PHI(2)**2+AA142*PHI(2)+AA143)/AA101RF
      F12RF=(AA144*DDPHI+AA145*PHI(2)**2+AA146*PHI(2)+AA147)/AA79F
      PN=(I2S*DDPHI+AA48*PHI(2)**2+F23RF*AA49R+AA50)/AA51
      IF(F23RF.GT.F23RFMX)F23RFMX=F23RF
      IF(F12RF.GT.F12RFMX)F12RFMX=F12RF
      IF(PN.GT.PNMAX)PNMAX=PN
      PNPSI=(IPR*DPSI2+AA32*DPSI**2+AA31*DPSI+AA119-MP*RCP*(KX*SB-KY*CB)
      +)/AA29
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5
      WRITE(6,103)T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23RF,F12RF,PN,PNPSI,
      1DDPHI
      GO TO 5
      4 DDPHI=(-AA149*PHI(2)**2-AA150*PHI(2)+AA151+AA152*(OX*SG-OY*CG)
      1+AA153*(KX*SB-KY*CB))/AA148
      DPSI2=U*DDPHI+V*PHI(2)**2
      F23FR=(AA154*DDPHI+AA155*PHI(2)**2+AA156*PHI(2)+AA157)/AA101FR
      F12FR=(AA158*DDPHI+AA159*PHI(2)**2+AA160*PHI(2)+AA161)/AA79R
      PN=(I2S*DDPHI+AA48*PHI(2)**2+F23FR*AA49F+AA50)/AA51
      IF(F23FR.GT.F23FRMX)F23FRMX=F23FR
```



```

115 IF(F12FR.GT.F12FRMX)F12FRMX=F12FR
    IF(PN.GT.PNMAX)PNMAX=PN
    PNPSI=(IPR*DPSI2+AA32*DPSI+2*AA31*DPSI+AA119-MP+RCP*(KX*SB-KY*CB
    +)/AA29
120 IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5
    WRITE(6,104)T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23FR,F12FR,PN,PNPSI,
    1DDPHI
C
C
C
125 5 IF(PHID.GT.150.)GO TO 6
    IF(.NOT.(G.GE.O.AND.PN.GT.O))PRMT(5)=1.
    GO TO 7
130 6 IF(.NOT.(G.LE.O.AND.PN.GT.O))PRMT(5)=1.
    IF(PHITOT.LT.PHICUTO)GO TO 8
    PRMT(5)=1.
    8 TIME=T
    RETURN
C
C
C
135 101 FORMAT(6X,T=,F8.5,5X,PHI=,F7.2,5X,PHIDOT=,F7.2,5X,*G=,
    1F6.4,5X,PSID=,F7.2,5X,PSIDOT=,F8.2,5X,PHITOT=,F7.2/18X,
    2*F23FR=,F7.4,5X,*F12RR=,F7.4,5X,6X,*PN=,F7.4,5X,*PNPSI=,
    3F7.4,5X,*DDPHI=,E12.4)
140 102 FORMAT(6X,T=,F8.5,5X,PHI=,F7.2,5X,PHIDOT=,F7.2,5X,*G=,
    1F6.4,5X,PSID=,F7.2,5X,PSIDOT=,F8.2,5X,PHITOT=,F7.2/18X,
    2*F23FR=,F7.4,5X,*F12FF=,F7.4,5X,*PN=,F7.4,5X,*PNPSI=,
    3F7.4,5X,*DDPHI=,E12.4)
145 103 FORMAT(6X,T=,F8.5,5X,PHI=,F7.2,5X,PHIDOT=,F7.2,5X,*G=,
    1F6.4,5X,PSID=,F7.2,5X,PSIDOT=,F8.2,5X,PHITOT=,F7.2/18X,
    2*F23FR=,F7.4,5X,*F12RF=,F7.4,5X,*PN=,F7.4,5X,*PNPSI=,
    3F7.4,5X,*DDPHI=,E12.4)
150 104 FORMAT(6X,T=,F8.5,5X,PHI=,F7.2,5X,PHIDOT=,F7.2,5X,*G=,
    1F6.4,5X,PSID=,F7.2,5X,PSIDOT=,F8.2,5X,PHITOT=,F7.2/18X,
    2*F23FR=,F7.4,5X,*F12FR=,F7.4,5X,*PN=,F7.4,5X,*PNPSI=,
    3F7.4,5X,*DDPHI=,E12.4)
    END
019870
019880
019890
019900
019910
019920
019930
019940
019950
019960
019970
019980
019990
020000
020010
020020
020030
020040
020050
020060
020070
020080
020090
020100
020110
020120
020130
020140
020150
020160
020170
020180
020190
020200
020210
020220
020230
020240
020250
020260

```



```

60      GO TO 5
        4 Z1=AA174
          Z2=AA175
          Z3=AA176
          Z4=AA177
        5 DX(1)=X(2)
          DX(3)=X(4)
          DX(2)=(-Z2+X(2)+2-Z3+X(2)-Z4)/Z1
          DX(4)=(-AA32+X(4)+2-AA31+X(4)-AA119+MP+RCP*(KX*SB-KY*CB))/IPR
          RETURN
          END
65
020840
020850
020860
020870
020880
020890
020900
020910
020920
020930
020940

```

```

1  SUBROUTINE OUTPF(T,X,DX,IHLF,NDIM2,PRMT)
   COMMON/DATA2/KX,KY,OX,OY
   DIMENSION X(4),DX(4),PRMT(5)
   COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,
5  +IEZP,IXS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IV2,IZ2,IXX,RY,
   +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,
   +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMMA3P,
   +GAMMA3,GAMMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,
   +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,DPMAX,PN,ALPHEN,ALPHEX,BETA1,
   +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,
10  +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2
   + RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2
   + F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,
   +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,
15  +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,PSGN1R,PSGN1F,PSGN2F
   COMMON/ZETA/PSI,TIME,DPSI,GP,PHICUTO
   COMMON/DATA5/LU,LL,MU,MU1
   COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,
   +PHI2P,PHI1,PHI2,GAM
20  COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S
   COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,
   +AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,
   +AA130,AA131,AA132
   COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51,
25  +AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101R,AA101RR,
   +AA101FF,AA101RF,AA102RR,AA102RF,AA102FF,AA102RF,AA103,AA104,
   +AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129
   COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,
   +AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,
30  +AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,
   +AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,
   +AA171,AA172,AA173,AA174,AA175,AA176,AA177
   REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IV2,IZ2,IXS,IYSO21270
   +,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,
35  +NP2,NP3,N,NT,LX1,LY1,LL1,LX2,LY2,LL2,L1,L2,KX,KY,IPR
   PHID=X(1)/ZZ
   PSID=X(3)/ZZ
   DELPHI=PHID-PHIPR
   PHITOT=PHITOT+DELPHI
40  PHIT=PHITOT+ZZ
   PHIPR=PHID
   DDPHSD=DELPHI
   DDPHIS=DDPHSD+ZZ
   PHIS=PHIS+DDPHIS
   CALL AFIVE(T,X(1),X(2),X(3),X(4),DELPHI,IPR)
45  CALL ASIX(T,X(1),X(2),X(3),X(4),DELPHI,IPR)
   BETA=X(3)+PSIC
   SB=SIN(BETA)
   CB=COS(BETA)
   DPSI2=(-AA32*X(4)+2-AA31*X(4)-AA119+MP+RCP*(KX+SB-KY+CB))/IPR
50
   C
   C
   C
   COMPUTATION OF CONTACT FORCES
   IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 1
   IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 2
55  IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 3
   IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 4

```

```

1 DDPHI=(-AA163*X(2)+*2-AA164*X(2)-AA165)/AA162
  T23RR=-(IZS*DDPHI+AA48*X(2)+*2+AA50)/AA49R
  T12RR=(AA115+DDPHI+AA116*X(2)+*2+AA117*X(2)+AA118)/AA79R
  IF(T23RR.GT.T23RRMX)T23RRMX=T23RR
  IF(T12RR.GT.T12RRMX)T12RRMX=T12RR
  IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5
  WRITE(6,101)PHID,X(2),PSID,X(4),PHITOT,T23RR,T12RR
101 FORMAT(6X,*T=*,F8.5X,*PHI=*,F7.2,5X,*PHIDOT=*,F7.2,5X,
+*PSI=*,F7.2,5X,*PSIDOT=*,F8.2,5X,*PHITOT=*,F7.2/20X,*T23RR=*,
+F7.3,5X,*T12RR=*,F7.3)
  GO TO 5
2 DDPHI=(-AA167*X(2)+*2+AA168*X(2)+AA169)/AA166
  T23FF=-(IZS*DDPHI+AA48*X(2)+*2+AA50)/AA49F
  T12FF=(AA130+DDPHI+AA131*X(2)+*2+AA132*X(2)+AA133)/AA79F
  IF(T23FF.GT.T23FFMX)T23FFMX=T23FF
  IF(T12FF.GT.T12FFMX)T12FFMX=T12FF
  IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5
  WRITE(6,102)PHID,X(2),PSID,X(4),PHITOT,T23FF,T12FF
102 FORMAT(6X,*T=*,F8.5X,*PHI=*,F7.2,5X,*PHIDOT=*,F7.2,5X,
+*PSI=*,F7.2,5X,*PSIDOT=*,F8.2,5X,*PHITOT=*,F7.2/20X,*T23FF=*,
+F7.3,5X,*T12FF=*,F7.3)
  GO TO 5
3 DDPHI=(-AA171*X(2)+*2+AA172*X(2)+AA173)/AA170
  T23RF=-(IZS*DDPHI+AA48*X(2)+*2+AA50)/AA49R
  T12RF=(AA144+DDPHI+AA145*X(2)+*2+AA146*X(2)+AA147)/AA79F
  IF(T23RF.GT.T23RFMX)T23RFMX=T23RF
  IF(T12RF.GT.T12RFMX)T12RFMX=T12RF
  IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5
  WRITE(6,103)PHID,X(2),PSID,X(4),PHITOT,T23RF,T12RF
103 FORMAT(6X,*T=*,F8.5X,*PHI=*,F7.2,5X,*PHIDOT=*,F7.2,5X,
+*PSI=*,F7.2,5X,*PSIDOT=*,F8.2,5X,*PHITOT=*,F7.2/20X,*T23RF=*,
+F7.3,5X,*T12RF=*,F7.3)
  GO TO 5
4 DDPHI=(-AA175*X(2)+*2+AA176*X(2)+AA177)/AA174
  T23FR=-(IZS*DDPHI+AA48*X(2)+*2+AA50)/AA49F
  T12FR=(AA158+DDPHI+AA159*X(2)+*2+AA160*X(2)+AA161)/AA79R
  IF(T23FR.GT.T23FRMX)T23FRMX=T23FR
  IF(T12FR.GT.T12FRMX)T12FRMX=T12FR
  IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5
  WRITE(6,104)PHID,X(2),PSID,X(4),PHITOT,T23FR,T12FR
104 FORMAT(6X,*T=*,F8.5X,*PHI=*,F7.2,5X,*PHIDOT=*,F7.2,5X,
+*PSI=*,F7.2,5X,*PSIDOT=*,F8.2,5X,*PHITOT=*,F7.2/20X,*T23FR=*,
+F7.3,5X,*T12FR=*,F7.3)
  GO TO 5
C
C CHECK FOR CONTINUED FREE MOTION
C
5 IF(T.EQ.TIME)GO TO 9
  F=A*SIN(X(3)+ALPHR)-B*SIN(X(1)-X(3)-ALPHR)-C*SIN(ALPHR)
  PHI1D=PHI1/ZZ
  PHI2D=PHI2/ZZ
  PHISD=PHIS/ZZ
  PHI2PD=PHI2P/ZZ
  GP=A*COS(X(3)+ALPHR)+B*COS(X(1)-X(3)-ALPHR)-C*COS(ALPHR)
  IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 10
  WRITE(6,105)F,GP
105 FORMAT(22X,*F=*,F5.3,3X,*GP=*,F5.3)
10 IF(PHID.LT.145..AND.F.GT.O)GO TO 6

```

SUBROUTINE OUTPF

74/860 OPT=1

FTN 4.8*650

09/27/89 15.21.25

PAGE

3

115

IF(PHID.GE.145...AND.F.LT.O)GO TO 7
PRMT(5)=1.

