COMPUTER PROGRAM FOR PREDICTION OF FUEL CONSUMPTION
STATISTICAL DATA FOR AN UPPER STAGE THREE-AXES
STABILIZED ON-OFF CONTROL SYSTEM

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COMPUTER PROGRAM FOR PREDICTION OF FUEL CONSUMPTION STATISTICAL DATA
FOR AN UPPER STAGE THREE-AXES STABILIZED ON-OFF CONTROL SYSTEM

by R. N. Knauber
Vought Corporation

SUMMARY

This report describes a FORTRAN coded computer program and method to predict the reaction control fuel consumption statistics for a three axis stabilized rocket vehicle upper stage. It uses a Monte Carlo approach which is made more efficient by using closed form estimates of impulse usage. It includes effects of rocket motor thrust misalignment, static unbalance, aerodynamic disturbances, and deviations in trajectory, mass properties and control system characteristics. This routine has been used for over a decade to accurately predict the control fuel consumption statistics for the Scout launch vehicle second and third stage reaction control systems.

By selection of input data and options this routine can be applied to many types of on-off reaction controlled vehicles.

The psuedo random number generation and statistical analyses subroutines including the output histograms can easily be used for other Monte Carlo analyses problems.

A typical run of 200 samples requires 2 seconds of central processor time on a CDC CYBER 175 computer.
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LIST OF SYMBOLS (Cont.)

\[ \begin{align*}
T & \quad \text{booster thrust (lbf)} \\
T_1 & \quad \text{total system turn-on time delay (seconds)} \\
T_2 & \quad \text{total system turn-off time delay (seconds)} \\
t & \quad \text{time (seconds)} \\
V & \quad \text{velocity (ft/sec)} \\
W & \quad \text{weight of vehicle (unsubscripted) (lbs)} \\
W_\i & \quad \text{control fuel weight (subscripted) (lbs)} \\
x & \quad \text{body station measured positive toward tail (inches)} \\
z & \quad \text{normal location on body from centerline (inches)}
\end{align*} \]

Greek Letters

\[ \begin{align*}
\alpha & \quad \text{angle of attack (degrees)} \\
\beta & \quad \text{angle of sideslip (degrees)} \\
\gamma & \quad \text{flight path angle measured from local horizontal (degrees)} \\
\Delta & \quad \text{incremental change} \\
\epsilon & \quad \text{misalignment angle of thrust (degrees)} \\
\zeta & \quad \text{azimuth (degrees)} \\
\theta & \quad \text{pitch attitude (degrees)} \\
\lambda & \quad \text{forward cant angle of control motors (degrees)} \\
\pi & \quad \text{ratio of circular circumference to diameter} \\
\rho & \quad \text{atmospheric density (slugs/ft}^3) \\
\rho_{xy} & \quad \text{correlation coefficient of x versus y variable} \\
\sigma & \quad \text{standard deviation} \\
\phi & \quad \text{roll attitude (degrees)} \\
\psi & \quad \text{yaw attitude (degrees)}
\end{align*} \]
### LIST OF SYMBOLS (Cont.)

#### Subscripts
- **boost** during boost phase
- **C** control
- **CAP** associated with capture transient
- **coast** associated with coast period
- **cg** center of gravity
- **cp** aerodynamic center of normal force
- **D** disturbance
- **db** due to deadband
- **e** error
- **jet** control motor thrust
- **p** pitch
- **pr** predicted
- **R** roll
- **RETRO** retro following coast period
- **r** booster thrust
- **W** wind
- **x** roll axis
- **y** yaw or transverse
- **o** initial value
- **l** start or on
- **2** end or off

#### Special Notation
- Dots above a parameter denote differentiation with respect to time.
1.0 INTRODUCTION

Reaction control system fuel consumption predictions for missiles, launch vehicles and space vehicles is usually required to be accurate so that weight can be minimized without unduly sacrificing mission success probability. Almost all reaction controlled missiles, launch vehicles and spacecraft would result in loss of control and mission failure if the control fuel usage were seriously underpredicted. On many vehicles overprediction of fuel requirements results in costly weight and volume penalties. The control system designer requires an accurate prediction of the statistical distribution of required impulse or control fuel to size the system. For missions with different coast periods a prediction of fuel usage is needed for propellant loading.

The method and computer program for predicting reaction control system fuel consumption statistics presented in this report has been used over the past fifteen years for the Scout launch vehicle second and third stage reaction control systems. Predictions using this method correlate well with flight data statistics. There is a slight tendency of the method to be conservative particularly at the low end of the probability distribution. This is due to an assumption of symmetric attitude limit cycle motion when undisturbed. In actuality a certain small percentage of vehicles achieve a near zero duty cycle in an axis rather than a symmetric limit cycle. As a result fuel consumption can be lower than the minimum predicted by the method.

Prediction of control fuel by this method is only as good as the accuracy of the input data; i.e., "Garbage in - garbage out." Scout experience in accurate prediction results from accurate knowledge of disturbance statistics, particularly rocket booster motor thrust misalignment. These are derived from detailed post-flight data analyses.
2.0 METHODOLOGY

The Monte Carlo method, used herein, is a relatively straightforward approach for predicting the statistical outcome of a highly non-linear process involving many variables. On-off reaction control system fuel consumption prediction for an upper stage rocket booster vehicle is a good candidate for this method. Large amounts of computer time are normally associated with the Monte Carlo approach. The method described herein is made efficient by using a series of closed form approximations to the fuel consumption during transient maneuvers and steady state operation. As a result several hundred samples can be computed with a few seconds of computer time on a high speed digital computer. Assumptions and equations used in the computer program are described in the following paragraphs.

2.1 Fuel Consumption Assumptions

Many assumptions are made to simplify the control fuel consumption prediction process. These include:

- Uncoupled axes (pitch, yaw, roll) each having its own set of control motors.

- On-off control has a simple deadband with constant switching slope for each phase of the flight (boost and coast) (see phase plane Figure 1).

- When undisturbed each axis control achieves a symmetric limit cycle motion.

- Disturbing torques and impulses are balanced by the control system without exceeding the zero rate deadband attitude error.

- Disturbing torques of sufficient magnitude to cause deadband crossing results in fuel consumption based on angular impulse balance plus symmetric limit cycle motion (Figure 1).

- When sets of reaction control motors are shared by two or more axes, each axis has full use of the motors in an uncoupled sense (e.g., yaw-roll mixing with four (4) jets is decomposed into a yaw-axis control with 2 motors in each sense and roll axes control with 2 motors forming a couple in each sense or direction).

- Sensor, computational, filter, and control motor switching hardware responses are treated as a simple equivalent time transport lag.

- Structural mode coupling with the control system is limited. An effective time transport lag is assumed to adequately account for structurally coupling. This is the case for the Scout launch vehicle (see Appendix D of Reference 1).

- Reaction control motor pulse shapes can be expressed as an equivalent square wave with appropriate thrust level and time delays.

- Aerodynamic stability derivatives are linear and can be expressed as a constant normal force coefficient slope with angle of attack and a constant aerodynamic center location.
The vehicle is axisymmetric in terms of moments of inertia and aerodynamic configuration.

Trajectory parameters are as input and are not significantly perturbed by the off-nominal control behavior.

Changing control fuel consumption does not alter the vehicle mass properties.

Aerodynamic angle of attack includes the attitude error equal to the deadband halfwidth.

2.2 Equations

Equations describing the disturbances and fuel consumption are presented below. Trajectory geometry and definition of angles are presented in Figure 2.

2.2.1 Attitude Control Acceleration

Control angular accelerations are:

\[ \theta_c, \psi_c = \frac{F_c \phi_c}{12I_y} \]  

\[ \phi_c = \frac{2F_c R_c}{12I_x} \]

where,

\[ \phi_c = [(X_c - X_{cg}) \cos \lambda + Z_c \sin \lambda] / 12 \]
2.2.2 Disturbances

Disturbing accelerations are due to booster thrust misalignment, vehicle static unbalance and aerodynamic torques.

\[
\dot{\theta}_D = \frac{1}{I_Y} \left[ \frac{T_{r_Y}(X_r - X_{CG})}{57.3} + \frac{T_{SU} p}{W} - \frac{C_{Na} S\alpha(X_{CG} - X_{CP})}{12} \right]
\]

(2-3)

\[
\dot{\psi}_D = \frac{T_{r_Y}}{I_Y} \left[ \frac{T_{r_Y}(X_r - X_{CG})}{57.3} + \frac{T_{SU} p}{W} - \frac{C_{Na} S\beta(X_{CG} - X_{CP})}{12} \right]
\]

(2-4)

\[
\phi_D = \frac{1}{I_x} \left[ \frac{T}{57.3 W} \left( \epsilon_{r_Y} S_{U_p} - \epsilon_{r_Y} S_{U_y} \right) + \frac{C_{Na} S\alpha(X_{CG} - X_{CP})}{W} \right]
\]

(2-5)

\[
+ S_{U_y} \left[ \frac{T}{\xi_c W} \left( \epsilon_{r_Y} \frac{(X_r - X_{CG})}{12} + S_{U_y} \right) + \frac{C_{Na} S\alpha(X_{CG} - X_{CP})}{\xi_c W} \right]
\]

\[
- S_{U_p} \left[ \frac{T}{\xi_c W} \left( \epsilon_{r_Y} \frac{(X_r - X_{CG})}{12} + S_{U_y} \right) - \frac{C_{Na} S\beta(X_{CG} - X_{CP})}{\xi_c W} \right]
\]

Angles of attack and sideslip are:

\[
\alpha = \theta_{PR} - \gamma_{PR} - \gamma_{e_1} + \alpha_W + \Delta \alpha_{db}
\]

(2-6)

\[
\beta = \beta_{PR} + \xi_{e_1} \cos \gamma_{PR} + \beta_W + \Delta \beta_{db}
\]

(2-7)

(see Figure 2)

where \( \gamma_{e_1} \) is the perturbation flight path angle from previous stages plus the integrated change in flight path angle due to pointing error (deadband).

\( \zeta_{e_1} \) is the equivalent flight path deviation in the yaw plane.

\[
\gamma_{e_1} = \frac{57.3}{V} \left| \frac{\gamma_{e_0} \sqrt{g}}{57.3} + \frac{T}{W/g} \frac{\dot{\theta}_e}{dt} \right|
\]

(2-8)

\[
\xi_{e_1} = \frac{57.3}{V} \left| \frac{\xi_{e_0} \sqrt{g}}{57.3} + \frac{T}{W/g} \frac{\dot{\psi}_e}{dt} \right|
\]

(2-9)

Angles of attack and sideslip due to wind are:

\[
\alpha_w = 57.3 \frac{V_w \sin \gamma_{PR} \cos (\xi_w - \xi_{PR})}{V + V_w \cos \gamma_{PR} \cos (\xi_w - \xi_{PR})}
\]

(2-10)

\[
\beta_w = 57.3 \frac{V_w \sin (\xi_w - \xi_{PR})}{V + V_w \cos \gamma_{PR} \cos (\xi_w - \xi_{PR})}
\]

(2-11)
Incremental angles of attack and sideslip due to pointing errors are:

\[(2-12) \quad \Delta \alpha_{db} = \pm d - (\gamma_e - \gamma_{e1})/2 \]
\[(2-13) \quad \Delta \beta_{db} = \pm d + (\xi_e - \xi_{e1})/2 \]

2.2.3 Control System Duty Cycles

Control system duty cycles during boost include those due to disturbance torque balance and undisturbed limit cycle behavior.

\[(2-14) \quad DC_p = \frac{\theta_d}{\theta_c} \quad ; \quad \| \dot{\theta}_d \| \geq \dot{\theta}_{\text{TEST}} \]
\[(2-15) \quad DC_p = \frac{\theta_d}{\theta_c} + DC_{p(\text{LIMIT CYCLE})} \cdot \| \dot{\theta}_d \| < \dot{\theta}_{\text{TEST}} \]

Test accelerations are those disturbing accelerations which define the boundary between a one-sided motor firing and crossing the deadband as shown in Figure 1 and 3.

2.2.4 Limit Cycle Motion

Undisturbed limit cycle motion results in a duty cycle dependent on control system characteristics.

\[(2-16) \quad DC_{p(\text{LIMIT CYCLE})} = \frac{K_1}{1 + \frac{\theta_c}{\theta} \left( \frac{d + T_1 - K_R/K_D}{a} \right)} \]

where,

\[(2-17) \quad a = \frac{K_1 \theta_c T_2 (K_R/K_D - T_2/2) + dH}{2 K_R/K_D - T_1 - T_2} \]

\[K_1 = 1 \quad \text{for square wave pulse of control motor} \]
\[(2-18) \quad K_1 = 1 + \frac{t_p}{PW 2\pi} \left( \pi - \nu - 2\sin \nu \right) \quad \text{for thrust with overshoot (Figure 4)} \]
\[(2-19) \quad PW = \frac{2a}{K_1 \theta_c} \]
\[(2-20) \quad \nu = \tan^{-1} \left[ \frac{\pi}{\ln \left( \frac{F_p/F_c - 1}{1} \right)} \right] \]
With control motor thrust overshoot the above equations for duty cycle are computed with one iteration starting with $K_1 = 1$.

When control acceleration is very high, long delay times can result in a deadband overshoot condition; i.e., the error signal crosses the total deadband before the opposite motor actually turns off. The control acceleration at which this occurs is:

\[
(2-21) \quad \ddot{\theta}_{c,\text{MAX}} = \frac{d[2KR/KD - T_1 - T_2 - H (KR/KD - T_2/2)]}{T_2 (KR/KD - T_2/2) (KR/KD - T_1/2)}
\]

If $\ddot{\theta}_c > \ddot{\theta}_{c,\text{MAX}}$, the duty cycle becomes,

\[
(2-22) \quad DC = \frac{1}{1 + \frac{1}{2T_2 - A + \frac{1}{K_R/K_D}} \left[ \frac{A}{2} + (T_2 - A) \right] \left[ T_1 - T_2 + A \right]}
\]

where,

\[
(2-23) \quad A = \frac{2d (1 - H/2)}{\dot{\theta}_c KR/K_D}
\]

Equations for yaw and roll duty cycles are the same.

### 2.2.5 Fuel Consumption

Control fuel consumption is dependent on the total impulse and effective specific impulse of the control motors. The specific impulse of the control motors used for pitch and yaw is assumed to be the same. A separate roll motor specific impulse can be used. In most cases the specific impulse during coast is different than during boost. Boost fuel consumption is:

\[
(2-24) \quad W_{\text{BOOST}} = W_{\text{BOOST}}^p + W_{\text{BOOST}}^\gamma + W_{\text{BOOST}}^R
\]

For pitch and yaw the fuel consumed is:

\[
(2-25) \quad W_{\text{BOOST}}^p = \frac{1}{I_{SP}} \left[ \int F_{CP} DC_p \, dt + I_{\text{CAP}}^p \right]
\]

where $I_{\text{CAP}}$ is the additional impulse needed to "capture" at separation/ignition from the initial conditions on rate and displacement,

\[
(2-26) \quad I_{\text{CAP}}^p \approx \frac{F_C}{\dot{\theta}_c} \left[ \bigg| \dot{\theta}_o + \frac{2 (\dot{\theta}_o - d)}{KR/KD} \bigg| + \left| \dot{\theta}_c \right| T_2 \right]
\]
Roll fuel consumption includes an amount for booster roll torque (RTI) and pitch and yaw motor misalignment.

\[ W_{\text{BOOST}} = \frac{1}{I_{\text{SPR}}} \left[ \int F_{C_r} DC_R \, dt + I_{\text{CAPR}} + \text{RTI} + \left| \varepsilon_{\text{JET}_p} \right| \frac{Z_c}{R_c} \int F_{C_p} DC_p \, dt + \left| \varepsilon_{\text{JET}_y} \right| \frac{Z_c}{R_c} \int F_{C_y} DC_y \, dt \right] \]

During the coast phase a symmetric limit cycle is assumed. Coast fuel consumption also includes (1) an incremental amount for transients due to deadband reduction from boost to coast system, (2) guidance program attitude rate changes in pitch and yaw, and (3) an optional retro maneuver with the boost pitch and yaw control motors.

\[ W_{\text{COAST}} = \frac{\int F_{C_p} DC_p \, dt}{I_{\text{SP}_p}} + \frac{\int F_{C_y} DC_y \, dt}{I_{\text{SP}_y}} + \frac{\int F_{C_R} DC_R \, dt}{I_{\text{SP}_R}} + W_{\text{RETO}} + \Delta W_i \]

\[ W_{\text{RETO}} = 2 \left| F_{C_p} + F_{C_y} + F_{C_R} \right| \frac{I_{\text{SP}_R}}{I_{\text{SP}_R}} \]

This assumes that the four boost pitch and yaw motors fire continuously and the system operates at a 100 percent duty cycle. Additional fuel for deadband reduction and torquing rate changes for each axis is

\[ \Delta W_i = \frac{F_c}{I_{\text{SP}}} \left[ 2 T_2 + \frac{\left| \Delta \dot{\theta}_C + 57.3 a_b + \frac{2 (d_b - d_c)}{K_R/K_D} \right|}{57.3 \dot{\theta}_C} \right] \]

where \( \Delta \dot{\theta} \) is the change in guidance pitch or yaw program rate (deg/sec)

\( a_b \) is the boost system limit cycle rate (rad/sec)

\( d_b, d_c \) is the boost and coast system deadband halfwidth (degrees)

\( K_R/K_D \) is the coast system rate to displacement gain rational (sec)

\( \dot{\theta}_C \) is the coast system control acceleration (rad/sec²)
2.2.6 Trajectory and Vehicle Characteristics

Time histories of pertinent trajectory and vehicle characteristics are input to use in the calculations. These include dynamic pressure, velocity, booster thrust and propellant weight remaining, altitude, flight path angle, and azimuth. Wind velocity versus altitude is also input. Thrust misalignment is assumed to be described as an initial value and a slope which is correlated (see section 2.3).

Mass properties (center of mass station and transverse moment of inertia) is assumed to be a second order polynomial of fraction of booster propellant consumed.

Given a three point curve \((x_1, y_1), (x_2, y_2)\) and \((x_3, y_3)\) the second order function is,

\[
y = y_1 + k_1 x + k_2 x^2
\]

where,

\[
k_2 = \frac{y_3 - y_1 - \frac{x_3}{x_2}(y_2 - y_1)}{(x_3^2 - x_2x_3)}
\]

and,

\[
k_1 = \frac{(y_2 - y_1)}{x_2} - k_2x_2
\]

The independent variable \((x)\) is the fraction of booster propellant consumed, and the dependent variable is either center of mass station or the moment of inertia. The three input points should include the 0, 0.5 and 1.0 fractional propellant consumed values for best results. The burnout, or 1.0 fractional propellant consumed, values are used for coast calculations.

2.2.7 Optional Trajectory Characteristics

An optional input for certain trajectory calculations is available to approximate dynamic pressure, altitude and flight path angle. This option is used primarily where many parametric runs are required for which there are no trajectories. Given the initial flight path angle \((\gamma_0)\), velocity \((V_0)\) and dynamic pressure \((Q_0)\) the density at ignition is calculated.

\[
\rho_0 = \frac{2Q_0}{V_0^2}
\]
This density is used with a standard atmosphere logarithmic density versus altitude data set to obtain initial altitude. Thrust, weight, and drag coefficient \((C_D S)\) are input and used to propagate a gravity turn trajectory.

The set of first order equations used to propagate the trajectory is:

\[
\begin{align*}
\dot{V} &= \frac{g_0 (T - C_D S Q)}{W} - g \sin \gamma \\
\dot{h} &= -57.3 g C_D S \gamma \\
\dot{\gamma} &= V \sin \gamma
\end{align*}
\]

where,

\[
\begin{align*}
\rho &= \frac{\dot{q}}{\frac{1}{2} \rho V^2} \\
g &= \frac{g_0}{1 + \left(\frac{h}{R_0}\right)^3}
\end{align*}
\]

and,

\[
\begin{align*}
g_0 &= 32.174 \text{ ft/sec}^2 \\
R_0 &= 20,919,668 \text{ ft}
\end{align*}
\]

A Runge-Kutta integration subroutine is used to integrate these equations during boost to obtain the nominal trajectory parameters \((V, h, \gamma, Q)\).

2.3 Statistical Analysis

The analysis method used in this routine is the Monte Carlo Technique. It is based on random sampling of a set of random input variables for the vehicle, trajectory, disturbances, and control system and computing the resulting total fuel consumption, boost fuel, coast fuel, and retro time. By computing a large number of such flights the statistical variation of fuel consumption is obtained. The method of treatment of input variables and analysis of output is listed below.

2.3.1 Input Random Variables

There are many random variables required as input. These variables are assumed to be Gaussian (Normal Distribution Function). A mean and standard deviation is entered for each of these variables. In all cases except booster thrust misalignment each variable is uncorrelated with all other variables.
For uncorrelated variables the random sample is:

\[(2-40) \quad X = \bar{X} + \text{RND} \sigma_x \]

where \(\bar{X}\) is the mean value of \(x\), \(\sigma_x\) is the standard deviation of \(x\), and \(\text{RND}\) is a random normal deviate (computed by routine).

Where there is a correlation between two variables as in the case of thrust misalignment the random samples are,

\[(2-41) \quad y = \bar{Y} + \text{RND}_1 \sigma_y \rho_{xy} + \text{RND}_2 \sigma_y \sqrt{\frac{N-1}{N-2}} \left(1 - \rho_{xy}^2\right)^{\frac{1}{2}} \]

where \(\rho_{xy}\) is the correlation coefficient of the \(x\) and \(y\) variables and \(N\) is the number of samples used to derive the correlation coefficient.

The following is a list of random variables for input:

- \(\varepsilon_{r_0}\) initial value of booster thrust misalignment
- \(\varepsilon_r\) slope of booster thrust misalignment with time
- \(\dot{\theta}_o, \dot{\psi}_o, \dot{\phi}_o\) initial pitch, yaw and roll rate
- \(\theta_e, \psi_e, \phi_e\) initial attitude error in pitch, yaw, and roll
- \(\gamma_e, \zeta_e\) initial flight path and azimuth error
- \(Q_{\text{FRACT}}\) dynamic pressure fractional deviation \((Q/Q_{pr})\)
- \(I_y\) transverse moment of inertia
- \(X_{cg}\) center of mass station
- \(SU_p, SU_y\) pitch and yaw static unbalance
- \(RTI\) booster roll torque impulse
- \(\varepsilon_{\text{JET}}\) boost control motor misalignment angles
- \(V_w\) wind velocity versus altitude
- \(\zeta_w\) wind direction
- \(F_c\) control motor force levels
- \(I_{sp}\) control motor specific impulse, boost and coast
- \(F_P/F_c\) pitch and yaw control motor overshoot ratio
- \(t_p\) pitch and yaw control motor time from on to peak thrust
- \(t_{1m}\) control motor effective turn on time delay
- \(t_{2m}\) control motor effective turn-off time delay
- \(t_f\) autopilot filter effective time delay
- \(t_{\text{RG}}\) autopilot rate gyro effective time delay
- \(K_{R}/K_{D}\) autopilot rate to displacement gain ratio
- \(d\) control system deadband halfwidth
- \(H\) switching hysteresis fraction
Other input variables are not treated as random.

2.3.2 Output Statistical Analysis

The routine calculates boost, coast, and total fuel consumption for N samples (flights). The output includes the values of fuel consumption with the calculated discrete probability levels for the N samples. In addition to these discrete, the sample population mean, standard deviation, skewness, and kurtosis are output for the parameters and the logarithm of the parameters. The probability distribution function parameters and key probability levels are based on three distribution functions: (1) Normal, (2) Log-Normal, and (3) Weibull. An equivalent level of significance for each of these three distribution functions is estimated and output based on the CHI-Squared Goodness of Fit Test.

When the fuel consumption samples are arranged in ascending order, the probability that the fuel consumption will be under a particular value is given by the following equation:

\[ P \text{(fuel consumption} < W_i) = \frac{N_i}{N+1} \]

where,  
\( W_i \) is a particular value of fuel consumption.  
\( N_i \) is the sample number corresponding to \( W_i \) in the arranged fuel consumption distribution.  
\( N \) is the total number of samples calculated.

It is desirable to obtain confidence intervals about a given probability level. This is also a function of the sample size. The two sided confidence interval for the standard deviation \( \sigma \) of a population of sample size \( N \) extracted from a Normal Distribution Function is provided by the following equation:

\[ \frac{\sigma}{S_x} = \frac{1}{1 \pm k \sqrt{\frac{2}{N-1}}} \]

where,  
\( S_x \) is the sample standard deviation calculated from \( N \) samples.  
\( \sigma \) is the true standard deviation.  
\( k \) is the number of standard deviations on a Normal Distribution which provide a probability level equal to the confidence coefficient (i.e., 0.95 confidence \( -1.96 \sigma \), \( k = 1.96 \)). If only one side of the confidence interval (high side) is desired, the values of \( k \) become based on cumulative Normal Distribution probabilities.
The confidence limits for other probability levels can be established assuming normality. That is, once the standard deviation is established with an upper confidence limit (say 95 percent) then the value at another probability level can be expressed as a number of standard deviations from the mean.

\[ y' = \bar{y} + \frac{K \sqrt{2}}{1 + K \sqrt{\frac{2}{N - 1}}} \]  

(95% confidence \( k_y = 1.645 \) for one sided upper limit of confidence interval.)

where 

- \( y' \) is the value of parameter 'y' at a probability level equivalent to the mean plus 'K' standard deviations on a Normal Distribution with the desired confidence coefficient.
- \( \bar{y} \) is the sample mean (assumed to be the true mean value of the distribution function).
- \( K \) is the number of standard deviations required to provide the desired probability level.

The following is a short table for values of 'K' and 'k' for various probability levels and confidence coefficients.

<table>
<thead>
<tr>
<th>Probability Level</th>
<th>K, k ( \sqrt{2} ) (one-sided)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.500</td>
<td>0</td>
</tr>
<tr>
<td>0.900</td>
<td>1.282</td>
</tr>
<tr>
<td>0.950</td>
<td>1.645</td>
</tr>
<tr>
<td>0.995</td>
<td>2.575</td>
</tr>
<tr>
<td>0.999</td>
<td>3.090</td>
</tr>
</tbody>
</table>

For example, to find the value of 'y' at 99.5% probability at 95 percent confidence, given sample mean, \( \bar{y} \), and variance, \( S^2 \), from \( N \) samples

\[ y' = \bar{y} + \frac{2.575 S_x}{\sqrt{1 - 1.645 \sqrt{\frac{2}{N - 1}}}} \]

In the case of fuel consumption, the distribution function is not usually Gaussian (Normal Distribution). Therefore, several approximate distribution functions are tested in the routine based on the Chi-Squared Goodness of Fit Test. These include the Normal, Log-Normal and three parameter Weibull distribution. The Log-Normal Distribution is simply a transformation of the 'y' parameter to the logarithm of 'y'. As shown in the sketch below, if the probability density function is one sided, the density function of the log 'y'
may approximate a Normal Distribution. If this occurs the properties of the Normal Distribution function such as probability level and confidence coefficient, can be applied to log 'y'.

Log-Normal Density Function

\[ f(y) \]

The three parameter Weibull distribution is also used. This distribution function is described in detail in Reference (2). The cumulative probability distribution function and density function can be described in terms of three parameters 'a', 'b', and 'c' by the following equations.

\[ f(y) = \frac{c}{b} a^c b^{-c} y^{c-1} e^{-a y / b} \]

(2-46) density function

\[ F(y) = 1 - e^{-a y / b} \]

(2-47) distribution function

where,

\[ A = \left( \frac{y-a}{b} \right)^c \]

and where 'a', 'b', 'c' are values greater than zero.