6 IF(GP.LT.O)PRMT(5)=1.

GO TO 8

7 IF(GP.GT.O)PRMT(5)=1.

8 TIME=T

IF(PHITOT.LT.PHICUTD)GO TO 9

PRMT(5)=1.

9 RETURN

END

120

021980
021990
022000
022010
022020
022030
022040
022050
022060
022070

```

1  SUBROUTINE IMPACT(PHI,DPHI,PSI,DPSI)
COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,
+IEZP,IXS,IVS,IZS,IXX1,IEE1,IZZ1,IXE1,IEZ1,IX2,IEZ2,IZ2,RX,RY,
5  +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,
+NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,
+GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,
+RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,
+RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,
10  +AP1,AG2,AP2,ALPHOP1,ALPHOP2,DELGT,DELGT2,FP1,FP2,B1,B2,L1,L2
+RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2
+RHOGRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,
+F12FFMX,T23RRMX,T12RRMX,T23RFMX,T23RFMX,T12RFMX,
15  +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F
COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,
+PHI2P,PHI1,PHI2,GAM
COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S
COMMON/DATA7/DER2R,DER2F,DER1R,DER1F
REAL ISTOT,IZS,IZ2,IZZ1,IZZP
20  AONE=B* $\cos(\text{PHI}-\text{PSI}-\text{ALPHR})$ 
DONE=C* $\cos(\text{ALPHR})+G$ 
DPHIIN=DPHI
DPSIIN=DPSI
IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))ISTOT=IZS+IZ2+DER2R**2
+IZZ1*DER2R**2+DER1R**2
25  IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))ISTOT=IZS+IZ2+DER2F**2
+IZZ1*DER1F**2+DER2F**2
IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))ISTOT=IZS+IZ2+DER2R**2
+IZZ1*DER1F**2+DER2R**2
30  IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))ISTOT=IZS+IZ2+DER2F**2
+IZZ1*DER1R**2+DER2F**2
DPHI=(DPHIIN*(ISTOT+DONE**2-EREST*IZZP+AONE**2))+DPSIIN*IZZP+
IAONE+DONE*(1.+EREST)/(IZZP+AONE**2+ISTOT+DONE**2)
DPSI=(DPHI+AONE-EREST*(DPSIIN+DONE-DPHIIN+AONE))/DONE
PHID=PHI/ZZ
PSID=PSI/ZZ
35  IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 1
WRITE(6,2)
WRITE(6,3)PHID,DPHI,PSID,DPSI,PHITOT
1 RETURN
2 FORMAT('O+.5X,+IMPACT+')
40  3 FORMAT('O+.1BX,+PHI =*,F8.3,5X,+PHIDOT =*,F8.3,5X,+PSI =*,F8.3,
15X,+PSIDOT =*,F8.3,5X,+PHITOT =*,F8.3)
END

```

```

1  SUBROUTINE GEAR(CAPRP, CAPRO, RHOG, TCG, AG, DELG)
    BETA=TCG/(2.*CAPRP)
    CAPRPX=-CAPRP*SIN(BETA)
    CAPRPY=CAPRP*COS(BETA)
    A=RHOG*RHOG-CAPRO*CAPRO
    B=RHOG*RHOG-CAPRP*CAPRP
    C=A-B
    D=2.*(CAPRO-CAPRPY)
    E=2.*CAPRPX
    F=-(C+D-CAPRO+E)
    G=SQRT((C+D-CAPRO+E)**2-(D*D+E+E)*(C-C-A+E+E))
    H=D*D+E+E
    CY1=(F+G)/H
    CY2=(F-G)/H
    IF(CY1.LT.CY2)GO TO 7
    CY=CY2
    GO TO 8
7  CY=CY1
8  CX=(C+D+CY)/E
    IG=SQRT(CX*CX+CY*CY)
    DELG=ASIN(CX/AG)
    RETURN
    END
022510
022520
022530
022540
022550
022560
022570
022580
022590
022600
022610
022620
022630
022640
022650
022660
022670
022680
022690
022700
022710
022720
022730

```


022740
022750
022760
022770
022780
022790
022800
022810

SUBROUTINE PINION(RP,RO,RHOP,AP,DELP,ALPHP,FP)
AP=RP
DELP=0
GAMP=ASIN(RHOP/AP)
ALPHP=GAMP-DELP
FP=AP*COS(GAMP)
RETURN
END

1

5

A = .22600 B = .16850 C = .13242 ALPHEN = 44.0056 ALPHEX = 28.8277
 NT = 4. CONFIG = 2.
 EREST = 0.00 LAMBDA = 91.989 N = 22.
 NG1 = 41. NG2 = 29. NP2 = 6. NP3 = 6.
 CAPRP1 = .46585 CAPRP2 = .22835
 RP2 = .06815 RP3 = .04725
 CAPR01 = .49560 CAPR02 = .24860 R02 = .08575 R03 = .05950
 M1 = .38510E-04 M2 = .38500E-05 M3 = .25920E-05 MP = .29800E-05
 IXX1 = .1748E-05 IEE1 = .2324E-05 IZZ1 = .3462E-05 IXE1 = -.4256E-06 IZX1 = -.3446E-06 IEZ1 = -.4020E-
 IX2 = .4260E-07 IY2 = .4260E-07 IZ2 = .4031E-07
 IXS = .3094E-07 IYS = .3094E-07 IZS = .1639E-07
 IXXP = .6285E-07 IEEP = .4827E-07 IZZP = .7173E-07 IXEP = .2813E-07 IZXP = 0. IEZP = 0.
 RC1 = .1000 RCP = 0.0000 RHOP = .0140 RPM = 30000. PHIRCD = -113.1200 PSICCD = 0.0000 PHID = 141.0000
 PHICUTD = 1595.
 MU = .10 MU1 = .10
 LU = .177 LL = .177
 RH01 = .04650 RH02 = .02300 RH03 = .01700
 RH0F1 = .0540 RH0F2 = .0270 RH0F3 = .0200 RH0F = .0180
 RH0P1 = .0176 RH0G1 = .0440 TCG1 = .0350
 RH0P2 = .0122 RH0G2 = .0300 TCG2 = .0240
 R1 = .22500 R2 = .40800 R3 = .36900 R4 = .38800
 AG1 = .4610 AP1 = .0682 ALPHP1 = .261 DELP1 = 0.000 DELG1 = .057
 RH0P1 = .018 RH0G1 = .044 FP1 = .0658
 AG2 = .2251 AP2 = .0473 ALPHP2 = .261 DELP2 = 0.000 DELG2 = .079
 RH0P2 = .012 RH0G2 = .030 FP2 = .0456
 J1 = .95 J2 = .95
 RX = .001 RY = .001 RZ = 20.000 S8 = -1.
 BETA1D = 225.20 BETA2D = 130.04 BETA3D = 104.36
 GAMMA2D = -111.76 GAMMA3D = -152.93 GAMMA4D = -187.55
 PHI1TD = 224.918 PH2PTD = 17.547
 PHI1ID = 219.978 PH2PID = 51.315 PH1IFD = 228.758 PH2PFD = -8.685
 PHI2TD = 130.328 PH1STD = 338.070
 PHI2ID = 137.642 PH1SID = 302.743 PH12FD = 125.228 PH1SFD = 362.743
 PHI2I = .2402E+01 PH12R1 = .2031E+01 PH12R2 = .2402E+01
 COUPLED MOTION
 T = 0.00000 PHI = 141.00 PHIDOT = 0.00 G = .0135 PSID = 44.36 PSIDOT = 0.00 PHIDOT = -0.00

T = .00000	F23FF = 4.4350	F12FF = 17.4328	PN = 1.1551	PNPSI = 1.1551	DDPHI =	.1335E+07	PHITOT =	.00
T = .00000	F23FF = 4.4348	F12FF = 17.4318	PN = 1.1551	PNPSI = 44.36	PSIDOT =	3.31	PHITOT =	.00
T = .00000	F23FF = 4.4345	F12FF = 17.4307	PN = 1.1550	PNPSI = 44.36	PSIDOT =	4.88	PHITOT =	.00
T = .00001	F23FF = 4.4342	F12FF = 17.4296	PN = 1.1549	PNPSI = 44.37	PSIDOT =	6.45	PHITOT =	.00
T = .00001	F23FF = 4.4337	F12FF = 17.4274	PN = 1.1548	PNPSI = 44.37	PSIDOT =	9.59	PHITOT =	.00
T = .00001	F23FF = 4.4331	F12FF = 17.4252	PN = 1.1547	PNPSI = 44.37	PSIDOT =	12.73	PHITOT =	.00
T = .00002	F23FF = 4.4321	F12FF = 17.4205	PN = 1.1545	PNPSI = 44.37	PSIDOT =	1334E+07	PHITOT =	.01
T = .00002	F23FF = 4.4310	F12FF = 17.4155	PN = 1.1544	PNPSI = 44.38	PSIDOT =	1332E+07	PHITOT =	.02
T = .00003	F23FF = 4.4291	F12FF = 17.4049	PN = 1.1542	PNPSI = 44.40	PSIDOT =	1331E+07	PHITOT =	.03
T = .00004	F23FF = 4.4273	F12FF = 17.3934	PN = 1.1543	PNPSI = 44.42	PSIDOT =	1326E+07	PHITOT =	.06
T = .00005	F23FF = 4.4257	F12FF = 17.3810	PN = 1.1547	PNPSI = 44.45	PSIDOT =	1321E+07	PHITOT =	.10
T = .00006	F23FF = 4.4243	F12FF = 17.3677	PN = 1.1552	PNPSI = 44.49	PSIDOT =	1314E+07	PHITOT =	.14
T = .00007	F23FF = 4.4231	F12FF = 17.3537	PN = 1.1560	PNPSI = 44.59	PSIDOT =	1306E+07	PHITOT =	.19
T = .00008	F23FF = 4.4220	F12FF = 17.3387	PN = 1.1570	PNPSI = 44.66	PSIDOT =	1297E+07	PHITOT =	.24
T = .00009	F23FF = 4.4209	F12FF = 17.3220	PN = 1.1581	PNPSI = 44.72	PSIDOT =	1287E+07	PHITOT =	.31
T = .00010	F23FF = 4.4194	F12FF = 17.3047	PN = 1.1595	PNPSI = 44.80	PSIDOT =	1276E+07	PHITOT =	.38
T = .00011	F23FF = 4.4189	F12FF = 17.2867	PN = 1.1611	PNPSI = 44.88	PSIDOT =	1263E+07	PHITOT =	.46
T = .00012	F23FF = 4.4190	F12FF = 17.2683	PN = 1.1630	PNPSI = 44.97	PSIDOT =	1249E+07	PHITOT =	.54