The probability density function can take on many shapes by varying the values of 'a', 'b', and 'c' and thus has application to a wide variety of problems. For this application it will have a shape similar to that shown in the sketch.
For this distribution function the value of 'y' at a given probability level is given by:

\[ y = a - b \left[ \ln (1 - p) \right]^{1/c} \]

where \( P \) is the probability level.

The routine prints out the parameters 'a', 'b', and 'c' determined from the fit based on McClintock's method of Reference (2). It also prints out the values of the parameter at several key probability levels. Calculation of confidence intervals for this distribution function is not included in this routine.

In addition to the statistical analyses described above, histograms of the output are made on the line printer for ready comparison.
3.0 PROGRAM DESCRIPTION

3.1 General

This routine is programmed in FORTRAN IV for the CDC CYBER 175 system. The only non-ANSI code used is the pseudo random number generator (RANF). An ANSI option for a replacement is identified in the program listing. The routine requires approximately 16 K words. Program flow, and user instructions are presented in the following paragraphs.

3.2 Program Flow

The program flows straight forward in five basic parts.

- Input option selection
- Input of all data
- Precalculation of boost phase time histories at integration steps
- Monte Carlo calculation of specified number of cases of fuel consumption or coast time
- Statistical analysis of results

Flow charts showing the general sequence are presented in Figure 5. A list of subroutines, their cross references and common blocks are presented in Figure 6. A description of the subroutines is given in the following paragraphs.

3.3 Subroutine Description

Most of the repeated specialized calculations are performed in the seventeen subroutines. Subroutine and common reference map is presented in Figure 6. The descriptions of each follow in alphabetical order.

**ALTI**

'ALTI' is used by subroutine TABGEN when the input option requires generation of certain trajectory parameters. Given the dynamic pressure and velocity it computes the altitude based on the logarithm of inverse density versus altitude table (RHO) supplied in labeled common "DRH" defined in the 'TABGEN' subroutine.

The call to the subroutine is:

```
CALL ALTI (ALTO, VO, QO)
```

- `ALTO` - is the altitude in feet computed by this subroutine.
- `VO` - is the velocity input (ft/sec).
- `QO` - is the dynamic pressure input (lbs/ft²).
ASCEND

This subroutine rearranges an array of numbers in monotonically increasing or decreasing order.

The call to this subroutine is:

CALL ASCEND (L, VAL, M)

L - is the number of values in array VAL (input).
VAL - is the array to be rearranged (input and output).
M - input option for ascending or descending order,
   M = 0 ascending
   M = 1 descending

CALCU

This subroutine is used with "RUNGE" to calculate the trajectory state variables and their first derivatives in TABGEN. It is based on equations 2-35 through 2-39.

The call to this subroutine is:

CALL CALCU

Input and output is passed through labeled common blocks 'DDI', 'DDY', and 'DRH'. 'DDY' contains the state variables and time information.

CHISQ

This subroutine is based on the Chi-Squared Goodness of Fit Test to a known distribution. It tests for level of significance against a Normal, Log Normal, and a Weibull distribution function.

The call to this subroutine is:

CALL CHISQ (N, A, CR, NG, AM, AS, WA, WB, WC, LD)

N - is the total sample size input.
A - is the input array of values.
CR - is the output computed level of significance.
NG - is the number of cells for the CHI-Squared Goodness of Fit Test.
AM - is the computed mean.
AS - is the computed standard deviation.
WA - is the Weibull 'a' parameter.
WB - is the Weibull 'b' parameter.
WC - is the Weibull 'c' parameter.

LD = 0 for a two parameter distribution (the Normal and Log-Normal).
LD = 1 for a three parameter distribution (Weibull).

Tables of the cumulative Normal probability distribution 'C' versus number of standard deviations 'Z' are embedded in this subroutine and are part of labeled common block 'CZ'.
CYCLE

'CYCLE' computes the duty cycle for the on-off control during symmetric undisturbed limit cycle operation. It is based on equations 2-16 through 2-20. It includes the option for deadband overshoot and overshoot type control motor thrust response.

The call to this subroutine is:

CALL CYCLE (THEC, GR, DR, H, T1, T2, DC, A, NDOVER, FCT)

THEC - is the control acceleration (rad/sec^2).
GR - is the rate to displacement gain ratio (K_R/K_D sec).
DR - is the deadband halfwidth (rad).
H - is the switching hysteresis fraction.
T1 - is turn-on effective delay time (sec).
T2 - is turn-off effective delay time (sec).
DC - is the computed duty cycle.
A - is the computed limit cycle rate (rad/sec).
NDOVER - is a deadband overshoot condition check
= 0 no deadband overshoot
= 1 deadband overshoot
FCT - is a factor computed by subroutine OVRF used when second order thrust response is indicated. If FCT is less than or equal to zero iteration on pulse width is not used.

HISTO

This subroutine sorts and plots a histogram on the line printer from an array of numbers. It must be given maximum and minimum values, the number of values and the increment for each cell of the histogram. The maximum cell count is 94 to fit the line printer. Below each cell the numerical value of the cell range and the count is printed. Asterisks are used to build the histogram.

The call to this subroutine is:

CALL HISTO (X, N, XMAX, XMIN, DX)

X - is an array of numbers for the histogram (input).
N - is the number of values in the 'X' array (input).
XMAX - is maximum value value in 'X' (input).
XMIN - is minimum value in 'X' (input).
DX - is the histogram cell width (input).

OVRF

This short subroutine computes a factor for control motor thrust when characterized by an overshoot response.

The call to this subroutine is:

CALL OVRF (T, OR, FAC)

T - is given time from zero thrust to first overshoot peak (sec).
OR - is given overshoot ratio (Fp/Fc).
FAC - is computed factor to be used for thrust level on short pulse widths.
PAGEHD

For output this subroutine ejects a page and prints run number and page number at the top of each page.

The call to this subroutine is:

CALL PAGEHD (NRUN, NPAGE, NLINE)

NRUN - is the input run number to be printed.
NPAGE - is the input page number to be printed.
NLINE - is the returned line number count for the main routine.

PZC

This function subprogram computes the probability of a parameter falling in a specific range for a Normal or Weibull distribution function. It uses a table lookup of probability for the Normal Distribution function.

The call to this subroutine is:

CALL PZC (XL, XU, AM, AS, WA, WB, WC, LD, M)

XL - is input lower limit value.
XU - is input upper limit value.
AM - is input distribution mean value.
AS - is input distribution standard deviation.
WA, WB, WC - is input Weibull distribution parameters if LD > 0.
LD - is option
  LD ≤ 0 Normal distribution.
  LD > 0 Weibull distribution.
M - is current or last table lookup indicator.

This subroutine uses the Normal distribution tables in common block 'CZ' entered in Subroutine CHISQ. Probabilities for the Weibull distribution are based on Equation 2-47.

RANGE

'RANGE' is used for histogram preparation. It computes a desireable cell definition using the range of the data and a desired number of cells. The number of cells will be equal to or greater than that specified depending upon the evenness of the cell width. Acceptable engineering divisions are used in selecting cell starting and ending values. The array must be in ascending order. If it is in descending order it is first rearranged to ascending order.
The call to this subroutine is:

CALL RANGE (X, N, XMAX, XMIN, DX, NDX, ERR TB)

X - is an input array of values in ascending or descending order.
N - is number of values in 'X' array.
XMAX - is calculated upper value of 'X' array.
XMIN - is calculated lowest value of 'X' array.
DX - is computed cell width for histograms.
NDX - is the computed number of cells for the histogram.
ERRTB - is an error signal generated.
- 0 indicates no problems
- 1 indicates a zero range for the 'X' table

RNDX

A pseudo random number generator for a Normal Distribution, \( N(0, 1) \). It uses as computer supplied uniform random number generator (RANF) to generate a number from zero to one. This is transformed to give the Random Normal Deviate (RXD) from the Normal distribution having zero mean and unity variance. The coding presented in this report also shows an alternate pseudo random number generator which can be used in place of RANF.

The call to this subroutine is:

CALL RNDX (JK)

JK - is the number of random normal deviates to be calculated.

The input seed 'K' and the generated random normal deviates 'RXD' are transferred through blank common.

RUNGE

This is the basic fourth-order RUNGE-KUTTA integration method which is used in conjunction with CALC U to integrate the trajectory equations.

The call to this subroutine is:

CALL RUNGE (L, I)

L - is the control parameter for the Runge-Kutta integration formulae.
I - is the counter for the number of passes made in the multi-step process of one integration step. It is set to zero after completion of a complete cycle.

TABGEN

In cases where a ballistic (gravity turn) trajectory is flown following booster ignition certain trajectory tables are estimated by this subroutine. It uses a fourth order RUNGE-KUTTA integration of the trajectory equations in subroutines CALC U and RUNGE. It requires initial conditions of flight path angle, dynamic pressure, velocity, predicted attitude error, and drag coefficient. Input tables of thrust and weight are used. After filling tables of dynamic pressure, velocity, altitude and flight path angle, it changes the input pitch attitude error table (TABLE 6) to pitch attitude using the newly calculated flight path angle as the reference attitude.
The call to this subroutine is:

CALL TABGEN (QO, VO, GAMO)

QO - is the input initial dynamic pressure (lbs/ft²).
VO - is the input initial velocity (ft/sec).
GAMO - is the input initial flight path angle (degrees)

Output data is transferred via labeled common block 'DOUT'. Input data is transferred by common blocks 'DRH', 'DDI', and 'DDY'. This subroutine contains the data table of the logarithm of inverse atmospheric density versus altitude 'RHO' which is contained in common blocks 'DRH'.

TBLN

This is a single table lookup subroutine using linear interpolation between points. This subroutine requires separate arrays of abscissas and ordinates. The abscissas must be in ascending order.

The call to this subroutine is:

CALL TBLN (Y, X, T, A, NT, M)

Y - is the ordinate to be found.
X - is the given abscissa.
T - is the abscissa table.
A - is the corresponding ordinate table.
NT - is the number of values in each table.
M - is a current locator for the search of the table.
   'M' must be greater than zero and less than or equal to 'NT'. M returns the current location found for the abscissa and should be used for the next lookup of the same table to reduce the search time.

TBLU

This is also a single table lookup. It is based on linear interpolation between points for a single array having alternating values of abscissas and ordinates. The abscissas must be in ascending order.

The call to this subroutine is:

CALL TBLU (NT, Y, X, T, M)

NT - number of values in table 'T' including abscissas and ordinates.
Y - is the ordinate to be found.
X - is the given abscissa.
T - is the table of alternating abscissas and ordinates.
M - is the table locator described under 'TBLN' above.
THEMIN

'THEMIN' computes the minimum acceleration for which one sided limit cycle motion can occur (Figure 3).

The call to this subroutine is:

CALL THEMIN (THEC, GR, DR, H, T1, T2, THMIN)

THEC - is the given control acceleration (rad/sec\(^2\)).
GR - is the rate to displacement gain ratio (KR/KD sec).
DR - is the deadband halfwidth (radians).
H - is the switching hysteresis fraction.
T1 - is the turn-on time delay (seconds).
T2 - is the turn-off time delay (seconds).
THMIN - is the computed disturbing angular acceleration at which the deadband will get crossed (rad/sec\(^2\)).

WBL

'WBL' is the main subroutine which computes the statistical parameters from an array of numbers. It computes the mean, standard deviation, skewness and kurtosis parameters as well as selected probability levels based on the Normal, Log-Normal and Weibull probability distribution functions. It also estimates a Level of Significance based on the Chi-Squared Goodness of Fit Test.

The call to this subroutine is:

CALL WBL (N, Y, NG, F)

N - is the number of values in the sample population.
Y - is the sample population array.
NG - is the number of cells to be used for the CHI-Squared Goodness of Fit Test.
F - is an array of 20 numbers containing the output information.
F(1) - is sample mean
F(2) - standard deviation
F(3) - skewness
F(4) - kurtosis
F(5) - mean of logarithm of values
F(6) - standard deviation of logarithm of values
F(7) - skewness of logarithm of values
F(8) - kurtosis of logarithm of values
F(9) - 0.995 probability level, 0.95 confidence level, for Normal Distribution
F(10) - predicted 0.995 probability level, 0.95 confidence level, based on Log-Normal distribution
F(11) - 'a' parameter for Weibull Distribution
F(12) - 'b' parameter for Weibull Distribution
F(13) - 'c' parameter for Weibull Distribution
F(14) - 0.5 probability level for Weibull Distribution
F(15) - 0.990 probability level for Weibull Distribution
F(16) - 0.995 probability level for Weibull Distribution
F(17) - 0.999 probability level for Weibull Distribution
F(18) - level of significance for Normal Distribution
F(19) - level of significance for Log-Normal Distribution
F(20) - level of significance for Weibull Distribution
3.4 Input Data Description

Input data is in fixed field format and includes fixed point, hollerith and floating point fields. Figure 7 presents a sample run input listing. Basic groups of input include the following:

1) one card of fixed point numbers including all of the run options, run number, number of random samples and number of boost phase integration steps,
2) two cards of Hollerith data describing the run for output heading,
3) initial random sequence integer for the pseudo random number generator,
4) moment of inertia and center of mass table,
5) list of single values of vehicle, mission and control system constants,
6) list of statistical means and standard deviations of random variables for the boost phase,
7) optional separate coast control variables,
8) tables of vehicle, trajectory time histories and wind versus altitude tables,
9) Optional vehicle and trajectory inputs replacing Group 8

3.4.1 Group 1 Input (Input Options)

The first card of input includes eleven fixed point constants in fields of five, right justified, starting in columns 1 through 5. These are:

<table>
<thead>
<tr>
<th>Card Column</th>
<th>FORTRAN Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>NRUN</td>
<td>An arbitrary run number</td>
</tr>
<tr>
<td>6-10</td>
<td>IT</td>
<td>Number of random cases to be computed by the Monte Carlo procedure (current dimensions limit this to 1000 samples)</td>
</tr>
<tr>
<td>15</td>
<td>IO(1)</td>
<td>Output print option</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Gives output information for each sample and the statistical distribution information</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Gives only the statistical distribution information</td>
</tr>
<tr>
<td>20</td>
<td>IO(2)</td>
<td>2 Assumes the coast control and boost controls are the same</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 Coast control system uses different input than boost system (this requires additional input under Group 7)</td>
</tr>
</tbody>
</table>
3.4.2 Group 2 Title

Group 2 includes two cards of Hollerith arbitrary data for the user to describe the run. It includes only the first seventy two (72) columns on each card. This information is written on the first page of output of the run.