T = .00013	F23FF = 4.4189	F12FF = 17.2493	PN = 1.1651	PNPSI = 45.07	PSIDOT =	1234E+07	PHITOT =	.64
T = .00014	F23FF = 4.4174	F12FF = 17.2300	PN = 1.1674	PNPSI = 45.17	PSIDOT =	1218E+07	PHITOT =	.74
T = .00015	F23FF = 4.4196	F12FF = 17.2104	PN = 1.1700	PNPSI = 45.28	PSIDOT =	1201E+07	PHITOT =	.84
T = .00016	F23FF = 4.4205	F12FF = 17.1906	PN = 1.1729	PNPSI = 45.40	PSIDOT =	1183E+07	PHITOT =	.96
T = .00017	F23FF = 4.4217	F12FF = 17.1706	PN = 1.1760	PNPSI = 45.52	PSIDOT =	1164E+07	PHITOT =	1.08
T = .00018	F23FF = 4.4233	F12FF = 17.1505	PN = 1.1794	PNPSI = 45.65	PSIDOT =	1144E+07	PHITOT =	1.20
T = .00019	F23FF = 4.4253	F12FF = 17.1304	PN = 1.1831	PNPSI = 45.79	PSIDOT =	1122E+07	PHITOT =	1.34
T = .00020	F23FF = 4.4278	F12FF = 17.1105	PN = 1.1871	PNPSI = 46.01	PSIDOT =	1100E+07	PHITOT =	1.48
T = .00021	F23FF = 4.4308	F12FF = 17.0907	PN = 1.1913	PNPSI = 46.24	PSIDOT =	1077E+07	PHITOT =	1.62
T = .00022	F23FF = 4.4342	F12FF = 17.0712	PN = 1.1959	PNPSI = 46.41	PSIDOT =	1052E+07	PHITOT =	1.77
T = .00023	F23FF = 4.4382	F12FF = 17.0521	PN = 1.2007	PNPSI = 46.58	PSIDOT =	1027E+07	PHITOT =	1.93
T = .00024	F23FF = 4.4427	F12FF = 17.0335	PN = 1.2053	PNPSI = 46.76	PSIDOT =	1001E+07	PHITOT =	2.09
T = .00025	F23FF = 4.4478	F12FF = 17.0155	PN = 1.2114	PNPSI = 46.95	PSIDOT =	9739E+06	PHITOT =	2.44
T = .00026	F23FF = 4.4544	F12FF = 17.0000	PN = 1.2181	PNPSI = 47.20	PSIDOT =	9459E+06	PHITOT =	2.44

T = .00045	PHI = 211.32	PHIDOT = 39.07	G = -.0144	PSID = 316.44	PSIDOT = -44.97	PHITOT = 4.87
	F23RF = 3.8654	F12RF = 16.7772	PN = .9163	PNPSI = .9163	DDPHI = .7907E+06	
T = .00046	PHI = 211.34	PHIDOT = 47.00	G = -.0143	PSID = 316.42	PSIDOT = -53.99	PHITOT = 4.89
	F23RF = 3.8633	F12RF = 16.7708	PN = .9158	PNPSI = .9158	DDPHI = .7958E+06	
T = .00047	PHI = 211.37	PHIDOT = 54.99	G = -.0142	PSID = 316.38	PSIDOT = -63.03	PHITOT = 4.92
	F23RF = 3.8617	F12RF = 16.7665	PN = .9156	PNPSI = .9156	DDPHI = .8020E+06	
T = .00048	PHI = 211.41	PHIDOT = 63.03	G = -.0141	PSID = 316.34	PSIDOT = -72.08	PHITOT = 4.95
	F23RF = 3.8606	F12RF = 16.7643	PN = .9155	PNPSI = .9155	DDPHI = .8094E+06	
T = .00049	PHI = 211.45	PHIDOT = 71.17	G = -.0140	PSID = 316.30	PSIDOT = -81.15	PHITOT = 4.99
	F23RF = 3.8600	F12RF = 16.7643	PN = .9156	PNPSI = .9156	DDPHI = .8181E+06	
T = .00050	PHI = 211.49	PHIDOT = 79.39	G = -.0138	PSID = 316.25	PSIDOT = -90.25	PHITOT = 5.03
	F23RF = 3.8599	F12RF = 16.7665	PN = .9159	PNPSI = .9159	DDPHI = .8282E+06	
T = .00051	PHI = 211.54	PHIDOT = 87.72	G = -.0136	PSID = 316.20	PSIDOT = -99.37	PHITOT = 5.08
	F23RF = 3.8603	F12RF = 16.7710	PN = .9164	PNPSI = .9164	DDPHI = .8395E+06	
T = .00052	PHI = 211.59	PHIDOT = 96.17	G = -.0135	PSID = 316.14	PSIDOT = -108.53	PHITOT = 5.13
	F23RF = 3.8612	F12RF = 16.7778	PN = .9171	PNPSI = .9171	DDPHI = .8523E+06	
T = .00053	PHI = 211.65	PHIDOT = 104.75	G = -.0133	PSID = 316.07	PSIDOT = -117.72	PHITOT = 5.19
	F23RF = 3.8626	F12RF = 16.7870	PN = .9179	PNPSI = .9179	DDPHI = .8666E+06	
T = .00054	PHI = 211.71	PHIDOT = 113.48	G = -.0131	PSID = 316.00	PSIDOT = -126.96	PHITOT = 5.25
	F23RF = 3.8646	F12RF = 16.7987	PN = .9190	PNPSI = .9190	DDPHI = .8823E+06	
T = .00055	PHI = 211.78	PHIDOT = 122.38	G = -.0128	PSID = 315.93	PSIDOT = -136.25	PHITOT = 5.32
	F23RF = 3.8672	F12RF = 16.8127	PN = .9202	PNPSI = .9202	DDPHI = .8997E+06	
T = .00056	PHI = 211.85	PHIDOT = 131.46	G = -.0126	PSID = 315.85	PSIDOT = -145.58	PHITOT = 5.40
	F23RF = 3.8703	F12RF = 16.8292	PN = .9216	PNPSI = .9216	DDPHI = .9188E+06	
T = .00057	PHI = 211.93	PHIDOT = 140.74	G = -.0123	PSID = 315.76	PSIDOT = -154.98	PHITOT = 5.47
	F23RF = 3.8739	F12RF = 16.8482	PN = .9232	PNPSI = .9232	DDPHI = .9396E+06	
T = .00058	PHI = 212.01	PHIDOT = 150.23	G = -.0120	PSID = 315.67	PSIDOT = -164.44	PHITOT = 5.56
	F23RF = 3.8781	F12RF = 16.8697	PN = .9249	PNPSI = .9249	DDPHI = .9623E+06	
T = .00059	PHI = 212.10	PHIDOT = 159.96	G = -.0117	PSID = 315.57	PSIDOT = -173.96	PHITOT = 5.65
	F23RF = 3.8828	F12RF = 16.8937	PN = .9268	PNPSI = .9268	DDPHI = .9870E+06	
T = .00060	PHI = 212.19	PHIDOT = 169.94	G = -.0114	PSID = 315.47	PSIDOT = -183.56	PHITOT = 5.74
	F23RF = 3.8881	F12RF = 16.9202	PN = .9289	PNPSI = .9289	DDPHI = .1014E+07	
T = .00061	PHI = 212.29	PHIDOT = 180.21	G = -.0111	PSID = 315.36	PSIDOT = -193.24	PHITOT = 5.84
	F23RF = 3.8939	F12RF = 16.9491	PN = .9311	PNPSI = .9311	DDPHI = .1043E+07	
T = .00062	PHI = 212.40	PHIDOT = 190.77	G = -.0107	PSID = 315.25	PSIDOT = -202.98	PHITOT = 5.95
	F23RF = 3.9003	F12RF = 16.9805	PN = .9334	PNPSI = .9334	DDPHI = .1074E+07	
T = .00063	PHI = 212.51	PHIDOT = 201.66	G = -.0103	PSID = 315.13	PSIDOT = -212.83	PHITOT = 6.06
	F23RF = 3.9071	F12RF = 17.0144	PN = .9359	PNPSI = .9359	DDPHI = .1108E+07	
T = .00064	PHI = 212.63	PHIDOT = 212.90	G = -.0099	PSID = 315.00	PSIDOT = -222.76	PHITOT = 6.18
	F23RF = 3.9145	F12RF = 17.0506	PN = .9385	PNPSI = .9385	DDPHI = .1145E+07	
T = .00065	PHI = 212.76	PHIDOT = 224.52	G = -.0095	PSID = 314.87	PSIDOT = -232.79	PHITOT = 6.30
	F23RF = 3.9224	F12RF = 17.0893	PN = .9412	PNPSI = .9412	DDPHI = .1184E+07	
T = .00066	PHI = 212.89	PHIDOT = 236.53	G = -.0091	PSID = 314.74	PSIDOT = -242.90	PHITOT = 6.43
	F23RF = 3.9308	F12RF = 17.1303	PN = .9439	PNPSI = .9439	DDPHI = .1226E+07	
T = .00067	PHI = 213.03	PHIDOT = 249.00	G = -.0086	PSID = 314.59	PSIDOT = -253.13	PHITOT = 6.57
	F23RF = 3.9395	F12RF = 17.1736	PN = .9467	PNPSI = .9467	DDPHI = .1271E+07	
T = .00068	PHI = 213.17	PHIDOT = 261.92	G = -.0081	PSID = 314.45	PSIDOT = -263.44	PHITOT = 6.72
	F23RF = 3.9487	F12RF = 17.2189	PN = .9495	PNPSI = .9495	DDPHI = .1321E+07	
T = .00069	PHI = 213.33	PHIDOT = 275.36	G = -.0076	PSID = 314.29	PSIDOT = -273.88	PHITOT = 6.87
	F23RF = 3.9583	F12RF = 17.2664	PN = .9523	PNPSI = .9523	DDPHI = .1374E+07	
T = .00070	PHI = 213.49	PHIDOT = 289.34	G = -.0070	PSID = 314.13	PSIDOT = -284.41	PHITOT = 7.04
	F23RF = 3.9682	F12RF = 17.3158	PN = .9549	PNPSI = .9549	DDPHI = .1431E+07	
T = .00071	PHI = 213.66	PHIDOT = 303.93	G = -.0065	PSID = 313.97	PSIDOT = -295.07	PHITOT = 7.21
	F23RF = 3.9785	F12RF = 17.3670	PN = .9575	PNPSI = .9575	DDPHI = .1493E+07	
T = .00072	PHI = 213.84	PHIDOT = 319.14	G = -.0059	PSID = 313.79	PSIDOT = -305.82	PHITOT = 7.38
	F23RF = 3.9889	F12RF = 17.4199	PN = .9598	PNPSI = .9598	DDPHI = .1559E+07	
T = .00073	PHI = 214.03	PHIDOT = 335.06	G = -.0052	PSID = 313.62	PSIDOT = -316.72	PHITOT = 7.57
	F23RF = 3.9996	F12RF = 17.4743	PN = .9619	PNPSI = .9619	DDPHI = .1632E+07	
T = .00074	PHI = 214.22	PHIDOT = 351.71	G = -.0046	PSID = 313.43	PSIDOT = -327.70	PHITOT = 7.77
	F23RF = 4.0104	F12RF = 17.5302	PN = .9637	PNPSI = .9637	DDPHI = .1710E+07	