3.4.3 Group 3 Initial Random Number Seed

The fourth card of input is an integer number for the start of the pseudo-random number generator. It is located in the first eighteen (18) columns on the card and is right justified. On IBM machines having seven digit accuracy this should be changed to a seven digit integer (eg. 1234567) and a Format change would be required. This also requires the optional coding in the subroutine RNDX shown in the FORTRAN listing.
3.4.4 Group 4 Mass Properties

This group provides the transverse moment of inertia and center of mass station versus fraction of booster propellant consumed. It uses three points (0, 0.5 and 1.0) of propellant consumed to fit the data to a second order polynomial. The nine values are stored in array TABLE 1. Data is entered three to a card in three fields of 10 columns as follows,

<table>
<thead>
<tr>
<th>Col. 1-10</th>
<th>11-20</th>
<th>21-30</th>
<th>values at</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>Iy (Slug-Ft^2)</td>
<td>Xcg (Sta. in.)</td>
<td>ignition</td>
</tr>
<tr>
<td>0.5</td>
<td>Iy</td>
<td>Xcg</td>
<td>50%</td>
</tr>
<tr>
<td>1.0</td>
<td>Iy</td>
<td>Xcg</td>
<td>burnout</td>
</tr>
</tbody>
</table>

3.4.5 Group 5 Single Constants

This group used on all runs consists of single valued constants. There are twenty-one cards in this group. Each card has a single value located in the first fifteen columns (Format El5.5). The first sixteen values are stored in the "A" array. These start with card eight.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>FORTRAN Variable</th>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>A (1)</td>
<td>N</td>
<td>--</td>
<td>number of samples for correlating thrust misalignment initial value with slope</td>
</tr>
<tr>
<td>9</td>
<td>A (2)</td>
<td>\rho_{\epsilon_o \epsilon_r}</td>
<td></td>
<td>correlation coefficient for pitch thrust misalignment</td>
</tr>
<tr>
<td>10</td>
<td>A (3)</td>
<td>\rho_{\epsilon_o \epsilon_r}</td>
<td></td>
<td>correlation coefficient for yaw thrust misalignment</td>
</tr>
<tr>
<td>11</td>
<td>A (4)</td>
<td>Xc</td>
<td>inches</td>
<td>body station of control motors</td>
</tr>
<tr>
<td>12</td>
<td>A (5)</td>
<td>Zc</td>
<td>inches</td>
<td>radial location of pitch and yaw control motors</td>
</tr>
<tr>
<td>13</td>
<td>A (6)</td>
<td>X_T</td>
<td>inches</td>
<td>body station of booster nozzle throat or action point of thrust misalignment</td>
</tr>
<tr>
<td>14</td>
<td>A (7)</td>
<td>R_c</td>
<td>inches</td>
<td>roll control motor moment arm from centerline</td>
</tr>
<tr>
<td>15</td>
<td>A (8)</td>
<td>\cos \lambda</td>
<td>--</td>
<td>cosine of the pitch and yaw control motors forward cant angle</td>
</tr>
<tr>
<td>Card No.</td>
<td>FORTRAN Variable</td>
<td>Symbol</td>
<td>Units</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>------------------</td>
<td>--------</td>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>16</td>
<td>A (9)</td>
<td>(\sin \lambda)</td>
<td>--</td>
<td>sine of the pitch and yaw control motor forward cant angle</td>
</tr>
<tr>
<td>17</td>
<td>A (10)</td>
<td>(t_f)</td>
<td>seconds</td>
<td>time from ignition during which the filter delay is operating with the control system</td>
</tr>
<tr>
<td>18</td>
<td>A (11)</td>
<td>(t_{\text{coast}})</td>
<td>seconds</td>
<td>coast time from burnout</td>
</tr>
<tr>
<td>19</td>
<td>A (12)</td>
<td>(W_f)</td>
<td>pounds</td>
<td>total control fuel available (used to compute retro time or coast time with appropriate options)</td>
</tr>
<tr>
<td>20</td>
<td>A (13)</td>
<td>(t_{\text{web}})</td>
<td>seconds</td>
<td>booster web time or action time from ignition</td>
</tr>
<tr>
<td>21</td>
<td>A (14)</td>
<td>(t_{bo})</td>
<td>seconds</td>
<td>booster burnout time after ignition</td>
</tr>
<tr>
<td>22</td>
<td>A (15)</td>
<td>(W_{bo})</td>
<td>pounds</td>
<td>vehicle weight at booster burnout</td>
</tr>
<tr>
<td>23</td>
<td>A (16)</td>
<td>(I_x)</td>
<td>slug-ft(^2)</td>
<td>vehicle roll moment of inertia at burnout</td>
</tr>
<tr>
<td>24</td>
<td>CNAS</td>
<td>(C_{N'a})</td>
<td>ft(^2)/rad</td>
<td>aerodynamic normal force coefficient slope</td>
</tr>
<tr>
<td>25</td>
<td>XCP</td>
<td>(X_{cp})</td>
<td>inches</td>
<td>vehicle aerodynamic center of pressure station</td>
</tr>
<tr>
<td>26</td>
<td>GAMEL</td>
<td>(\gamma_{e1})</td>
<td>degrees</td>
<td>standard deviation of initial flight path angle</td>
</tr>
<tr>
<td>27</td>
<td>ZEI</td>
<td>(\zeta_{e1})</td>
<td>degrees</td>
<td>standard deviation of initial azimuth</td>
</tr>
<tr>
<td>28</td>
<td>QFRAC</td>
<td>--</td>
<td>--</td>
<td>standard deviation of dynamic pressure ratio (Q_{\text{actual}}/Q_{\text{nominal}})</td>
</tr>
</tbody>
</table>

- 25 -
3.4.6 Group 6 Random Variables

This group includes the mean and standard deviation of related boost system random variables. These are read in two values per card (format 2E15.5). This group starts with card 29 and continues through card 59.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>FORTRAN Variable</th>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>ORM,ORS</td>
<td>$F_p/F_c$</td>
<td>--</td>
<td>boost pitch and yaw, control motor overshoot ratio mean and standard deviation for second order thrust response (Fig. 4) (if ORM = 1.0, constant square wave thrust is assumed)</td>
</tr>
<tr>
<td>30</td>
<td>TPM,TPS</td>
<td>$t_p$</td>
<td>seconds</td>
<td>pitch and yaw control motor time to peak overshoot thrust mean and standard deviation (Ignored if ORM = 1)</td>
</tr>
<tr>
<td>31</td>
<td>T2PM,TRPS</td>
<td>$t_o$</td>
<td>seconds</td>
<td>effective turn off delay time due to vehicle flexibility, mean and standard deviation (not used when filter is included)</td>
</tr>
<tr>
<td>32</td>
<td>B(1), B(2)</td>
<td>$\epsilon_{r_{op}}$</td>
<td>degrees</td>
<td>initial value of pitch thrust misalignment (mean and standard deviation)</td>
</tr>
<tr>
<td>33</td>
<td>B(3), B(4)</td>
<td>$\epsilon_{r_{oy}}$</td>
<td>degrees</td>
<td>initial value of yaw thrust misalignment (mean and standard deviation)</td>
</tr>
<tr>
<td>34</td>
<td>B(5), B(6)</td>
<td>$\dot{\epsilon}<em>r</em>{p}$</td>
<td>deg/sec</td>
<td>mean and standard deviation of time rate of change of pitch thrust misalignment</td>
</tr>
<tr>
<td>35</td>
<td>B(2), B(8)</td>
<td>$\dot{\epsilon}<em>r</em>{y}$</td>
<td>deg/sec</td>
<td>mean and standard deviation of time rate of change of yaw thrust misalignment</td>
</tr>
<tr>
<td>36</td>
<td>B(9), B(10)</td>
<td>$I_{sp}$</td>
<td>seconds</td>
<td>boost control motor specific impulse mean and standard deviation</td>
</tr>
<tr>
<td>37</td>
<td>B(11), B(12)</td>
<td>$\dot{\theta}_o$</td>
<td>deg/sec</td>
<td>mean and standard deviation of initial pitch rate</td>
</tr>
<tr>
<td>38</td>
<td>B(13), B(14)</td>
<td>$\theta_{o0}$</td>
<td>degrees</td>
<td>mean and standard deviation of initial pitch attitude error</td>
</tr>
<tr>
<td>Card No.</td>
<td>FORTRAN Variable</td>
<td>Symbol</td>
<td>Units</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>------------------</td>
<td>--------</td>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>39</td>
<td>B(15), B(16)</td>
<td>$\psi_0$</td>
<td>deg/sec</td>
<td>mean and standard deviation of initial yaw rate</td>
</tr>
<tr>
<td>40</td>
<td>B(17), B(18)</td>
<td>$\psi_e$</td>
<td>degrees</td>
<td>mean and standard deviation of initial yaw attitude error</td>
</tr>
<tr>
<td>41</td>
<td>B(19), B(20)</td>
<td>RTI</td>
<td>ft-lb-sec</td>
<td>booster induced roll angular impulse mean and standard deviation</td>
</tr>
<tr>
<td>42</td>
<td>B(21), B(22)</td>
<td>$\zeta_{\text{JET}}$</td>
<td>degrees</td>
<td>mean and standard deviation of pitch and yaw control motor misalignment contributing to roll moment</td>
</tr>
<tr>
<td>43</td>
<td>B(23), B(24)</td>
<td>$\zeta_W$</td>
<td>degrees</td>
<td>mean and standard deviation of wind direction azimuth</td>
</tr>
<tr>
<td>44</td>
<td>B(25), B(26)</td>
<td>$\Delta I_y$</td>
<td>$\Delta X_{cg}$</td>
<td>standard deviation of transverse moment of inertia and standard deviation of center of mass station in inches</td>
</tr>
<tr>
<td>45</td>
<td>C(1), C(2)</td>
<td>$\Delta t_f$</td>
<td>seconds</td>
<td>pitch and yaw filter delay time mean and standard deviation</td>
</tr>
<tr>
<td>46</td>
<td>C(3), C(4)</td>
<td>$t_{rg}$</td>
<td>seconds</td>
<td>mean and standard deviation of pitch and yaw gyro time delay</td>
</tr>
<tr>
<td>47</td>
<td>C(5), C(6)</td>
<td>$t_{1m}$</td>
<td>seconds</td>
<td>mean and standard deviation of pitch and yaw control motor turn-on delay time</td>
</tr>
<tr>
<td>48</td>
<td>C(7), C(8)</td>
<td>$t_{2m}$</td>
<td>seconds</td>
<td>mean and standard deviation of pitch and yaw control motor turn-off delay time</td>
</tr>
<tr>
<td>49</td>
<td>C(9), C(10)</td>
<td>$K_R/K_D$</td>
<td>seconds</td>
<td>mean and standard deviation of boost pitch and yaw control system gain ratio</td>
</tr>
<tr>
<td>50</td>
<td>C(11), C(12)</td>
<td>$d_b$</td>
<td>degrees</td>
<td>boost pitch and yaw control deadband halfwidth mean and standard deviation</td>
</tr>
<tr>
<td>51</td>
<td>C(13), C(14)</td>
<td>$H$</td>
<td>--</td>
<td>mean and standard deviation of boost pitch and yaw control hysteresis fraction $(1-d_{off}/d_{on})$</td>
</tr>
<tr>
<td>52</td>
<td>C(15), C(16)</td>
<td>$F_c$</td>
<td>pounds</td>
<td>boost pitch and yaw control motor thrust mean and standard deviation</td>
</tr>
<tr>
<td>Card No.</td>
<td>FORTRAN Variable</td>
<td>Symbol</td>
<td>Units</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>------------------</td>
<td>--------</td>
<td>---------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>53</td>
<td>C(17), C(18)</td>
<td>t_{RG}</td>
<td>seconds</td>
<td>roll rate gyro delay time mean and standard deviation</td>
</tr>
<tr>
<td>54</td>
<td>C(19), C(20)</td>
<td>t_{1M}</td>
<td>seconds</td>
<td>boost roll motor turn-on delay time mean and standard deviation</td>
</tr>
<tr>
<td>55</td>
<td>C(21), C(22)</td>
<td>t_{2M}</td>
<td>seconds</td>
<td>boost roll motor turn-off delay time mean and standard deviation</td>
</tr>
<tr>
<td>56</td>
<td>C(23), C(24)</td>
<td>K_{R}/K_{D}</td>
<td>seconds</td>
<td>boost roll control gain ratio mean and standard deviation</td>
</tr>
<tr>
<td>57</td>
<td>C(25), C(26)</td>
<td>d_{b}</td>
<td>degrees</td>
<td>boost roll deadband halfwidth mean and standard deviation</td>
</tr>
<tr>
<td>58</td>
<td>C(27), C(28)</td>
<td>H</td>
<td>--</td>
<td>boost roll switching hysteresis (1 - d_{off}/d_{on}) mean and standard deviation</td>
</tr>
<tr>
<td>59</td>
<td>C(29), C(30)</td>
<td>F_{C}</td>
<td>pounds</td>
<td>boost roll control motor thrust mean and standard deviation</td>
</tr>
</tbody>
</table>

### 3.4.7 Group 7 Separate Coast System Variables (IO(2) = 3 Only)

This group is an optional input if a separately defined coast control system is used. This information must be input if IO(2) = 3 on the first card. This allows separate control motors, gains, time delays and a retro function during coast using the canted forward boost control motors. The first four cards are input one value per card with format E15.5. They are:

<table>
<thead>
<tr>
<th>Card No.</th>
<th>FORTRAN Variable</th>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>PTRC</td>
<td>Δ\dot{θ}_C</td>
<td>deg/sec</td>
<td>total pitch program rate changes during coast</td>
</tr>
<tr>
<td>61</td>
<td>YTRC</td>
<td>Δ\dot{ψ}_C</td>
<td>deg/sec</td>
<td>total yaw program rate change during coast</td>
</tr>
<tr>
<td>62</td>
<td>TRETRO</td>
<td>t_{retro}</td>
<td>seconds</td>
<td>retro time required following coast with four boost pitch and yaw control motors</td>
</tr>
</tbody>
</table>
In addition to these four cards, there are nine (9) additional cards of statistical control system values having two values per card (format 2E15.5). These are:

<table>
<thead>
<tr>
<th>Card No.</th>
<th>FORTRAN Variable</th>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>D(1), D(2)</td>
<td>d_c</td>
<td>degrees</td>
<td>coast system pitch and yaw</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>deadband halfwidth, mean and standard deviation</td>
</tr>
<tr>
<td>65</td>
<td>D(3), D(4)</td>
<td>F_c</td>
<td>pounds</td>
<td>coast pitch control motor force, mean and standard deviation</td>
</tr>
<tr>
<td>66</td>
<td>D(5), D(6)</td>
<td>t_1M</td>
<td>seconds</td>
<td>coast pitch motor turn-on delay time, mean and standard deviation</td>
</tr>
<tr>
<td>67</td>
<td>D(7), D(8)</td>
<td>t_2M</td>
<td>seconds</td>
<td>coast pitch motor turn-off delay time, mean and standard deviation</td>
</tr>
<tr>
<td>68</td>
<td>D(9), D(10)</td>
<td>d_c</td>
<td>degrees</td>
<td>coast roll deadband halfwidth, mean and standard deviation</td>
</tr>
<tr>
<td>69</td>
<td>D(11), D(12)</td>
<td>F_c</td>
<td>pounds</td>
<td>coast roll motor thrust, mean and standard deviation</td>
</tr>
<tr>
<td>70</td>
<td>D(13), D(14)</td>
<td>t_1M</td>
<td>seconds</td>
<td>coast roll motor turn-on delay time, mean and standard deviation</td>
</tr>
<tr>
<td>71</td>
<td>D(15), D(16)</td>
<td>t_2M</td>
<td>seconds</td>
<td>coast roll motor turn-off delay time, mean and standard deviation</td>
</tr>
<tr>
<td>72</td>
<td>D(17), D(18)</td>
<td>I_sp</td>
<td>seconds</td>
<td>coast control specific impulse, mean and standard deviation</td>
</tr>
</tbody>
</table>

3.4.8 Group 8 Trajectory Tables IO(8) = 0

This group concludes the input data stream for a run. It includes tables of time and altitude histories. If IO(8) = 1 certain tables are deleted as described in Group 9 in the following paragraph. Each table is input in the same format. Preceding each table a card having the integer number of values in the table is located in columns 1 through 5, right justified (Format I5).
The values are entered alternating abscissas and ordinates in fields of ten columns. These are entered six (6) per card until the table is completed. Figure 7 is the input for the sample problem which shows this format. The format for the whole table is (I5/(6F10.3)). A description of the tables and their order is:

<table>
<thead>
<tr>
<th>TABLE NAME</th>
<th>ORDINATE</th>
<th>UNITS</th>
<th>ABSCISSA</th>
<th>UNITS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE 1</td>
<td>Q</td>
<td>lbs/ft²</td>
<td>t</td>
<td>sec</td>
<td>dynamic pressure versus time after ignition</td>
</tr>
<tr>
<td>TABLE 2</td>
<td>T</td>
<td>lbs</td>
<td>t</td>
<td>sec</td>
<td>booster nominal thrust versus time after ignition</td>
</tr>
<tr>
<td>TABLE 3</td>
<td>W&lt;sub&gt;p&lt;/sub&gt;</td>
<td>lbs</td>
<td>t</td>
<td>sec</td>
<td>booster propellant weight remaining versus time after ignition</td>
</tr>
<tr>
<td>TABLE 4</td>
<td>θ&lt;sub&gt;c&lt;/sub&gt;</td>
<td>deg</td>
<td>t</td>
<td>sec</td>
<td>pitch program attitude from local horizontal versus time after ignition</td>
</tr>
<tr>
<td>TABLE 5</td>
<td>V</td>
<td>ft/sec</td>
<td>t</td>
<td>sec</td>
<td>nominal velocity versus time after ignition</td>
</tr>
<tr>
<td>TABLE 6</td>
<td>γ&lt;sub&gt;PR&lt;/sub&gt;</td>
<td>degrees</td>
<td>t</td>
<td>sec</td>
<td>flight path angle from local horizontal versus time after ignition</td>
</tr>
<tr>
<td>TABLE 7</td>
<td>ζ&lt;sub&gt;PR&lt;/sub&gt;</td>
<td>degrees</td>
<td>t</td>
<td>sec</td>
<td>nominal azimuth versus time after ignition</td>
</tr>
<tr>
<td>TABLE 8</td>
<td>β&lt;sub&gt;NOM&lt;/sub&gt;</td>
<td>degrees</td>
<td>t</td>
<td>sec</td>
<td>nominal angle of sideslip versus time after ignition on an undisturbed trajectory</td>
</tr>
<tr>
<td>TABLE 9</td>
<td>V&lt;sub&gt;Wµ&lt;/sub&gt;</td>
<td>ft/sec</td>
<td>h</td>
<td>ft</td>
<td>mean value of wind velocity versus altitude above sea level</td>
</tr>
<tr>
<td>TABLE 10</td>
<td>V&lt;sub&gt;Wσ&lt;/sub&gt;</td>
<td>ft/sec</td>
<td>h</td>
<td>ft</td>
<td>standard deviation of wind velocity versus altitude above sea level</td>
</tr>
<tr>
<td>TABLE 11</td>
<td>h</td>
<td>feet</td>
<td>t</td>
<td>sec</td>
<td>altitude versus time after ignition</td>
</tr>
</tbody>
</table>

Each of the above tables is limited to ninety (90) values which is a maximum of forty-five (45) pairs of abscissas and ordinates.
For parametric studies the option to generate nominal trajectory parameters becomes useful. This option generates a gravity turn trajectory from other input data. With this option Group 9 data replaces Group 8 data. Figure 8 presents a sample input for the case. The first card includes four variables read in four fields of ten columns (format AFIO.3). These variables are:

<table>
<thead>
<tr>
<th>FORTRAN VARIABLE</th>
<th>SYMBOL</th>
<th>UNITS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q0</td>
<td>Q₀</td>
<td>lbs/ft²</td>
<td>nominal dynamic pressure at ignition</td>
</tr>
<tr>
<td>VO</td>
<td>V₀</td>
<td>ft/sec</td>
<td>nominal velocity at ignition</td>
</tr>
<tr>
<td>GAMO</td>
<td>Y₀</td>
<td>degrees</td>
<td>nominal flight path angle at stage ignition</td>
</tr>
<tr>
<td>CDS</td>
<td>C PSD</td>
<td>ft²</td>
<td>aerodynamic drag coefficient times reference area</td>
</tr>
</tbody>
</table>

Following this card seven tables are entered. Each table is preceded by a card containing the integer number of values in the table in a field of five (5) right justified (format I5). Following this card the table is entered in floating point numbers in fields of ten (10) columns, six (6) values per card. The format is (6F10.3). The order and description of these tables are as follows:

<table>
<thead>
<tr>
<th>TABLE NAME</th>
<th>ORDINATE</th>
<th>UNITS</th>
<th>ABSCISSA</th>
<th>UNITS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2</td>
<td>T</td>
<td>lbs</td>
<td>t</td>
<td>sec</td>
<td>booster nominal thrust versus time after ignition</td>
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<td>W</td>
<td>lbs</td>
<td>t</td>
<td>sec</td>
<td>booster nominal thrust versus time after ignition</td>
</tr>
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<td>θ₀-γPR</td>
<td>degrees</td>
<td>t</td>
<td>sec</td>
<td>difference between nominal pitch attitude and flight path angle versus time after ignition</td>
</tr>
<tr>
<td>Table 7</td>
<td>ζPR</td>
<td>degrees</td>
<td>t</td>
<td>sec</td>
<td>predicted azimuth time history</td>
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<td>Table 8</td>
<td>βNOM</td>
<td>degrees</td>
<td>t</td>
<td>sec</td>
<td>nominal angle of sideslip versus time after ignition</td>
</tr>
<tr>
<td>Table 9</td>
<td>Wµ</td>
<td>ft/sec</td>
<td>h</td>
<td>feet</td>
<td>mean value of wind, velocity versus altitude</td>
</tr>
<tr>
<td>Table 10</td>
<td>Wσ</td>
<td>ft/sec</td>
<td>h</td>
<td>feet</td>
<td>standard deviation of wind velocity versus altitude</td>
</tr>
</tbody>
</table>
3.5 Output Description

All output is on a line printer. There are several options for the output which are selected by the run options presented in paragraph 3.4.1.

There are five basic parts to the output, two of which can be deleted by input option. These include:

1) printout of selected parameters from each random sample (IO(1) = 1), can be deleted if (IO(1) = 2),

2) printout of all fuel consumption values arranged in ascending order with associated sample population probability level (always output),

3) sample distribution statistical parameters, final random number generator seed and number of samples having deadband overshoot occurrences,

4) summary statistics and level of significance for Normal, Log-Normal and Weibull Distribution functions,

5) histograms of the fuel consumption (IO(9) = 0), can be omitted if (IO(9) = 1)

Details of these parts of the output are presented in the following subparagraphs.

3.5.1 Individual Sample Parameters

If the input option (IO(1) = 1), two lines of parameters from each Monte Carlo random sample case are printed out after each case. This option results in a relatively large amount of printout. A typical page of output of these parameters is presented in Figure 9. A description of each in the order of output is:

<table>
<thead>
<tr>
<th>OUTPUT NAME</th>
<th>UNITS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMPL</td>
<td>--</td>
<td>an integer sequence of the Monte Carlo case number</td>
</tr>
<tr>
<td>CAPT IMP</td>
<td>lb-sec</td>
<td>staging &quot;capture&quot; transient impulse</td>
</tr>
<tr>
<td>ROLL TORQIMP</td>
<td>lb-sec</td>
<td>roll control motor impulse due to rocket booster induced roll torque (RTI)</td>
</tr>
<tr>
<td>BOOSTIMP</td>
<td>lb-sec</td>
<td>total control impulse required during boost phase</td>
</tr>
<tr>
<td>T(WEB)</td>
<td>sec</td>
<td>booster web time</td>
</tr>
<tr>
<td>T(TO)</td>
<td>sec</td>
<td>booster tail off time</td>
</tr>
</tbody>
</table>

- 32 -
### OUTPUT NAME | UNITS | DESCRIPTION
--- | --- | ---
BOOST FUEL | lbs | control fuel consumption during boost
ISP | sec | control fuel specific impulse
CST FUEL | lbs | control fuel consumption during coast (not including retro fuel)
FLOW RATE | lbs/sec | coast fuel consumption flow rate with boost system - filter in
DB RED TORQ FUEL | lbs | fuel consumption required for deadband reduction transient and pitch program rate changes during coast
FLOW RATE COAST | lbs/sec | fuel flow rate during coast
RETRO TIME | sec | retro time achieved with remaining fuel consumption after coast
NO. OF DB OVERSHOTS | | number of times deadband overshoot occurred during boost in pitch or yaw, in the roll channel, and during coast in pitch or yaw
TOTAL FUEL | lbs | total fuel consumption including boost, coast and retro

When the coast time option is used, \((10(3) = 1)\), \((TOTAL FUEL)\) and \((COAST FUEL)\) is deleted and \((COAST TIME)\) is output in seconds.

#### 3.5.2 Discrete Probability Levels

Fuel consumption in boost and coast, total fuel consumption and under some options retro time or coast time is printed versus probability of occurrence after being arranged in ascending order. A sample output is presented in Figure 10.

#### 3.5.3 Sample Distribution and Final Seed

This page of output is presented in Figure 11. It includes the computed mean, standard deviation and estimated 99.5 percent probability with 95 percent confidence level of fuel consumption.

The last value calculated of the pseudo random number generator seed is output. This can be used as a starting value if an additional run is to be made to increase the sample size with the least risk of repeating parts of the sequence generated in the previous run.
The total number of cases having exceeded the deadband overshoot criteria at least once is also output on this page. Differentiation between boost and coast phases is made as well as roll axes during boost. The deadband overshoot criteria is an indicator of a very poorly designed on-off control system since it approaches a 100 percent duty cycle.

3.5.4 Summary Statistics and Level of Significance

A page of statistical information is output for comparison of the sample population with known distributions. Figure 12 presents a typical example. Sample population mean, standard deviation, skewness and kurtosis parameters are output under Normal Distribution. The estimated upper 95 percent confidence level at the 99.5 percent probability level is based on a prediction if the distribution were truly Gaussian (which is usually not the case). Level of Significance is computed based on the Chi-Squared Goodness of Fit Test. The level of significance is output for each of the distributions. A higher level of significance generally indicates a better fit. However, histogram output should also be considered in the statistical analysis.

Under the Log-Normal Distribution the sample distribution parameters for the natural logarithm of the fuel consumption is shown. The fuel consumption at the upper 95 percent confidence level at 99.5 percent probability level predicted by the Log-Normal distribution is also shown in pounds. Note that the parameters are expressed as the logarithm but the 99.5 percent level is not the logarithm. Level of significance is also presented from the Chi-Squared Goodness of Fit Test.

Weibull Distribution parameters (a, b, c) are presented which are based on the sample population. Values of fuel consumption at several selected probability levels as predicted by the fit to a Weibull Distribution are also output. Level of Significance from a Chi-Squared Goodness of Fit Test to the ideal Weibull Distribution having these parameters is also output.