T = .00075	PHI = 214.43	PHIDOT = 369.20	G = -.0039	PSID = 313.24	PSIDOT = -338.83	PHITOT = 7.97
	F23RF = 4.0213	F12RF = 17.5872	PN = .9650	PNPSI = .9650	DDPHI = .1794E+07	

T = .00077 PHI = 214.87 PHIDOT = 406.84 G = -.0024 PSID = 312.84 PSIDOT = -361.40 PHITOT = 8.42
 F23RF = 4.0430 F12RF = 17.7039 PN = .9661 PNPSI = .9661 DDPHI = .1985E+07
 T = .00078 PHI = 215.11 PHIDOT = 427.15 G = -.0016 PSID = 312.63 PSIDOT = -372.83 PHITOT = 8.66
 F23RF = 4.0537 F12RF = 17.7632 PN = .9655 PNPSI = .9655 DDPHI = .2092E+07
 T = .00079 PHI = 215.36 PHIDOT = 448.61 G = -.0008 PSID = 312.41 PSIDOT = -384.39 PHITOT = 8.91
 F23RF = 4.0641 F12RF = 17.8225 PN = .9640 PNPSI = .9640 DDPHI = .2209E+07
 T = .00080 PHI = 215.63 PHIDOT = 471.24 G = -.0001 PSID = 312.19 PSIDOT = -396.00 PHITOT = 9.17
 F23RF = 4.0741 F12RF = 17.8817 PN = .9615 PNPSI = .9615 DDPHI = .2336E+07

FREE MOTION

T = .00080 PHI = 133.81 PHIDOT = 471.24 PSI = 44.18 PSIDOT = -396.00 PHITOT = 9.17
 T23RF = 3.516 T12RF = 16.387
 T = .00081 PHI = 134.10 PHIDOT = 546.94 PSI = 43.95 PSIDOT = -393.23 PHITOT = 9.46
 T23RF = 3.531 T12RF = 16.458
 F = .012 GP = .030
 T = .00082 PHI = 134.44 PHIDOT = 623.02 PSI = 43.73 PSIDOT = -390.47 PHITOT = 9.80
 T23RF = 3.546 T12RF = 16.531
 F = .011 GP = .029
 T = .00083 PHI = 134.81 PHIDOT = 699.83 PSI = 43.50 PSIDOT = -387.71 PHITOT = 10.18
 T23RF = 3.562 T12RF = 16.605
 F = .010 GP = .029
 T = .00084 PHI = 135.24 PHIDOT = 777.09 PSI = 43.28 PSIDOT = -384.96 PHITOT = 10.60
 T23RF = 3.578 T12RF = 16.682
 F = .009 GP = .028
 T = .00085 PHI = 135.71 PHIDOT = 855.15 PSI = 43.06 PSIDOT = -382.22 PHITOT = 11.07
 T23RF = 3.594 T12RF = 16.761
 F = .007 GP = .028
 T = .00086 PHI = 136.22 PHIDOT = 933.69 PSI = 42.84 PSIDOT = -379.49 PHITOT = 11.58
 T23RF = 3.612 T12RF = 16.842
 F = .006 GP = .027
 T = .00087 PHI = 136.78 PHIDOT = 1013.14 PSI = 42.63 PSIDOT = -376.76 PHITOT = 12.14
 T23RF = 3.630 T12RF = 16.926
 F = .004 GP = .026
 T = .00088 PHI = 137.38 PHIDOT = 1093.09 PSI = 42.41 PSIDOT = -374.04 PHITOT = 12.74
 T23RF = 3.648 T12RF = 17.012
 F = .003 GP = .025
 T = .00089 PHI = 138.03 PHIDOT = 1174.05 PSI = 42.20 PSIDOT = -371.33 PHITOT = 13.39
 T23RF = 3.668 T12RF = 17.102
 F = .001 GP = .024
 T = .00090 PHI = 138.72 PHIDOT = 1255.54 PSI = 41.99 PSIDOT = -368.63 PHITOT = 14.09
 T23RF = 3.689 T12RF = 17.194
 F = -.001 GP = .023
 VP = -43.452 VS = 128.111

IMPACT

PHI = 138.724 PHIDOT = 65.162 PSI = 41.987 PSIDOT = 56.407 PHITOT = 14.088
 VS = 6.649

COUPLED MOTION

T = .00090 PHI = 138.72 PHIDOT = 65.16 G = .0221 PSID = 42.30 PSIDOT = 57.07 PHITOT = 14.09
 F23RF = 4.4646 F12RF = 19.3304 PN = 1.1945 PNPSI = 1.1945 DDPHI = .1679E+07
 T = .00091 PHI = 138.77 PHIDOT = 81.98 G = .0219 PSID = 42.34 PSIDOT = 71.89 PHITOT = 14.13
 F23RF = 4.4913 F12RF = 19.4383 PN = 1.2036 PNPSI = 1.2036 DDPHI = .1686E+07
 T = .00092 PHI = 138.82 PHIDOT = 98.86 G = .0217 PSID = 42.38 PSIDOT = 86.83 PHITOT = 14.18
 F23RF = 4.5187 F12RF = 19.5483 PN = 1.2133 PNPSI = 1.2133 DDPHI = .1692E+07
 T = .00093 PHI = 138.88 PHIDOT = 115.80 G = .0215 PSID = 42.44 PSIDOT = 101.89 PHITOT = 14.24
 F23RF = 4.5466 F12RF = 19.6603 PN = 1.2235 PNPSI = 1.2235 DDPHI = .1696E+07
 T = .00094 PHI = 138.95 PHIDOT = 132.76 G = .0212 PSID = 42.50 PSIDOT = 117.06 PHITOT = 14.31
 F23RF = 4.5752 F12RF = 19.7743 PN = 1.2342 PNPSI = 1.2342 DDPHI = .1699E+07
 T = .00095 PHI = 139.03 PHIDOT = 149.76 G = .0209 PSID = 42.53 PSIDOT = 133.85 PHITOT = 14.38

T = .09200 T12RR = 15.814 T23RR = 3.912 PHI = 134.18 PHIDOT = 687.27 PSI = 43.89 PSIDOT = -496.69 PHITOT = 1580.45
 T23RR = 3.894 F = .012 GP = .030 T12RR = 15.751
 T = .09201 PHI = 134.60 PHIDOT = 779.25 PSI = 43.61 PSIDOT = -493.52 PHITOT = 1580.87
 T23RR = 3.877 F = .011 GP = .029 T12RR = 15.693
 T = .09202 PHI = 135.07 PHIDOT = 870.91 PSI = 43.33 PSIDOT = -490.34 PHITOT = 1581.34
 T23RR = 3.863 F = .009 GP = .029 T12RR = 15.642
 T = .09203 PHI = 135.59 PHIDOT = 962.19 PSI = 43.05 PSIDOT = -487.14 PHITOT = 1581.87
 T23RR = 3.849 F = .007 GP = .028 T12RR = 15.597
 T = .09204 PHI = 136.17 PHIDOT = 1053.23 PSI = 42.77 PSIDOT = -483.93 PHITOT = 1582.44
 T23RR = 3.838 F = .006 GP = .027 T12RR = 15.559
 T = .09205 PHI = 136.80 PHIDOT = 1143.98 PSI = 42.49 PSIDOT = -480.71 PHITOT = 1583.07
 T23RR = 3.828 F = .004 GP = .026 T12RR = 15.527
 T = .09206 PHI = 137.48 PHIDOT = 1234.60 PSI = 42.22 PSIDOT = -477.48 PHITOT = 1583.76
 T23RR = 3.821 F = .002 GP = .025 T12RR = 15.503
 T = .09207 PHI = 138.22 PHIDOT = 1325.01 PSI = 41.94 PSIDOT = -474.24 PHITOT = 1584.49
 T23RR = 3.816 F = .000 GP = .024 T12RR = 15.486
 T = .09208 PHI = 139.00 PHIDOT = 1415.38 PSI = 41.67 PSIDOT = -470.99 PHITOT = 1585.27
 T23RR = 3.812 F = -.002 GP = .022 T12RR = 15.476
 VP = -55.487 VS = 142.459

IMPACT

PSI = 1.856 VS = 1.856 PHIDOT = 18.438 PSIDOT = 15.752 PHITOT = 1585.273
 COUPLED MOTION
 T = .09208 PHI = 139.00 PHIDOT = 18.44 G = .0210 PSID = 42.54 PSIDOT = 16.28 PHITOT = 1585.27
 F23RR = 4.2364 F12RR = 16.0074 PN = 1.1910 PNPSI = 1.1910 DDPHI = .1597E+07
 T = .09209 PHI = 139.02 PHIDOT = 34.27 G = .0210 PSID = 42.56 PSIDOT = 30.28 PHITOT = 1585.29
 F23RR = 4.1936 F12RR = 15.8548 PN = 1.1780 PNPSI = 1.1780 DDPHI = .1570E+07
 T = .09210 PHI = 139.04 PHIDOT = 49.84 G = .0209 PSID = 42.58 PSIDOT = 44.06 PHITOT = 1585.31
 F23RR = 4.1505 F12RR = 15.7011 PN = 1.1651 PNPSI = 1.1651 DDPHI = .1543E+07
 T = .09211 PHI = 139.07 PHIDOT = 65.12 G = .0208 PSID = 42.61 PSIDOT = 57.63 PHITOT = 1585.35
 F23RR = 4.1073 F12RR = 15.5467 PN = 1.1523 PNPSI = 1.1523 DDPHI = .1513E+07
 T = .09212 PHI = 139.11 PHIDOT = 80.10 G = .0206 PSID = 42.64 PSIDOT = 70.97 PHITOT = 1585.39
 F23RR = 4.0638 F12RR = 15.3915 PN = 1.1396 PNPSI = 1.1396 DDPHI = .1483E+07
 T = .09213 PHI = 139.16 PHIDOT = 94.77 G = .0204 PSID = 42.69 PSIDOT = 84.09 PHITOT = 1585.44
 F23RR = 4.0203 F12RR = 15.2358 PN = 1.1271 PNPSI = 1.1271 DDPHI = .1451E+07
 T = .09214 PHI = 139.22 PHIDOT = 109.11 G = .0202 PSID = 42.74 PSIDOT = 96.98 PHITOT = 1585.50
 F23RR = 3.9767 F12RR = 15.0797 PN = 1.1147 PNPSI = 1.1147 DDPHI = .1418E+07
 T = .09215 PHI = 139.29 PHIDOT = 123.11 G = .0200 PSID = 42.80 PSIDOT = 109.65 PHITOT = 1585.56
 F23RR = 3.9330 F12RR = 14.9233 PN = 1.1025 PNPSI = 1.1025 DDPHI = .1383E+07
 T = .09216 PHI = 139.36 PHIDOT = 136.77 G = .0197 PSID = 42.87 PSIDOT = 122.09 PHITOT = 1585.64
 F23RR = 3.8893 F12RR = 14.7668 PN = 1.0904 PNPSI = 1.0904 DDPHI = .1348E+07
 T = .09217 PHI = 139.45 PHIDOT = 150.08 G = .0194 PSID = 42.94 PSIDOT = 134.30 PHITOT = 1585.72
 F23RR = 3.8457 F12RR = 14.6102 PN = 1.0784 PNPSI = 1.0784 DDPHI = .1312E+07
 T = .09218 PHI = 139.54 PHIDOT = 163.01 G = .0190 PSID = 43.02 PSIDOT = 146.28 PHITOT = 1585.81
 F23RR = 3.8020 F12RR = 14.4538 PN = 1.0665 PNPSI = 1.0665 DDPHI = .1275E+07
 T = .09219 PHI = 139.63 PHIDOT = 175.58 G = .0190 PSID = 43.11 PSIDOT = 158.03 PHITOT = 1585.91
 F23RR = 3.7585 F12RR = 14.2977 PN = 1.0548 PNPSI = 1.0548 DDPHI = .1238E+07
 T = .09220 PHI = 139.74 PHIDOT = 187.77 G = .0188 PSID = 43.20 PSIDOT = 169.55 PHITOT = 1586.01
 F23RR = 3.7152 F12RR = 14.1420 PN = 1.0431 PNPSI = 1.0431 DDPHI = .1200E+07

T = .09222	PHI = 139.97	PHIDOT = 210.99	G = .0174	PSID = 43.41	PSIDOT = 191.89	PHITOT = 1586.24
F23RR = 3.6290	F12RR = 13.8323	F12RR = 13.8323	PN = 1.0203	PNPSI = 1.0203	DDPHI = 1.122E+07	
T = .09223	PHI = 140.09	PHIDOT = 222.01	G = .0169	PSID = 43.52	PSIDOT = 202.71	PHITOT = 1586.36
F23RR = 3.5862	F12RR = 13.6787	F12RR = 13.6787	PN = 1.0091	PNPSI = 1.0091	DDPHI = 1.082E+07	
T = .09224	PHI = 140.22	PHIDOT = 232.63	G = .0164	PSID = 43.64	PSIDOT = 213.29	PHITOT = 1586.49
F23RR = 3.5438	F12RR = 13.5260	F12RR = 13.5260	PN = .9980	PNPSI = .9980	DDPHI = 1.042E+07	
T = .09225	PHI = 140.36	PHIDOT = 242.86	G = .0159	PSID = 43.77	PSIDOT = 223.65	PHITOT = 1586.63
F23RR = 3.5017	F12RR = 13.3745	F12RR = 13.3745	PN = .9871	PNPSI = .9871	DDPHI = 1.002E+07	
T = .09226	PHI = 140.50	PHIDOT = 252.68	G = .0154	PSID = 43.90	PSIDOT = 233.78	PHITOT = 1586.77
F23RR = 3.4599	F12RR = 13.2243	F12RR = 13.2243	PN = .9763	PNPSI = .9763	DDPHI = .9621E+06	
T = .09227	PHI = 140.65	PHIDOT = 262.10	G = .0148	PSID = 44.03	PSIDOT = 243.68	PHITOT = 1586.92
F23RR = 3.4186	F12RR = 13.0754	F12RR = 13.0754	PN = .9656	PNPSI = .9656	DDPHI = .9217E+06	
T = .09228	PHI = 140.80	PHIDOT = 271.11	G = .0142	PSID = 44.18	PSIDOT = 253.34	PHITOT = 1587.07
F23RR = 3.3777	F12RR = 12.9281	F12RR = 12.9281	PN = .9551	PNPSI = .9551	DDPHI = .8814E+06	
T = .09229	PHI = 140.96	PHIDOT = 279.72	G = .0136	PSID = 44.32	PSIDOT = 262.79	PHITOT = 1587.23
F23RR = 3.3373	F12RR = 12.7826	F12RR = 12.7826	PN = .9448	PNPSI = .9448	DDPHI = .8411E+06	
T = .09230	PHI = 141.12	PHIDOT = 287.93	G = .0130	PSID = 44.48	PSIDOT = 272.01	PHITOT = 1587.39
F23RR = 3.2975	F12RR = 12.6388	F12RR = 12.6388	PN = .9346	PNPSI = .9346	DDPHI = .8009E+06	
T = .09231	PHI = 141.29	PHIDOT = 295.74	G = .0124	PSID = 44.63	PSIDOT = 281.00	PHITOT = 1587.56
F23RR = 3.2582	F12RR = 12.4971	F12RR = 12.4971	PN = .9246	PNPSI = .9246	DDPHI = .7609E+06	
T = .09232	PHI = 141.46	PHIDOT = 303.15	G = .0117	PSID = 44.80	PSIDOT = 289.78	PHITOT = 1587.73
F23RR = 3.1268	F12RR = 12.3559	F12RR = 12.3559	PN = .9198	PNPSI = .9198	DDPHI = .7283E+06	
T = .09233	PHI = 141.63	PHIDOT = 310.22	G = .0110	PSID = 44.97	PSIDOT = 298.39	PHITOT = 1587.91
F23RR = 3.0893	F12RR = 12.2188	F12RR = 12.2188	PN = .9093	PNPSI = .9093	DDPHI = .6876E+06	
T = .09234	PHI = 141.81	PHIDOT = 316.91	G = .0103	PSID = 45.14	PSIDOT = 306.80	PHITOT = 1588.09
F23RR = 3.0524	F12RR = 12.0841	F12RR = 12.0841	PN = .8990	PNPSI = .8990	DDPHI = .6474E+06	
T = .09235	PHI = 142.00	PHIDOT = 323.20	G = .0096	PSID = 45.32	PSIDOT = 314.98	PHITOT = 1588.27
F23RR = 3.0163	F12RR = 11.9520	F12RR = 11.9520	PN = .8890	PNPSI = .8890	DDPHI = .6076E+06	
T = .09236	PHI = 142.18	PHIDOT = 329.09	G = .0089	PSID = 45.50	PSIDOT = 322.94	PHITOT = 1588.46
F23RR = 2.9808	F12RR = 11.8225	F12RR = 11.8225	PN = .8791	PNPSI = .8791	DDPHI = .5833E+06	
T = .09237	PHI = 142.37	PHIDOT = 334.59	G = .0081	PSID = 45.69	PSIDOT = 330.68	PHITOT = 1588.65
F23RR = 2.9461	F12RR = 11.6959	F12RR = 11.6959	PN = .8694	PNPSI = .8694	DDPHI = .5295E+06	
T = .09238	PHI = 142.57	PHIDOT = 339.71	G = .0074	PSID = 45.88	PSIDOT = 338.21	PHITOT = 1588.84
F23RR = 2.9122	F12RR = 11.5721	F12RR = 11.5721	PN = .8599	PNPSI = .8599	DDPHI = .4914E+06	
T = .09239	PHI = 142.76	PHIDOT = 344.44	G = .0066	PSID = 46.08	PSIDOT = 345.53	PHITOT = 1589.04
F23RR = 2.8792	F12RR = 11.4514	F12RR = 11.4514	PN = .8506	PNPSI = .8506	DDPHI = .4539E+06	
T = .09240	PHI = 142.96	PHIDOT = 348.81	G = .0058	PSID = 46.28	PSIDOT = 352.65	PHITOT = 1589.23
F23RR = 2.8470	F12RR = 11.3340	F12RR = 11.3340	PN = .8416	PNPSI = .8416	DDPHI = .4171E+06	
T = .09241	PHI = 143.16	PHIDOT = 352.81	G = .0050	PSID = 46.48	PSIDOT = 359.55	PHITOT = 1589.44
F23RR = 2.8157	F12RR = 11.2198	F12RR = 11.2198	PN = .8327	PNPSI = .8327	DDPHI = .3810E+06	
T = .09242	PHI = 143.37	PHIDOT = 356.46	G = .0042	PSID = 46.69	PSIDOT = 366.26	PHITOT = 1589.64
F23RR = 2.7854	F12RR = 11.1091	F12RR = 11.1091	PN = .8242	PNPSI = .8242	DDPHI = .3456E+06	
T = .09243	PHI = 143.57	PHIDOT = 359.75	G = .0034	PSID = 46.90	PSIDOT = 372.78	PHITOT = 1589.84
F23RR = 2.7560	F12RR = 11.0019	F12RR = 11.0019	PN = .8159	PNPSI = .8159	DDPHI = .3111E+06	
T = .09244	PHI = 143.78	PHIDOT = 362.71	G = .0025	PSID = 47.12	PSIDOT = 379.10	PHITOT = 1590.05
F23RR = 2.7276	F12RR = 10.8984	F12RR = 10.8984	PN = .8078	PNPSI = .8078	DDPHI = .2775E+06	
T = .09245	PHI = 143.99	PHIDOT = 365.33	G = .0017	PSID = 47.33	PSIDOT = 385.24	PHITOT = 1590.26
F23RR = 2.7002	F12RR = 10.7987	F12RR = 10.7987	PN = .8000	PNPSI = .8000	DDPHI = .2447E+06	
T = .09246	PHI = 144.20	PHIDOT = 367.63	G = .0009	PSID = 47.56	PSIDOT = 391.19	PHITOT = 1590.47
F23RR = 2.6739	F12RR = 10.7029	F12RR = 10.7029	PN = .7925	PNPSI = .7925	DDPHI = .2128E+06	
T = .09247	PHI = 144.41	PHIDOT = 369.61	G = -.0000	PSID = 47.78	PSIDOT = 396.97	PHITOT = 1590.68
F23RR = 2.6487	F12RR = 10.6111	F12RR = 10.6111	PN = .7853	PNPSI = .7853	DDPHI = .1818E+06	

FREE MOTION

T = .09247	PHI = 209.86	PHIDOT = 369.61	PSI = 315.79	PSIDOT = 396.97	PHITOT = 1590.68
T23RR = 2.219	T12RR = 9.621	T12RR = 9.621			
T = .09248	PHI = 210.09	PHIDOT = 415.82	PSI = 316.02	PSIDOT = 393.39	PHITOT = 1590.91
T23RR = 2.203	T12RR = 9.559	T12RR = 9.559			
T = .09249	PHI = 210.34	PHIDOT = 461.55	PSI = 316.24	PSIDOT = 389.81	PHITOT = 1591.16
F = -.003 GP = .017					

T = .09250 PHI = 210.62 PHIDOT = 506.76 PSI = 316.41 PSIDOT = 386.25 PHITOT = 1591.43
T23RR = 2.175 T12RR = 9.453
F = -.001 GP = .016
T = .09251 PHI = 210.92 PHIDOT = 551.55 PSI = 316.69 PSIDOT = 382.69 PHITOT = 1591.74
T23RR = 2.164 T12RR = 9.409
F = -.000 GP = .015
T = .09252 PHI = 211.25 PHIDOT = 595.88 PSI = 316.91 PSIDOT = 379.14 PHITOT = 1592.07
T23RR = 2.154 T12RR = 9.371
F = .001 GP = -.015
VP = 79.272 VS = -70.357

IMPACT

VP = 18.916 VS = 18.916 PHI = 211.248 PHIDOT = -160.209 PSI = 316.905 PSIDOT = 182.620 PHITOT = 1592.066

COUPLED MOTION

T = .09252 PHI = 211.25 PHIDOT = -160.21 G = -.0146 PSID = 316.53 PSIDOT = 185.33 PHITOT = 1592.07
F23RR = 3.8644 F12RR = 12.1610 PN = 1.6835 PNPSI = 1.6835 DDPHI = .2638E+07
T = .09253 PHI = 211.16 PHIDOT = -134.13 G = -.0149 PSID = 316.62 PSIDOT = 156.11 PHITOT = 1591.98