3.5.5 Histograms

Histograms of the sample populations of fuel consumption and retro times are an optional output. Samples of this output are presented in Figure 13. Each output histogram includes:

- Identification
- Total number of samples
- Minimum and maximum values
- Number of values in each cell printed numerically below each cell
- Numerical value of starting and end points of each cell printed under each cell
- Graphical display of each cell by number of stars or asterisks rising from the base
Maximum number of samples in a cell is 94 for display purposes. If a cell is completely filled the actual height can be obtained from the number printed at the base of the cell. The number of cells is automatically set at 30 or more over the range of data. In order to select aesthetically pleasing cell divisions the number of cells will vary somewhat and occasionally spill over more than a single page of output.
4.0 REFERENCES


Figure 1
Control Phase Plane - Limit Cycles

Symmetric Undisturbed Limit Cycles

One-Sided

Two-Sided

Disturbed Limit Cycles

slope: $-\frac{1}{K_R/K_D}$
Figure 2
Trajectory and Angle Definitions
Figure 3
Minimum Acceleration for Deadband Crossing

\[ \ddot{\theta}_{\text{test}} = \left| -\frac{E}{2D} \pm \sqrt{\left(\frac{E}{2D}\right)^2 + \frac{F}{D}} \right| \]

\[ \begin{align*}
D &= B \left( \frac{K_R}{K_D} - T_1 \right) \left( \frac{B-C}{A} \right) - 0.5 \left( \frac{K_R}{K_D} \right)^2 - 0.5 \left( \frac{B-C}{A} \right)^2 \\
E &= -2d \left( \frac{K_R}{K_D} - T_1 \right) \left( \frac{dH - C \ddot{\theta}_c}{A} \right) / A - C \left( \frac{B-C}{A^2} \right) \ddot{\theta}_c \\
F &= \frac{1}{A^2} \left[ 0.5 \left( dH + C \ddot{\theta}_c \right)^2 + dH \left( B-C \right) \right] \\
A &= 2 \frac{K_R}{K_D} - T_1 - T_2 \\
B &= \frac{K_R}{K_D} T_1 - T_1^2 / 2 \\
C &= \frac{K_R}{K_D} T_2 - T_2^2 / 2
\]
Figure 4
Control Motor Thrust Responses

\[ t_m = tv_1 + tp \left( 1 - \nu / 2 \right) / 2 \]

\[ \nu = \tan^{-1} \left[ \frac{\pi}{\ln \left( \frac{1}{F_p / F_c - 1} \right)} \right] \]
Figure 5
General Flow Chart of MAIN Routine

Start

Input Run Option
Heading Titles
Table 1, A, B, C
Array & Const's

IO(2)
Test Coast .Control
≤2

Sep. Coast [Control
Boost & Coast Control Same

Read Coast Data & D Array

IO(8)
Test Trajectory Input
≠0

Read Input Tables
Q, T, W, θC, V, γ, ζ, βNOM, V₇μ, V₇σ, h

- Curve Fit Iᵧ, XCG
- Compute Boost Phase Integration Points
- Precalculate Time Histories of Multipliers

IO(3)
Fuel or Coast Time?

N=0

IO(1)
Printout?

≤2 Yes

Print Individual Case Results

Test No. of Cases N ≥ N_MAX

2 Statistical Analysis

(Next Page)
Figure 5 (Cont.)
General Flow Chart of MAIN Routine

2 Statistical Analysis

Coast Time Option

- Rearrange in Ascending Order
- Compute $W_{\text{boost}}$, $T_{\text{Coast}}$ Probabilities $\mu$ & $\sigma$, 0.995 Prob.

Print Statistics

Go To Start #10

10(3)-2 Coast Time Or Fuel2

Fuel Option

- Rearrange in Ascending Order
- Compute $\mu$, $\sigma$, 0.995 Prob. of "Boost", "Coast", "Tot." $T_{\text{Retro}}$

Print Sample Statistics

- Compute Normal Log-Normal & Weibull Parameters
- Compute Level of Significance
Subroutine WBL

Print Statistical Results for Each Distribution

Yes

10(9) Histograms?

1

No

End Run
Go To Start #10

No

End Run
Go To Start #10

Histogram Range and Cell Parameter Subr. RANGE

Plot Histograms on Line Printer Subr. HISTO

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### FIGURE 6

Program Subroutines and Common Interaction Map Subroutines

#### Called Subroutines

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*Note: X indicates a call or interaction.*
**Figure 7**

Sample Problem Input \( I0(8) = 0 \)

<table>
<thead>
<tr>
<th>SAMPLE PROBLEM SCOUT</th>
<th>SECOND STAGE, FUEL OPTION, FILTER OUT IN COAST, SEPARATE COAST CONTROL, NO YAW-ROLL MIXING ( I0(8) = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>499 2 3 2 1 12 4 1 0 0</td>
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<tr>
<td>INITIAL RANDOM SEQ</td>
<td>NO RANDOM</td>
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<tr>
<td>0.</td>
<td>49241.45 282.07 IYY AND XCG IGNITATION (SLUG-50% PROP FT**2)</td>
</tr>
<tr>
<td>0.5</td>
<td>41574.21 258.47 @BURNOUT</td>
</tr>
<tr>
<td>1.0</td>
<td>27991.96 206.73</td>
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<td>NO. OF SAMPLES FOR CORR COEFF</td>
<td>19.</td>
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<tr>
<td>CORR COEFF PITCH</td>
<td>-0.573</td>
</tr>
<tr>
<td>CORR COEFF YAW</td>
<td>-0.756</td>
</tr>
<tr>
<td>467.76</td>
<td>CONTROL MOTOR STATION</td>
</tr>
<tr>
<td>14.93</td>
<td>CONTROL MOTOR LAT. LOC. (IN.)</td>
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<td>448.51</td>
<td>BOOSTER NOZZLE THROAT STATION</td>
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<td>16.89</td>
<td>ROLL CONTROL MOTOR ARM (IN.)</td>
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<td>COAS OF CANT ANGLE (NO CANT)</td>
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</tr>
<tr>
<td>SIN OF CANT ANGLE (NO CANT)</td>
<td>0.</td>
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<td>FILTER IN TIME (SEC)</td>
<td>42.32</td>
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<td>COAST TIME (SEC)</td>
<td>34.92</td>
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<tr>
<td>CONTROL FUEL (LB)</td>
<td>167.</td>
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<td>BOOSTER WEB TIME (SEC)</td>
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### FIGURE 7 (Continued)

Sample Problem Input IO(8)=0

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FIGURE 7 (Continued)
Sample Problem Input IO(8)=0

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Sample Problem Input IO(8)=0

8 MEAN WIND VELOCITY(FT/SEC) VS. ALTITUDE(FEET)
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400000. 310.

8 SIGMA WIND VELOCITY(FT/SEC) VS. ALTITUDE(FEET)
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400000. 100.

10 ALTITUDE (FEET) VS. TIME (SEC)
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28.84 203371. 43.84 262430.
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FIGURE 8 (Continued)
Sample Problem Input 10(8)=1

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| 125.0     | 0.00036  | BOOST CONTROL ISP (SEC)   | 000036 |
| -0.098    | 0.326    | INITIAL PITCH RATE (DEG/SEC) | 000037 |
| 0.292     | 0.340    | INITIAL PITCH ERROR (DEG)  | 000038 |
| 0.085     | 0.197    | INITIAL YAW RATE (DEG/SEC) | 000039 |
| 0.0105    | 0.243    | INITIAL YAW ERROR (DEG)    | 000040 |
| 0.0166    | 0.0033   | BOOSTER ROLL ANG. IMPULSE (FT-LB-SEC) | 000041 |
| 259.0     | 20.0     | PITCH/YAW JET MISALIGNMENT (DEG) | 000042 |
| 0.0166    | 0.0033   | IYY AND XCG STANDARD DEVIATION | 000044 |
| 0.0459    | 0.0034   | FILTER DELAY TIME (SEC)    | 000047 |
| 0.0093    | 0.0017   | PITCH/YAW GYRO DELAY TIME (SEC) | 000048 |
| 0.0715    | 0.0038   | PITCH/YAW MOTOR T1 (SEC)   | 000049 |
| 0.0355    | 0.0052   | PITCH/YAW MOTOR T2 (SEC)   | 000050 |
| 0.5       | 0.01667  | KR/KD (SEC)                 | 000051 |
| 0.802     | 0.0267   | BOOST PITCH/YAW DEADBANDS (DEG) | 000052 |
| 0.035     | 0.0167   | BOOST PITCH/YAW HYSTERESIS (FRACTION) | 000053 |
| 517.3     | 14.5     | BOOST PITCH/YAW CONTROL FORCE (LB) | 000054 |
| 0.0069    | 0.0008   | ROLL RATE GYRO DELAY (SEC)  | 000055 |
| 0.0251    | 0.0048   | BOOST ROLL MOTOR T1 (SEC)   | 000056 |
| 0.0162    | 0.0030   | BOOST ROLL MOTOR T2 (SEC)   | 000057 |
| 0.45      | 0.015    | ROLL GAIN RATIO KR/KD (SEC) | 000058 |
| 1.432     | 0.0478   | BOOST ROLL DEADBAND (DEG)   | 000059 |
| 0.035     | 0.0167   | ROLL HYSTERESIS (FRACTION)  | 000060 |
| 45.45     | 1.68     | BOOST ROLL MOTOR FORCE (LB) | 000061 |
| 0.45      | 0.015    | PITCH PROGRAM RATE CHANGE (DEG/SEC) | 000062 |
| 0.125     | 0.0064   | YAW PROGRAM RATE CHANGE (DEG/SEC) | 000063 |
| 0.785     | 0.0267   | RETRO TIME (SEC)            | 000064 |
| 517.3     | 14.5     | RETRO ISP (SEC)             | 000065 |
| 0.0715    | 0.0088   | COAST PITCH MOTOR T1 (SEC)  | 000068 |
FIGURE 8 (Concluded)
Sample Problem Input IO(8)=1

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Sample Output - Individual Cases - IO(1) = 1

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FIGURE 10 (Continued)
Sample Output - Discrete Probability

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- 58 -
FIGURE 10 (Concluded)
Sample Output - Discrete Probability

<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>PROBABILITY</th>
<th>BOOST FUEL (POUNDS)</th>
<th>COAST FUEL (POUNDS)</th>
<th>RETRO TIME (SECONDS)</th>
<th>TOTAL FUEL (POUNDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.95600</td>
<td>70.160</td>
<td>25.429</td>
<td>4.5736</td>
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<td>25.107</td>
<td>4.5541</td>
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<td>25.268</td>
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<td>4.2486</td>
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</tbody>
</table>
Figure 11
Output Page of Sample Statistical Data

RUN NO.  1

SAMPLE PROBLEM SCOUT SECOND STAGE, FUEL OPTION, FILTER OUT IN COAST, SEPARATE COAST CONTROL, NO YAW-ROLL MIXING IO(8)=0

<table>
<thead>
<tr>
<th></th>
<th>BOOST FUEL</th>
<th>COAST FUEL</th>
<th>RETRO TIME</th>
<th>TOTAL FUEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN</td>
<td>49.783</td>
<td>19.660</td>
<td>5.9572</td>
<td>70.988</td>
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<tr>
<td>STD. DEVIATION</td>
<td>11.490</td>
<td>3.029</td>
<td>.7685</td>
<td>12.132</td>
</tr>
<tr>
<td>0.995 PROB</td>
<td>88.179</td>
<td>31.395</td>
<td>3.3356</td>
<td>112.182</td>
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<tr>
<td>0.95 CONFID</td>
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<td></td>
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</tbody>
</table>

FINAL VALUE OF RANDOM SEQUENCE INTEGER = 274469945168434565

NO. OF SAMPLES WITH DEADBAND OVERSHOOT

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BOOST(PITCH AND YAW)</td>
<td>0</td>
</tr>
<tr>
<td>(ROLL)</td>
<td>0</td>
</tr>
<tr>
<td>COAST</td>
<td>0</td>
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</table>
Figure 12
Summary Statistics and Level of Significance

<table>
<thead>
<tr>
<th>DISTRIBUTION FUNCTION FIT</th>
<th>BOOST</th>
<th>COAST</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORMAL DISTRIBUTION</td>
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<td>MEAN</td>
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<td>19.660</td>
<td>70.988</td>
</tr>
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<td>STANDARD DEVI</td>
<td>11.478</td>
<td>3.026</td>
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<td>SKEWNESS</td>
<td>0.302</td>
<td>0.363</td>
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<tr>
<td>KURTOSIS</td>
<td>2.744</td>
<td>3.408</td>
<td>2.987</td>
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<tr>
<td>0.995 PROB 0.95 CONF</td>
<td>81.378</td>
<td>27.990</td>
<td>104.350</td>
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<td>LEVEL OF SIGNIFICANCE</td>
<td>0.035</td>
<td>0.044</td>
<td>0.014</td>
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<tr>
<td>LOG NORMAL DISTRIBUTION</td>
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<td></td>
<td></td>
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<tr>
<td>(VALUES OF LOG)</td>
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<td></td>
<td></td>
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<tr>
<td>MEAN</td>
<td>3.880</td>
<td>2.967</td>
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<tr>
<td>STANDARD DEVI</td>
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<td>SKEWNESS</td>
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<td>0.107</td>
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<td>WEIBULL DISTRIBUTION</td>
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<tr>
<td>PARAMETERS A</td>
<td>21.6359</td>
<td>12.5937</td>
<td>42.2023</td>
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<tr>
<td>B</td>
<td>31.6198</td>
<td>7.9491</td>
<td>32.3661</td>
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<tr>
<td>C</td>
<td>2.6618</td>
<td>2.5267</td>
<td>2.5726</td>
</tr>
<tr>
<td>PROBABILITY 0.5000</td>
<td>49.201</td>
<td>19.473</td>
<td>70.284</td>
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<td>0.9900</td>
<td>77.734</td>
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<td>86.965</td>
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<tr>
<td>LEVEL OF SIGNIFICANCE</td>
<td>0.637</td>
<td>0.003</td>
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</table>
Figure 13 (Cont.)

Histogram Output
Figure 13 (Concluded)
Histogram Output
APPENDIX A

FORTRAN Program Listing

A complete listing of the FORTRAN Source Program is presented in the following pages. It starts with the MAIN routine and is followed by the seventeen (17) subroutines arranged in alphabetical order. There are a total of 947 cards in the MAIN routine. The total program including the subroutines contains 1,626 cards.

If the routine is used on a non-CDC computer the pseudo random number generation will change. In this case the calls to RANSET (line 29) and RANGET (lines 668, 743, and 829) should be deleted. Subroutine RNDX has an alternate pseudo random number generator coding which is listed as comment cards.
*DECK MAIN

PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)

C SCOUT UPPER STAGE STATISTICAL FUEL CONSUMPTION ROUTINE
C COMPUTES THE STATISTICAL DISTRIBUTION OF CONTROL FUEL CONSUMPTION
C FOR AN ON-OFF REACTION JET ATTITUDE CONTROL SYSTEM BY THE MONTE
C CARLO TECHNIQUE. THE EFFECT OF BOOSTER INDUCED DISTURBANCES AND
C AERODYNAMIC DISTURBANCES ARE CONSIDERED IN ADDITION TO THE SELF
C EXCITED LIMIT CYCLE MOTION.

DIMENSION IO(9), A(16), TABL1(9), B(30), C(30), D(18), BT(15),
1 PC(8), YC(8), RC(7), PDC(10), WBOOST(1000), TCOAST(1000),
2 WCOAS(1000),TRET(1000),UTOT(1000),FWB(20),FWC(20),FUT(20),
3 TBL1(90),TBL2(90),TBL3(90),TBL4(90),TBL5(90),TBL6(90),
4 TBL7(90),TBL8(90),TBL9(90),TBL10(90),TBL11(90),
5 TA1(50),TCX(50),VXX(50),GAP(50),ZPX(50),PSX(50),HX(50),
6 VELX(50),X1KA(50),X1KB(50),VWMX(50),VWSX(50),THX(50),TOU(50),
7 WGHt(50),XINER(50),CNASQ(50)

COMMON K, RXD(30)
COMMON/DOUT/NQT,TABL1,NVT,TBL5,NQT,TBL6,NHT,TBL11,TBO,NTC,TBL4
COMMON/DDI/TBL2,TBL3,NTHT,NUT,CDS,M2,M3,WBO
DATA NUMCHI/11/

C READ RUN NO., NUMBER OF SAMPLES, AND RUN OPTIONS

10 READ( 5,1330) NRUN,IT,(IO(I),I=1,9)
   IF (EOF(5).NE.0) STOP

C READ TWO CARDS OF TITLE INFORMATION FOR OUTPUT ONLY

READ( 5,1350)

C READ INITIAL SEQUENCE INTEGER FOR RANF PSEUDO RANDOM NUMBER

READ( 5,1320) K
CALL RANSET (K)
NPAGE=1
NLINE=0
CALL PAGEHD (NRUN,NPAGE,NLINE)
WRITE( 6,1350)
NLINE=NLINE+2
C READ IN XCG AND MOMENT OF INERTIA TABLE
READ( 5,1440) (TABLE1(I),I=1,9)

C READ IN SINGLE VALUED CONSTANTS
READ( 5,1450) (A(I),I=1,16),CNAS,XCP,GAMEI,ZEI,QFRAC
TBO=A(14)
WBO=A(15)
GAMEI=GAMEI/57.3
ZEI=ZEI/57.3

C READ IN MEAN AND STANDARD DEVIATIONS OF CONTROL MOTOR OVERSHOOT
C RATIO, TIME TO PEAK THRUST, ADDED TURN-OFF TIME DELAY DUE TO
C STRUCTURAL FLEXIBILITY
READ( 5,1460) ORM,ORS,TPM,TPS,T2FM,T2FS

C READ IN MEAN AND STANDARD DEVIATIONS OF BOOST AND CONTROL SYSTEM
READ( 5,1460) (B(I),I=1,30)
READ( 5,1460) (C(I),I=1,30)
IF (I0(2)-3 .LT. 0 ) GO TO 20

C SEPARATE COAST CONTROL SYSTEM OPTION I0(2)=3
C READ IN TORQUEING RATE CHANGES AND RETRO PARAMETERS
READ( 5,1450) PTRC,YTRC,TRETRO,RETRSI

C READ IN COAST CONTROL SYSTEM VARIABLES, MEAN AND SIGMA
READ( 5,1460) (D(I),I=1,18)

C READ IN TABLES
20 M2=1
M3=1

C TEST FOR INPUT OPTION TO CALCULATE OR READ IN Q,VEL,GAMMA,ALTITUDE
IF (I0(8).EQ.0) GO TO 30

C READ IN INITIAL Q,V,GAMMA AND DRAG COEFFICIENT CDS FOR CALCULATION
READ( 5,990) GO,VO,GAM0,CDS
READ( 5,1470) NTHT,(TBL2(I),I=1,NTHT)
READ( 5,1470) NUT,(TBL3(I),I=1,NWT)
READ( 5,1470) NTC,(TBL4(I),I=1,NTC)
READ( 5,1470) NAZT,(TBL7(I),I=1,NAZT)
READ( 5,1470) NSYT,(TBL8(I),I=1,NSYT)
READ( 5,1470) NUMH,(TBL9(I),I=1,NUMH)
READ(5,1470) NUSH,(TBL10(I),I=1,NUSH)
C
CALCULATE Q, VELOCITY, GAMMA, AND ALTITUDE TABLES
CALL TABGEN (QO, VO, GAMO)
GO TO 40
C
IO(8)=0 READ IN ALL TRAJECTORY TABLES
30 READ(5,1470) NQT,(TBL1(I),I=1,NQT)
READ(5,1470) NTHT,(TBL2(I),I=1,NTHT)
READ(5,1470) NUT,(TBL3(I),I=1,NUT)
READ(5,1470) NTC,(TBL4(I),I=1,NTC)
READ(5,1470) NUT,(TBL5(I),I=1,NUT)
READ(5,1470) NGT,(TBL6(I),I=1,NGT)
READ(5,1470) NAZT,(TBL7(I),I=1,NAZT)
READ(5,1470) NSYT,(TBL8(I),I=1,NSYT)
READ(5,1470) NUMH,(TBL9(I),I=1,NUMH)
READ(5,1470) NUSH,(TBL10(I),I=1,NUSH)
READ(5,1470) NHT,(TBL11(I),I=1,NHT)
C
COMPUTE CONSTANTS FOR SECOND ORDER CURVE FITTING MASS PROPERTIES
40 QR1=TABLE1(7)/TABLE1(4)
QR2=TABLE1(7)*(TABLE1(7)-TABLE1(4))
SL2YI=(TABLE1(8)-TABLE1(2)+QR1*(TABLE1(2)-TABLE1(5)))/QR2
SL1YI=(-TABLE1(2)+TABLE1(5)-SL2YI*TABLE1(4)/TABLE1(4))
SL2C=(TABLE1(9)-TABLE1(3)+QR1*(TABLE1(3)-TABLE1(6)))/QR2
SL1CG=(-TABLE1(3)+TABLE1(6)-SL2CG*TABLE1(4)/TABLE1(4))
NTB=IO(5)
NTT=IO(6)
MER1=0
MRER1=0
MERC=0
NPK1=0
NPK2=0
NPK3=0
NPK4=0
SUB=0.
STC=0.
SWC=0.
STR=0.
SWT=0.
ANTPW=IO(5)
ANTPT=IO(6)
TWEB=A(13)
WTC=TBL3(2)
DELT1=TWEB/ANTPW
DELT2=(TBO-TWEB)/ANTPT
PBFC=0.0
PCFC=0.0
YCF=0.0
YBF=0.0

C SET TABLE LOOKUP INDICES FOR INITIAL VALUE
M1=1
M2=1
M3=1
M4=1
M5=1
M6=1
M7=1
M8=1
M9=1
M10=1
M11=1
NTOT=NTB+NTT
DELT=DELT1

C CALCULATE AND STORE THRUST MISALIGNMENT AND AERO COEFFICIENTS
C AT TIME POINTS DURING BOOST PHASE
TA=0.
DO 50 J=1,NTOT
IF(J.GT.NTB) DELTA=DELT2
TA=TA+0.5*DELTA
\[ TA_1(J) = TA \]
\[ \text{CALL TBLU (NGT, Q, TA, TBL1, M1)} \]
\[ \text{CALL TBLU (NTHT, T, TA, TBL2, M2)} \]
\[ \text{CALL TBLU (NUT, WR, TA, TBL3, M3)} \]
\[ \text{CALL TBLU (NTC, TC, TA, TBL4, M4)} \]
\[ \text{CALL TBLU (NUT, V, TA, TBL5, M5)} \]
\[ \text{CALL TBLU (NGT, GAMP, TA, TBL6, M6)} \]
\[ \text{CALL TBLU (NAZT, ZP, TA, TBL7, M7)} \]
\[ \text{CALL TBLU (NSYT, BETPR, TA, TBL8, M8)} \]
\[ \text{CALL TBLU (NHT, H, TA, TBL11, M11)} \]
\[ \text{CALL TBLU (NUMH, VWM, H, TBL9, M9)} \]
\[ \text{CALL TBLU (NUSH, UUS, H, TBL10, M10)} \]

\[ TCX(J) = TC / 57.3 \]
\[ VX(J) = U / 57.3 \]
\[ GAP(J) = GAMP / 57.3 \]
\[ ZPX(J) = ZP / 57.3 \]
\[ PSX(J) = BETPR / 57.3 \]
\[ VWMX(J) = VWM \]
\[ UWSX(J) = UUS \]
\[ HX(J) = H \]
\[ PERCA = (WT - WR) / WT \]
\[ WT2 = WB0 + WR \]
\[ ACC = T * 32.173 / WT \]
\[ VELX(J) = ACC * DELTA * C(1) / 57.3 \]

C

CALCULATE MOMENT OF INERTIA AND XCG AVERAGE DURING WEB BURN

\[ \text{ERTIA} = \text{TABL1(2) + SL1IY * PERCA + SL2IY * PERCA * PERCA} \]
\[ \text{CGA} = \text{TABL1(3) + SL1CG * PERCA + SL2CG * PERCA * PERCA} \]
\[ XERT = 12.5 * ERTIA \]
\[ THX(J) = (((A(4) - CGA) * A(8) + A(5) * A(9)) / XERT \]
\[ X1KA(J) = CNA * Q * (CGA - XCP) / XERT \]
\[ X1KB(J) = (A(6) - CGA) * T / XERT \]
\[ XINER(J) = ERTIA \]
\[ TOW(J) = T / UT \]
\[ WHT(J) = WT \]
CONTINUE

BEGIN THE MONTE CARLO RUNS

DO 750 ITER=1,IT

CALCULATE AND TEST CONTROL MOTOR THRUST OVERSHOOT FACTORS

IF (ORM-1.0 .LE. 0 ) GO TO 140

CALL RNDX (8)

ORPB=ORM+RXD(1)*ORS
ORYB=ORM+RXD(2)*ORS
ORPC=ORM+RXD(3)*ORS
ORYC=ORM+RXD(4)*ORS
TPPB=TPM+RXD(5)*TPS
TPYB=TPM+RXD(6)*TPS
TPPC=TPM+RXD(7)*TPS
TPYC=TPM+RXD(8)*TPS