F23RR = 3.8530 F12RR = 12.1139 PN = 1.6814 PNPSI = 1.6814 DDPHI = .2581E+07
T = .09254 PHI = 211.09 PHIDOT = -108.57 G = -.0152 PSID = 316.71 PSIDOT = 126.99 PHITOT = 1591.91
F23RR = 3.8425 F12RR = 12.0712 PN = 1.6792 PNPSI = 1.6792 DDPHI = .2534E+07
T = .09255 PHI = 211.04 PHIDOT = -83.42 G = -.0153 PSID = 316.77 PSIDOT = 97.97 PHITOT = 1591.86
F23RR = 3.8330 F12RR = 12.0328 PN = 1.6770 PNPSI = 1.6770 DDPHI = .2497E+07
T = .09256 PHI = 211.00 PHIDOT = -58.61 G = -.0155 PSID = 316.82 PSIDOT = 69.03 PHITOT = 1591.82
F23RR = 3.8244 F12RR = 11.9990 PN = 1.6750 PNPSI = 1.6750 DDPHI = .2469E+07
T = .09257 PHI = 210.97 PHIDOT = -34.02 G = -.0156 PSID = 316.85 PSIDOT = 40.15 PHITOT = 1591.79
F23RR = 3.8169 F12RR = 11.9696 PN = 1.6731 PNPSI = 1.6731 DDPHI = .2450E+07
T = .09258 PHI = 210.96 PHIDOT = -9.59 G = -.0156 PSID = 316.86 PSIDOT = 11.33 PHITOT = 1591.78
F23RR = 3.8104 F12RR = 11.9449 PN = 1.6713 PNPSI = 1.6713 DDPHI = .2439E+07
T = .09258 PHI = 210.96 PHIDOT = -6.54 G = -.0156 PSID = 316.86 PSIDOT = 7.73 PHITOT = 1591.78
F23RR = 3.8097 F12RR = 11.9422 PN = 1.6711 PNPSI = 1.6711 DDPHI = .2438E+07
T = .09258 PHI = 210.96 PHIDOT = -3.50 G = -.0156 PSID = 316.87 PSIDOT = 4.13 PHITOT = 1591.78
F23RR = 3.8090 F12RR = 11.9395 PN = 1.6709 PNPSI = 1.6709 DDPHI = .2438E+07
T = .09259 PHI = 210.96 PHIDOT = -1.97 G = -.0156 PSID = 316.87 PSIDOT = 2.33 PHITOT = 1591.78
F23RR = 3.8086 F12RR = 11.9381 PN = 1.6708 PNPSI = 1.6708 DDPHI = .2437E+07
T = .09259 PHI = 210.96 PHIDOT = -.45 G = -.0156 PSID = 316.87 PSIDOT = .53 PHITOT = 1591.78
F23RR = 3.8083 F12RR = 11.9368 PN = 1.6707 PNPSI = 1.6707 DDPHI = .2437E+07
T = .09259 PHI = 210.96 PHIDOT = -.07 G = -.0156 PSID = 316.87 PSIDOT = .08 PHITOT = 1591.78
F23RR = 3.8082 F12RR = 11.9365 PN = 1.6707 PNPSI = 1.6707 DDPHI = .2437E+07
T = .09259 PHI = 210.96 PHIDOT = .10 G = -.0156 PSID = 316.87 PSIDOT = -.11 PHITOT = 1591.78
F23RR = 2.3842 F12RR = 9.7003 PN = .5759 PNPSI = .5759 DDPHI = .3620E+06
T = .09259 PHI = 210.96 PHIDOT = .15 G = -.0156 PSID = 316.87 PSIDOT = -.18 PHITOT = 1591.78
F23RR = 2.3840 F12RR = 9.6997 PN = .5758 PNPSI = .5758 DDPHI = .3620E+06
T = .09259 PHI = 210.96 PHIDOT = .21 G = -.0156 PSID = 316.87 PSIDOT = -.25 PHITOT = 1591.78
F23RR = 2.3839 F12RR = 9.6990 PN = .5758 PNPSI = .5758 DDPHI = .3619E+06
T = .09259 PHI = 210.96 PHIDOT = .32 G = -.0156 PSID = 316.87 PSIDOT = -.38 PHITOT = 1591.78
F23RR = 2.3835 F12RR = 9.6978 PN = .5757 PNPSI = .5757 DDPHI = .3618E+06
T = .09259 PHI = 210.96 PHIDOT = .44 G = -.0156 PSID = 316.87 PSIDOT = -.51 PHITOT = 1591.78
F23RR = 2.3832 F12RR = 9.6966 PN = .5755 PNPSI = .5755 DDPHI = .3617E+06
T = .09259 PHI = 210.96 PHIDOT = .66 G = -.0156 PSID = 316.87 PSIDOT = -.78 PHITOT = 1591.78
F23RR = 2.3825 F12RR = 9.6941 PN = .5753 PNPSI = .5753 DDPHI = .3615E+06
T = .09259 PHI = 210.96 PHIDOT = .89 G = -.0156 PSID = 316.87 PSIDOT = -1.05 PHITOT = 1591.78
F23RR = 2.3818 F12RR = 9.6917 PN = .5750 PNPSI = .5750 DDPHI = .3613E+06
T = .09259 PHI = 210.96 PHIDOT = 1.11 G = -.0156 PSID = 316.87 PSIDOT = -1.32 PHITOT = 1591.78
F23RR = 2.3811 F12RR = 9.6893 PN = .5748 PNPSI = .5748 DDPHI = .3612E+06
T = .09259 PHI = 210.96 PHIDOT = 1.34 G = -.0156 PSID = 316.87 PSIDOT = -1.58 PHITOT = 1591.78
F23RR = 2.3805 F12RR = 9.6869 PN = .5746 PNPSI = .5746 DDPHI = .3610E+06
T = .09259 PHI = 210.96 PHIDOT = 1.79 G = -.0156 PSID = 316.87 PSIDOT = -2.11 PHITOT = 1591.78
F23RR = 2.3792 F12RR = 9.6822 PN = .5741 PNPSI = .5741 DDPHI = .3606E+06
T = .09259 PHI = 210.96 PHIDOT = 2.24 G = -.0156 PSID = 316.87 PSIDOT = -2.65 PHITOT = 1591.78
F23RR = 2.3792 F12RR = 9.6822 PN = .5741 PNPSI = .5741 DDPHI = .3606E+06

T = .09260	F23RR = 2.3753	F12RR = 9.6686	PHI = 210.96	PHIDOT = 4.04	PN = .5727	PSID = 316.86	PNPSI = .5727	DDPHI = .3596E+06	PHITOT = 1591.78
T = .09260	F23RR = 2.3729	F12RR = 9.6599	PHI = 210.96	PHIDOT = 4.94	PN = .5719	PSID = 316.86	PNPSI = .5719	DDPHI = .3590E+06	PHITOT = 1591.78
T = .09260	F23RR = 2.3706	F12RR = 9.6515	PHI = 210.96	PHIDOT = 5.83	PN = .5710	PSID = 316.86	PNPSI = .5710	DDPHI = .3584E+06	PHITOT = 1591.78
T = .09261	F23RR = 2.3683	F12RR = 9.6435	PHI = 210.96	PHIDOT = 7.62	PN = .5702	PSID = 316.86	PNPSI = .5702	DDPHI = .3579E+06	PHITOT = 1591.78
T = .09261	F23RR = 2.3641	F12RR = 9.6284	PHI = 210.97	PHIDOT = 9.40	PN = .5686	PSID = 316.86	PNPSI = .5686	DDPHI = .3570E+06	PHITOT = 1591.78
T = .09262	F23RR = 2.3602	F12RR = 9.6147	PHI = 210.97	PHIDOT = 11.18	PN = .5672	PSID = 316.86	PNPSI = .5672	DDPHI = .3562E+06	PHITOT = 1591.79
T = .09262	F23RR = 2.3566	F12RR = 9.6022	PHI = 210.97	PHIDOT = 12.96	PN = .5658	PSID = 316.85	PNPSI = .5658	DDPHI = .3557E+06	PHITOT = 1591.79
T = .09263	F23RR = 2.3535	F12RR = 9.5911	PHI = 210.98	PHIDOT = 16.51	PN = .5646	PSID = 316.84	PNPSI = .5646	DDPHI = .3553E+06	PHITOT = 1591.80
T = .09264	F23RR = 2.3482	F12RR = 9.5727	PHI = 210.99	PHIDOT = 20.06	PN = .5625	PSID = 316.83	PNPSI = .5625	DDPHI = .3551E+06	PHITOT = 1591.81
T = .09265	F23RR = 2.3443	F12RR = 9.5597	PHI = 211.00	PHIDOT = 23.62	PN = .5608	PSID = 316.81	PNPSI = .5608	DDPHI = .3556E+06	PHITOT = 1591.82
T = .09266	F23RR = 2.3419	F12RR = 9.5520	PHI = 211.02	PHIDOT = 27.20	PN = .5596	PSID = 316.80	PNPSI = .5596	DDPHI = .3568E+06	PHITOT = 1591.84
T = .09267	F23RR = 2.3409	F12RR = 9.5495	PHI = 211.03	PHIDOT = 30.80	PN = .5589	PSID = 316.78	PNPSI = .5589	DDPHI = .3587E+06	PHITOT = 1591.85
T = .09268	F23RR = 2.3414	F12RR = 9.5524	PHI = 211.05	PHIDOT = 34.43	PN = .5586	PSID = 316.75	PNPSI = .5586	DDPHI = .3613E+06	PHITOT = 1591.87
T = .09269	F23RR = 2.3433	F12RR = 9.5605	PHI = 211.07	PHIDOT = 38.10	PN = .5587	PSID = 316.73	PNPSI = .5587	DDPHI = .3647E+06	PHITOT = 1591.89
T = .09270	F23RR = 2.3466	F12RR = 9.5739	PHI = 211.10	PHIDOT = 41.81	PN = .5593	PSID = 316.70	PNPSI = .5593	DDPHI = .3689E+06	PHITOT = 1591.92
T = .09271	F23RR = 2.3513	F12RR = 9.5926	PHI = 211.12	PHIDOT = 45.58	PN = .5604	PSID = 316.67	PNPSI = .5604	DDPHI = .3738E+06	PHITOT = 1591.94
T = .09272	F23RR = 2.3575	F12RR = 9.6164	PHI = 211.15	PHIDOT = 49.41	PN = .5619	PSID = 316.64	PNPSI = .5619	DDPHI = .3794E+06	PHITOT = 1591.97
T = .09273	F23RR = 2.3650	F12RR = 9.6455	PHI = 211.18	PHIDOT = 53.30	PN = .5639	PSID = 316.61	PNPSI = .5639	DDPHI = .3858E+06	PHITOT = 1592.00
T = .09274	F23RR = 2.3739	F12RR = 9.6796	PHI = 211.21	PHIDOT = 57.27	PN = .5662	PSID = 316.57	PNPSI = .5662	DDPHI = .3930E+06	PHITOT = 1592.03
T = .09275	F23RR = 2.3842	F12RR = 9.7188	PHI = 211.24	PHIDOT = 61.33	PN = .5691	PSID = 316.53	PNPSI = .5691	DDPHI = .4010E+06	PHITOT = 1592.06
T = .09276	F23RR = 2.3959	F12RR = 9.7631	PHI = 211.28	PHIDOT = 65.48	PN = .5723	PSID = 316.49	PNPSI = .5723	DDPHI = .4099E+06	PHITOT = 1592.10
T = .09277	F23RR = 2.4089	F12RR = 9.8123	PHI = 211.32	PHIDOT = 69.73	PN = .5760	PSID = 316.44	PNPSI = .5760	DDPHI = .4195E+06	PHITOT = 1592.14
T = .09278	F23RR = 2.4232	F12RR = 9.8664	PHI = 211.36	PHIDOT = 74.08	PN = .5801	PSID = 316.40	PNPSI = .5801	DDPHI = .4300E+06	PHITOT = 1592.18
T = .09279	F23RR = 2.4388	F12RR = 9.9253	PHI = 211.40	PHIDOT = 78.56	PN = .5846	PSID = 316.35	PNPSI = .5846	DDPHI = .4414E+06	PHITOT = 1592.22
T = .09280	F23RR = 2.4557	F12RR = 9.9890	PHI = 211.45	PHIDOT = 83.17	PN = .5895	PSID = 316.29	PNPSI = .5895	DDPHI = .4537E+06	PHITOT = 1592.27
T = .09281	F23RR = 2.4738	F12RR = 10.0574	PHI = 211.50	PHIDOT = 87.91	PN = .5948	PSID = 316.24	PNPSI = .5948	DDPHI = .4669E+06	PHITOT = 1592.32
T = .09282	F23RR = 2.4932	F12RR = 10.1303	PHI = 211.55	PHIDOT = 92.80	PN = .6005	PSID = 316.18	PNPSI = .6005	DDPHI = .4811E+06	PHITOT = 1592.37
T = .09283	F23RR = 2.5138	F12RR = 10.2076	PHI = 211.61	PHIDOT = 97.84	PN = .6066	PSID = 316.12	PNPSI = .6066	DDPHI = .4963E+06	PHITOT = 1592.42
T = .09284	F23RR = 2.5355	F12RR = 10.2894	PHI = 211.66	PHIDOT = 103.06	PN = .6130	PSID = 316.05	PNPSI = .6130	DDPHI = .5125E+06	PHITOT = 1592.48
T = .09285	F23RR = 2.5583	F12RR = 10.3754	PHI = 211.72	PHIDOT = 108.45	PN = .6198	PSID = 315.99	PNPSI = .6198	DDPHI = .5297E+06	PHITOT = 1592.54
T = .09286	F23RR = 2.5823	F12RR = 10.4655	PHI = 211.79	PHIDOT = 114.03	PN = .6269	PSID = 315.91	PNPSI = .6269	DDPHI = .5481E+06	PHITOT = 1592.61

T = .09288	F23RR = 2.6334	F12RR = 10.6578	PN = .6422	PNPSI = .6422	DDPHI = .5884E+06
F23RR = 2.6604	PHI = 211.93	PHIDOT = 125.81	G = -.0123	PSID = 315.76	PSIDOT = -138.57
T = .09289	F23RR = 2.6884	PHI = 212.00	PN = .6503	PNPSI = .6503	DDPHI = .6103E+06
F23RR = 2.7174	PHI = 212.08	PHIDOT = 132.03	G = -.0121	PSID = 315.68	PSIDOT = -144.64
T = .09290	F23RR = 2.7472	PHI = 212.16	PN = .6586	PNPSI = .6586	DDPHI = .6337E+06
F23RR = 2.7778	PHI = 212.24	PHIDOT = 138.49	G = -.0118	PSID = 315.60	PSIDOT = -150.87
T = .09291	F23RR = 2.8092	PHI = 212.33	PN = .6673	PNPSI = .6673	DDPHI = .6584E+06
F23RR = 2.8413	PHI = 212.43	PHIDOT = 145.21	G = -.0115	PSID = 315.51	PSIDOT = -157.26
T = .09292	F23RR = 2.8741	PHI = 212.52	PN = .6761	PNPSI = .6761	DDPHI = .6845E+06
F23RR = 2.9075	PHI = 212.63	PHIDOT = 152.20	G = -.0113	PSID = 315.42	PSIDOT = -163.82
T = .09293	F23RR = 2.9416	PHI = 212.73	PN = .6853	PNPSI = .6853	DDPHI = .7122E+06
F23RR = 2.9761	PHI = 212.85	PHIDOT = 159.47	G = -.0110	PSID = 315.32	PSIDOT = -170.53
T = .09294	F23RR = 3.0112	PHI = 212.96	PN = .6946	PNPSI = .6946	DDPHI = .7416E+06
F23RR = 3.0466	PHI = 213.09	PHIDOT = 167.05	G = -.0106	PSID = 315.22	PSIDOT = -177.43
T = .09295	F23RR = 3.0824	PHI = 213.22	PN = .7041	PNPSI = .7041	DDPHI = .7726E+06
F23RR = 3.1186	PHI = 213.35	PHIDOT = 174.94	G = -.0103	PSID = 315.12	PSIDOT = -184.49
T = .09296	F23RR = 3.1549	PHI = 213.49	PN = .7138	PNPSI = .7138	DDPHI = .8056E+06
F23RR = 3.1914	PHI = 213.64	PHIDOT = 183.18	G = -.0100	PSID = 315.01	PSIDOT = -191.75
T = .09297	F23RR = 3.2281	PHI = 213.79	PN = .7236	PNPSI = .7236	DDPHI = .8404E+06
F23RR = 3.2648	PHI = 213.96	PHIDOT = 191.77	G = -.0096	PSID = 314.90	PSIDOT = -199.18
T = .09298	F23RR = 3.2915	PHI = 214.13	PN = .7336	PNPSI = .7336	DDPHI = .8774E+06
F23RR = 3.3241	PHI = 214.30	PHIDOT = 200.75	G = -.0092	PSID = 314.78	PSIDOT = -206.81
T = .09299	F23RR = 3.3549	PHI = 214.46	PN = .7436	PNPSI = .7436	DDPHI = .9165E+06
F23RR = 3.3875	PHI = 214.63	PHIDOT = 210.12	G = -.0088	PSID = 314.66	PSIDOT = -214.62
T = .09300	F23RR = 3.4186	PHI = 214.80	PN = .7537	PNPSI = .7537	DDPHI = .9581E+06
F23RR = 3.4512	PHI = 214.97	PHIDOT = 219.93	G = -.0084	PSID = 314.54	PSIDOT = -222.64
T = .09301	F23RR = 3.4849	PHI = 215.04	PN = .7638	PNPSI = .7638	DDPHI = .1002E+07
F23RR = 3.5175	PHI = 215.21	PHIDOT = 230.19	G = -.0080	PSID = 314.41	PSIDOT = -230.85
T = .09302	F23RR = 3.5504	PHI = 215.38	PN = .7739	PNPSI = .7739	DDPHI = .1049E+07
F23RR = 3.5830	PHI = 215.55	PHIDOT = 240.94	G = -.0075	PSID = 314.27	PSIDOT = -239.26
T = .09303	F23RR = 3.6157	PHI = 215.75	PN = .7839	PNPSI = .7839	DDPHI = .10
F23RR = 3.6483	PHI = 215.92	PHIDOT = 252.20	G = -.0070	PSID = 314.13	PSIDOT = -247.88
T = .09304	F23RR = 3.6810	PHI = 216.09	PN = .7939	PNPSI = .7939	DDPHI = .11
F23RR = 3.7136	PHI = 216.26	PHIDOT = 264.01	G = -.0065	PSID = 313.99	PSIDOT = -256.70
T = .09305	F23RR = 3.7463	PHI = 216.43	PN = .8037	PNPSI = .8037	DDPHI = .12
F23RR = 3.7789	PHI = 216.60	PHIDOT = 276.40	G = -.0060	PSID = 313.84	PSIDOT = -265.72
T = .09306	F23RR = 3.8110	PHI = 216.77	PN = .8133	PNPSI = .8133	DDPHI = .1268E+07
F23RR = 3.8436	PHI = 216.94	PHIDOT = 289.41	G = -.0055	PSID = 313.68	PSIDOT = -274.96
T = .09307	F23RR = 3.8763	PHI = 217.14	PN = .8226	PNPSI = .8226	DDPHI = .1332E+07
F23RR = 3.9089	PHI = 217.31	PHIDOT = 303.08	G = -.0049	PSID = 313.52	PSIDOT = -284.40
T = .09308	F23RR = 3.9416	PHI = 217.51	PN = .8316	PNPSI = .8316	DDPHI = .1401E+07
F23RR = 3.9742	PHI = 217.68	PHIDOT = 317.47	G = -.0043	PSID = 313.36	PSIDOT = -294.05
T = .09309	F23RR = 4.0075	PHI = 217.85	PN = .8360	PNPSI = .8360	DDPHI = .1467E+07
F23RR = 4.0401	PHI = 218.02	PHIDOT = 330.20	G = -.0040	PSID = 313.20	PSIDOT = -303.20
T = .09310	F23RR = 4.0728	PHI = 218.22	PN = .8404	PNPSI = .8404	DDPHI = .1532E+07
F23RR = 4.1054	PHI = 218.41	PHIDOT = 343.03	G = -.0037	PSID = 313.03	PSIDOT = -312.47
T = .09311	F23RR = 4.1381	PHI = 218.49	PN = .8448	PNPSI = .8448	DDPHI = .1597E+07
F23RR = 4.1707	PHI = 218.68	PHIDOT = 355.84	G = -.0034	PSID = 312.86	PSIDOT = -321.72
T = .09312	F23RR = 4.2034	PHI = 218.87	PN = .8492	PNPSI = .8492	DDPHI = .1662E+07
F23RR = 4.2360	PHI = 219.06	PHIDOT = 368.65	G = -.0031	PSID = 312.69	PSIDOT = -331.03
T = .09313	F23RR = 4.2687	PHI = 219.26	PN = .8536	PNPSI = .8536	DDPHI = .1727E+07
F23RR = 4.3013	PHI = 219.45	PHIDOT = 381.46	G = -.0028	PSID = 312.52	PSIDOT = -340.34
T = .09314	F23RR = 4.3340	PHI = 219.49	PN = .8580	PNPSI = .8580	DDPHI = .1792E+07
F23RR = 4.3666	PHI = 219.68	PHIDOT = 394.27	G = -.0025	PSID = 312.35	PSIDOT = -349.65
T = .09315	F23RR = 4.3693	PHI = 219.73	PN = .8624	PNPSI = .8624	DDPHI = .1857E+07
F23RR = 4.4019	PHI = 219.92	PHIDOT = 407.08	G = -.0022	PSID = 312.18	PSIDOT = -358.96
T = .09316	F23RR = 4.4320	PHI = 220.00	PN = .8668	PNPSI = .8668	DDPHI = .1922E+07
F23RR = 4.4646	PHI = 220.19	PHIDOT = 419.89	G = -.0019	PSID = 312.01	PSIDOT = -368.27
T = .09317	F23RR = 4.4947	PHI = 220.28	PN = .8712	PNPSI = .8712	DDPHI = .1987E+07
F23RR = 4.5273	PHI = 220.48	PHIDOT = 432.69	G = -.0016	PSID = 311.84	PSIDOT = -377.58
T = .09318	F23RR = 4.5574	PHI = 220.57	PN = .8756	PNPSI = .8756	DDPHI = .2052E+07
F23RR = 4.5900	PHI = 220.77	PHIDOT = 445.50	G = -.0013	PSID = 311.67	PSIDOT = -386.89
T = .09319	F23RR = 4.6201	PHI = 220.86	PN = .8800	PNPSI = .8800	DDPHI = .2117E+07
F23RR = 4.6527	PHI = 221.06	PHIDOT = 458.31	G = -.0010	PSID = 311.50	PSIDOT = -396.20
T = .09320	F23RR = 4.6828	PHI = 221.15	PN = .8844	PNPSI = .8844	DDPHI = .2182E+07
F23RR = 4.7154	PHI = 221.35	PHIDOT = 471.12	G = -.0007	PSID = 311.33	PSIDOT = -405.51
T = .09321	F23RR = 4.7429	PHI = 221.44	PN = .8888	PNPSI = .8888	DDPHI = .2247E+07
F23RR = 4.7755	PHI = 221.64	PHIDOT = 483.93	G = -.0004	PSID = 311.16	PSIDOT = -414.82
T = .09322	F23RR = 4.7755	PHI = 221.64	PN = .8932	PNPSI = .8932	DDPHI = .2312E+07
F23RR = 4.8081	PHI = 221.84	PHIDOT = 496.74	G = -.0001	PSID = 310.99	PSIDOT = -424.13
T = .09323	F23RR = 4.8382	PHI = 221.93	PN = .8976	PNPSI = .8976	DDPHI = .2377E+07
F23RR = 4.8708	PHI = 222.14	PHIDOT = 509.55	G = -.0000	PSID = 310.82	PSIDOT = -433.44
T = .09324	F23RR = 4.9009	PHI = 222.23	PN = .9020	PNPSI = .9020	DDPHI = .2442E+07
F23RR = 4.9335	PHI = 222.44	PHIDOT = 522.36	G = -.0000	PSID = 310.65	PSIDOT = -442.75
T = .09325	F23RR = 4.9636	PHI = 222.52	PN = .9064	PNPSI = .9064	DDPHI = .2507E+07
F23RR = 4.9962	PHI = 222.74	PHIDOT = 535.17	G = -.0000	PSID = 310.48	PSIDOT = -452.06
T = .09326	F23RR = 5.0237	PHI = 222.83	PN = .9108	PNPSI = .9108	DDPHI = .2572E+07
F23RR = 5.0563	PHI = 223.05	PHIDOT = 547.98	G = -.0000	PSID = 310.31	PSIDOT = -461.37
T = .09327	F23RR = 5.0838	PHI = 223.14	PN = .9152	PNPSI = .9152	DDPHI = .2637E+07
F23RR = 5.1164	PHI = 223.36	PHIDOT = 560.79	G = -.0000	PSID = 310.14	PSIDOT = -470.68
T = .09328	F23RR = 5.1439	PHI = 223.23	PN = .9196	PNPSI = .9196	DDPHI = .2702E+07
F23RR = 5.1765	PHI = 223.58	PHIDOT = 573.60	G = -.0000	PSID = 309.97	PSIDOT = -480.00
T = .09329	F23RR = 5.2010	PHI = 223.57	PN = .9240	PNPSI = .9240	DDPHI = .2767E+07
F23RR = 5.2336	PHI = 223.89	PHIDOT = 586.41	G = -.0000	PSID = 309.80	PSIDOT = -489.31
T = .09330	F23RR = 5.2611	PHI = 223.86	PN = .9284	PNPSI = .9284	DDPHI = .2832E+07
F23RR = 5.2937	PHI = 224.24	PHIDOT = 599.22	G = -.0000	PSID = 309.63	PSIDOT = -498.62
T = .09331	F23RR = 5.3162	PHI = 224.13	PN = .9328	PNPSI = .9328	DDPHI = .2897E+07
F23RR = 5.3488	PHI = 224.51	PHIDOT = 612.03	G = -.0000	PSID = 309.46	PSIDOT = -507.93
T = .09332	F23RR = 5.3713	PHI = 224.42	PN = .9372	PNPSI = .9372	DDPHI = .2962E+07
F23RR = 5.4039	PHI = 224.89	PHIDOT = 624.84	G = -.0000	PSID = 309.29	PSIDOT = -517.24
T = .09333	F23RR = 5.4264	PHI = 224.71	PN = .9416	PNPSI = .9416	DDPHI = .3027E+07
F23RR = 5.4590	PHI = 225.28	PHIDOT = 637.65	G = -.0000	PSID = 309.12	PSIDOT = -526.55
T = .09334	F23RR = 5.4815	PHI = 225.00	PN = .9460	PNPSI = .9460	DDPHI = .3092E+07
F23RR = 5.5141	PHI = 225.67	PHIDOT = 650.46	G = -.0000	PSID = 308.95	PSIDOT = -535.86
T = .09335	F23RR = 5.5340	PHI = 225.42	PN = .9504	PNPSI = .9504	DDPHI = .3157E+07
F23RR = 5.5666	PHI = 226.24	PHIDOT = 663.27	G = -.0000	PSID = 308.78	PSIDOT = -545.17
T = .09336	F23RR = 5.5939	PHI = 226.00	PN = .9548	PNPSI = .9548	DDPHI = .3222E+07
F23RR = 5.6265	PHI = 226.91	PHIDOT = 676.08	G = -.0000	PSID = 308.61	PSIDOT = -554.48
T = .09337	F23RR = 5.6514	PHI = 226.77	PN = .9592	PNPSI = .9592	DDPHI = .3287E+07
F23RR = 5.6840	PHI = 227.80	PHIDOT = 688.89	G = -.0000	PSID = 308.44	PSIDOT = -563.79
T = .09338	F23RR = 5.7083	PHI = 227.00	PN = .9636	PNPSI = .9636	DDPHI = .3352E+07
F23RR = 5.7409	PHI = 228.03	PHIDOT = 701.70	G = -.0000	PSID = 308.27	PSIDOT = -573.10
T = .09339	F23RR = 5.7638	PHI = 227.27	PN = .9680	PNPSI = .9680	DDPHI = .3417E+07
F23RR = 5.7964	PHI = 229.16	PHIDOT = 714.51	G = -.0000	PSID = 308.10	PSIDOT = -582.41
T = .09340	F23RR = 5.8183	PHI = 227.76	PN = .9724	PNPSI = .9724	DDPHI = .3482E+07
F23RR = 5.8509	PHI = 230.31	PHIDOT = 727.32	G = -.0000	PSID = 307.93	PSIDOT = -591.72
T = .09341	F23RR = 5.8812	PHI = 228.00	PN = .9768	PNPSI = .9768	DDPHI = .3547E+07
F23RR = 5.9138	PHI = 231.80	PHIDOT = 740.13	G = -.0000	PSID = 307.76	PSIDOT = -601.03
T = .09342	F23RR = 5.9361	PHI = 228.49	PN = .9812	PNPSI = .9812	DDPHI = .3612E+07
F23RR = 5.9687	PHI = 234.80	PHIDOT = 752.94	G = -.0000	PSID = 307.59	PSIDOT = -610.34
T = .09343	F23RR = 5.9910	PHI = 229.00	PN = .9856	PNPSI = .9856	DDPHI = .3677E+07
F23RR = 6.0236	PHI = 238.79	PHIDOT = 765.75	G = -.0000	PSID = 307.42	PSIDOT = -619.65
T = .09344	F23RR = 6.0439	PHI = 229.77	PN = .9900	PNPSI = .9900	DDPHI = .3742E+07
F23RR = 6.0765	PHI = 243.78	PHIDOT = 778.56	G = -.0000	PSID = 307.25	PSIDOT = -628.96
T = .09345	F23RR = 6.0962	PHI = 230.50	PN = .9944	PNPSI = .9944	DDPHI = .3807E+07
F23RR = 6.1288	PHI = 248.79	PHIDOT = 791.37	G = -.0000	PSID = 307.08	PSIDOT = -638.27
T = .09346	F23RR = 6.1465	PHI = 231.27	PN = .9988	PNPSI = .9988	DDPHI = .3872E+07
F23RR = 6.1791	PHI = 253.80	PHIDOT = 804.18	G = -.0000	PSID = 306.91	PSIDOT = -647.58
T = .09347	F23RR = 6.1944	PHI = 232.16	PN = .1000	PNPSI = .1000	DDPHI = .3937E+07
F23RR = 6.2270	PHI = 258.81	PHIDOT = 816.99	G = -.0000	PSID = 306.74	PSIDOT = -656.89
T = .09348	F23RR = 6.2413	PHI = 233.14	PN = .1000	PNPSI = .1000	DDPHI = .4002E+07
F23RR = 6.2739	PHI = 263.82	PHIDOT = 829.80	G = -.0000	PSID = 306.57	PSIDOT = -666.20
T = .09349	F23RR = 6.2861	PHI = 234.3			

DISTRIBUTION LIST

Commander

Armament Research, Development and Engineering Center

U.S. Army Armament, Munitions and Chemical Command

ATTN: SMCAR-IMI-I (3)

SMCAR-GCL

SMCAR-AEF-C (8)

SMCAR-FSA

Picatinny Arsenal, NJ 07806-5000

Administrator

Defense Technical Information Center

ATTN: Accessions Division (12)

Cameron Station

Alexandria, VA 22304-6145

Director

U.S. Army Material Systems Analysis Activity

ATTN: AMXSU-MP

Aberdeen Proving Ground, MD 21005-5066

Commander

Chemical/Biological Defense Agency

U.S. Army Armament, Munitions and Chemical Command

ATTN: AMSCB-CII, Library

Aberdeen Proving Ground, MD 21010-5423

Director

U.S. Army Edgewood Research, Development and Engineering Center

ATTN: SCBRD-RTT (Aerodynamics Technical Team)

Aberdeen Proving Ground, MD 21010-5423

Director

U.S. Army Research Laboratory

ATTN: AMSRL-OP-CI-B, Technical Library

Aberdeen Proving Ground, MD 21005-5066

Chief
Benet Weapons Laboratory, CCAC
Armament Research, Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCAR-CCB-TL
Watervliet, NY 12189-5000

Director
U.S. Army TRADOC Analysis Command-WSMR
ATTN: ATRC-WSS-R
White Sands Missile Range, NM 88002

Commander
USA ARL
ATTN: Library
SMCAR-AEF-T, J. Beard
2800 Powder Mill Road
Adelphi, MD 20783