IF (ORPB-1.0 .LE. 0 ) GO TO 70

CALL OURF (TPPB,ORPB,PBFCT)
GO TO 80

70 PBFCT=0.0

IF (ORPC-1.0 .LE. 0 ) GO TO 90

CALL OURF (TPPC,ORPC,PCFCT)
GO TO 100

90 PCFCT=0.0

IF (ORYB-1.0 .LE. 0 ) GO TO 110

CALL OURF (TPYB,ORYB,YBFCT)
GO TO 120

110 YBFCT=0.0

IF (ORYC-1.0 .LE. 0 ) GO TO 130

CALL OURF (TPYC,ORYC,YCFCT)
GO TO 140

130 YCFCT=0.0

CALL RNDX (1)
C CALCULATE ADDITIONAL CONTROL MOTOR TURN-OFF DELAY DUE TO STRUCTURAL FLEXIBILITY
T2FLX=T2FM+RXD(1)*T2FS
C COMPUTE BOOST PHASE INITIAL CONDITIONS, ET, DISTURBANCES
CALL RNDX (16)
DO 150 J=1,12
150 BT(J)=B(2*J-1)+RXD(J)*B(2*J)
BT(13)=B(25)*RXD(13)+1.
BT(14)=B(26)*RXD(14)+1.
SUP=B(27)+RXD(15)*B(28)
SUH=B(29)+RXD(16)*B(30)
C CALCULATE WIND DIRECTION
DW=BT(12)/57.3
BT(3)=B(5)+B(6)*(RXD(1)*A(2)+RXD(3)*SQRT((A(1)-1.)*(1.-A(2)*A(2))/1.(A(1)-2.)))
BT(4)=B(7)+B(8)*(RXD(2)*A(3)+RXD(4)*SQRT((A(1)-1.)*(1.-A(3)*A(3))/1.(A(1)-2.)))
CALL RNDX (1)
QRD=1.+RXD(1)*QFRAC
C SELECT CONTROL SYSTEM RANDOM VARIABLES
CALL RNDX (16)
DO 160 J=1,8
PC(J)=C(2*J-1)+RXD(J)*C(2*J)
160 YC(J)=C(2*J-1)+RXD(J+8)*C(2*J)
CALL RNDX (7)
DO 170 J=1,7
170 RC(J)=C(2*J+15)+RXD(J)*C(2*J+16)
C TEST FOR STAGE OPTION 2-NO COAST CONTROL 3-COAST CONTROL
IF (IO(2)-3 .LT. 0 ) GO TO 190
C CALCULATE RANDOM CONTROL SYSTEM CHARACTERISTICS FOR COAST WITH SEPARATE COAST SYSTEM USING YAW-ROLL MIXING
CALL RNDX (10)
DO 180 J=1,4
180 PDC(J)=D(2*J-1)+RXD(J)*D(2*J)
180  PDC(J+4)=D(2*J+7)+RXD(J+4)*D(2*J+8)  
    PDC(9)=D(1)+RXD(9)*D(2)  
    PDC(10)=D(17)+RXD(10)*D(18)  
    IF (IO(7)-1 .LT. 0 ) GO TO 190  
    C COMPUTE COAST CONTROL VARIABLES WITHOUT YAW-ROLL MIXING  
    CALL RNDX (3)  
    YCF1=D(3)+RXD(1)*D(4)  
    YCT1=D(5)+RXD(2)*D(6)  
    YCT2=D(7)+RXD(3)*D(8)  
    C COMPUTE ROLL TORQUES IMPULSE, CONTROL MOTOR TIME DELAYS,CONTROL  
    C ACCELERATIONS AT IGNITION  
    RTI-ABSCBT(10)*12./A(7)  
    T1P=PC(1)+PC(2)+PC(3)  
    T2P=PC(1)+PC(2)+PC(4)  
    T1Y=YC(1)+YC(2)+YC(3)  
    T2Y=YC(1)+YC(2)+YC(4)  
    THEDDA=PC(8)*((A(4)-TABL1(3)*BT(14))*A(8)+A(9)*A(5))/(12.*TABL1(2))  
    PSDDA=THEDDA*YC(8)/PC(8)  
    C COMPUTE CAPTURE MANUEVER IMPULSE  
    CAPIMP=PC(8)*(2.*T2P+ABS((BT(6)+2.*(BT(7)-PC(6))/PC(5))/(57.3*THEDDA))  
    CAPIMP=PC(8)*(2.*T2P+ABS((BT(8)+2.*(BT(9)-YC(6))/YC(5))/(57.3*PSDDA))  
    2)))  
    BIMP=0.  
    THETP=0.0  
    THETY=0.0  
    CALL RNDX (3)  
    VEL1=GAMEI*TBL5(2)*RXD(1)  
    VEL2=ZEI*TBL5(2)*RXD(2)  
    WINDEX=RXD(3)  
    NER1=0  
    NRR1=0  
    NERC=0  
    C
C CALCULATE IMPULSE IN PITCH AND YAW DURING BOOST PHASE

DELTA=DELT1
DO 300 J=1,NTOT
IF(J.GT.NTB) DELTA=DELT2
TA=TA1(J)
H=HX(J)
TC=TCX(J)
V=VXX(J)
GAMP=GAP(J)
ZP=ZPX(J)
BETPR=PSX(J)
CTHX=THX(J)/BT(13)
UW=UWMX(J)+INDEX*UWSX(J)
SGAMP=SIN(GAMP)
CGAMP=COS(GAMP)
UWCSDZ=UW*COS(DW-ZP)
XNUM1=UWCSDZ*SGAMP
XNUM2=UW*SIN(DW-ZP)
XDEN1=U+UWCSDZ*CGAMP
QWDFAC=QRDX(XDEN1**2./U+(UW/V)**2-1.)
XKA=QWDFAC*X1KA(J)/BT(13)
XKB=XIKB(J)/BT(13)
C COMPUTE THRUST MISALIGNMENT
ETPA=(BT(1)+BT(3)*TA)/57.3
ETYA=(BT(2)+BT(4)*TA)/57.3
THEDDA=PC(8)*CTHX
PSDDA=THEDDA*YC(8)/PC(8)
C COMPUTE ANGLES OF ATTACK IN PITCH AND YAW
GAME1=VEL1/V
ZE1=VEL2/V
C CALCULATE ALPHA DUE TO WINDS
ALPHW=(XNUM1/XDEN1)
C CALCULATE BETA DUE TO WINDS
BETA_W = (XNUM2 / XDEN1)  
ALPHP = TC - GAMP - GAME1 + ALPHW  
BETAP = BETPR + BETA_W + ZE1  

C CALCULATE PITCH AND YAW ACCEL DUE TO THRUST MISALIGNMENT, AERO
C AND CG OFF-SET

TOWI = TOW(J) / (XINER(J) * BT(13))  
THETP = XKA * ALPHP + XKB * ETPA + SUP * TOWI  
THETY = -XKA * BETAP + XKB * ETA + SUY * TOWI

C PICK DEADBAND SIDE AND ADD DEADBAND TO ANGLE OF ATTACK
IF (THETP) 210, 220, 200
C COMPUTE CROSS TRACK VELOCITY ERROR UPDATE

200 VEL1 = VEL1 + VELX(J)
GAME = VEL1 / V
DALP = C(11) / 57.3 - (GAME - GAME1) / 2.
DADBP = DALP * XKA
THETP = THETP + DADBP
GO TO 220

210 VEL1 = VEL1 - VELX(J)
GAME = VEL1 / V
DALP = -C(11) / 57.3 - (GAME - GAME1) / 2.
DADBP = DALP * XKA
THETP = THETP + DADBP

220 IF (THETY) 240, 250, 230
230 VEL2 = VEL2 + VELX(J)
ZE = VEL2 / V
DBET = -C(11) / 57.3 + (ZE - ZE1) / 2.
DADBY = -DBET * XKA
THETY = THETY + DADBY
GO TO 250

240 VEL2 = VEL2 - VELX(J)
ZE = VEL2 / V
DBET = +C(11) / 57.3 + (ZE - ZE1) / 2.
DADBY = -DBET * XKA
THETY = THETY + DADBY
CALL SUBROUTINE FOR COMPUTING MINIMUM DISTURBING ACCELERATION FOR ONE SIDED LIMIT CYCLE

CALL THEMIN (THEDDA,PC(5),PC(6),PC(7),T1P,T2P,THMIN)
IF (ABS(THETP)-THMIN .GE. 0) GO TO 260
CALL CYCLE (THEDDA,PC(5),PC(6),PC(7),T1P,T2P,DCP,AP,NERR1,PBFCT)
GO TO 270

CALL THEMIN (PSDDA,YC(5),YC(6),YC(7),T1Y,T2Y,THMIN)
IF (ABS(THETY)-THMIN .GE. 0) GO TO 280
CALL CYCLE (PSDDA,YC(5),YC(6),YC(7),T1Y,T2Y,DCY,A,Y,NERR1,YBFCT)
GO TO 290

DCP=ABS(THETP/THEDDA)
DPI=DCP*PC(8)*DELTA
DCY=ABS(THETY/PSDDA)
DYI=DCY*YC(8)*DELTA

THXU=THX(J)*UGHT(J)
TWLTP=X1KB(J)/THXU
TUWLP=TWOU(J)/(THXU*XINER(J))
CNWL=QDFAC*X1KA(J)/THXU
ALP=DALP+ALPHP
BET=DBET+BETAP
RM=TOU(J)*(SUP*EYAT-SUY*EYPA)+QDFAC*CNASQ(J)*(SUY*ALP+
1 SUP*BET)/UGHT(J)+SUY*(WLTLP*ETPA+TWLTP*SUP+
2 CNWL*ALP)-SUP*(TWLTP*ETYA+TWLP*SUY-CNWL*BET)

THXU=THX(J)*UGHT(J)

RIMP=12.*ABS(RM)*DELTA/A(7)

BIMP=BIMP+ABS(DPI)+ABS(DYI)+RIMP

BIMP=(BIMP+CAPIMP)*(1.+(A(5)*A(8)*ABS(BT(11)))/(57.3*A(7)))+RTI
WBOOST(ITER)=BIMP/BT(5)
SUB=SUB+WBOOST(ITER)

COMPUTE LIMIT CYCLE FUEL CONSUMPTION DURING COAST WITH FILTER IN USING BOOST CONTROL SYSTEM
THEDDA = PC(8)*((A(4)-BT(14)*TABL1(9))*A(8)+A(5)*A(9))/(12.*TABL1(8))  
1*BT(13))  
PSDDA = THEDDA*YC(8)/PC(8)  
PHIDD = RC(7)*A(7)/(6.*A(16))  
CALL CYCLE (THEDDA,PC(5),PC(6),PC(7),T1P,T2P,DCP,AP,NERR1,PBFCT)  
NERR1 = NERR1+NERR1  
CALL CYCLE (PSDDA,VC(5),VC(6),VC(7),T1Y,T2Y,DCY,AY,NERR1,YBFCT)  
NERR1 = NERR1+NERR1  
T1R = RC(1)+RC(2)  
T2R = RC(1)+RC(3)  
CALL CYCLE (PHIDD,RC(4),RC(5),RC(6),T1R,T2R,DCR,AR,NERR1,0.)  
NERR1 = NERR1+NERR1  
C COMPUTE CONTROL FUEL FLOW RATE LIMIT CYCLE WITH BOOST CONTROLS  
WDFILT = (DCP*PC(8)+DCV*VC(8)+DCR*RC(7)*2.)/BT(5)  
TTO = TBO - TWEB  
C TEST FOR COAST FILTER OPTION 1-COAST FILTER OUT 2-COAST FILTER IN  
IF (IO(4)-2 .GE. 0 ) GO TO 420  
C COMPUTE FUEL WITH FILTER IN COAST FOR OPTION WITH FILTER SWITCHED  
C OUT DURING COAST  
DELTA = A(10)-TBO  
WFILTER = WDFILT*DELTA  
GO TO 530  
C TEST FOR STAGE OPTION 2-NO COAST CONTROL 3-COAST CONTROL  
420 IF (IO(2)-3 .GE. 0 ) GO TO 490  
C BOOST AND COAST CONTROL SYSTEM IS THE SAME  
C TEST FOR COAST OPTION 1-COAST TIME 2-COAST FUEL  
IF (IO(3)-2 .GE. 0 ) GO TO 460  
C STAGE 2 COAST TIME - FILTER IN  
TCOAST(ITER) = (A(12)-UBOOST(ITER))/WDFILT  
STC = STC + TCOAST(ITER)  
C TEST FOR PRINT OPTION 1-INDIVIDUAL SAMPLE DATA, 2-ONLY STATISTICS  
IF (IO(1)-2 .GE. 0 ) GO TO 600  
430 IF (NPK1 .NE. 0 ) GO TO 450  
440 NPAGE = NPAGE+1
CALL PAGEHD (NRUN,NPAGE,NLINE)
WRITE( 6,980)
WRITE( 6,1010)
NLINE=NLINE+6
NPK1=1
450 IF (NLINE+3-62 .GT. 0 ) GO TO 440
WRITE( 6,1000) ITER,CAPIMP,RTI,BIMP,TWEB,TTO,WBOOST(ITER),BT(5)
WRITE( 6,1020) TCOAST(ITER),WDFILT,NER1,NRR1
NLINE=NLINE+3
GO TO 600

C STAGE 2 COAST FUEL - FILTER IN
460 WCOAS(ITER)=A(11)*WDFILT
SWC=SWC+WCOAS(ITER)
WTOT(ITER)=WBOOST(ITER)+WCOAS(ITER)
SUT=SUT+WTOT(ITER)

C TEST PRINT OPTION 1-INDIVIDUAL SAMPLE DATA, 2-ONLY STATISTICAL
IF (IO(1)-2 .GE. 0 ) GO TO 600
IF (NPK1 .NE. 0 ) GO TO 480

470 NPAGE=NPAGE+1
CALL PAGEHD (NRUN,NPAGE,NLINE)
WRITE( 6,980)
WRITE( 6,1030)
NLINE=NLINE+6
NPK1=1
480 IF (NLINE+3-62 .GT. 0 ) GO TO 470
WRITE( 6,1000) ITER,CAPIMP,RTI,BIMP,TWEB,TTO,WBOOST(ITER),BT(5)
WRITE( 6,1040) WCOAS(ITER),WDFILT,NER1,NRR1,WTOT(ITER)
NLINE=NLINE+3
GO TO 600

C SEPARATE COAST CONTROL IO(2)=3
C TEST FOR COAST OPTION 1-COAST TIME 2-COAST FUEL AND RETRO TIME
490 IF (IO(3)-2 .GE. 0 ) GO TO 500
C COMPUTE STAGE 3 COAST TIME - FILTER IN
TCOAST(ITER)=(A(12)-WBOOST(ITER)-2.*(PC(8)+YC(8)+RC(7)))*TRETRO/RET442
IHI/WDILT
STC=STC+TCOAST(ITER)

C TEST PRINT OPTION 1-INDIVIDUAL SAMPLE DATA, 2-ONLY STATISTICAL
IF(IO(1)) 430,600,600
C
COMPUTE STAGE 3 COAST FUEL, RETRO TIME AND TOTAL FUEL FILTER IN
500 WCOAS(ITER)=A(11)*WDILT
WRETRO=A(12)-WBOOST(ITER)-WCOAS(ITER)
TRET(ITER)=WRETRO*RETRSI/(2.*(PC(8)+YC(8)+RC(7)))
SWC=SWC+WCOAS(ITER)
STR=STR+TRET(ITER)
WTOT(ITER)=A(12)-WRETRO*(1.-TRETRO/TRET(ITER))
SWT=SWT+WTOT(ITER)

C TEST PRINT OPTION 1-INDIVIDUAL SAMPLE DATA 2-ONLY STATISTICAL
IF (IO(1)-2 .GE. 0 ) GO TO 600
IF (NPK1 .NE. 0 ) GO TO 520

510 NPAGE=NPAGE+1
CALL PAGEHD (NRUN,NPAGE,NLINE)
WRITE( 6,980)
WRITE( 6,1030)
NLINE=NLINE+6
NPK1=1

520 IF (NLINE+3-62 .GT. 0 ) GO TO 510
WRITE( 6,1000) ITER,CAPIMP,RTI,BIMP,TWEB,TTO,WBOOST(ITER),BT(5)
WRITE( 6,1040) WCOAS(ITER),WDILT,NER1,NRR1,WTOT(ITER)
NLINE=NLINE+3
GO TO 600

C FILTER OUT COAST OPTION
C TEST FOR STAGE OPTION 2-NO COAST CONTROL 3-COAST CONTROL
530 IF (IO(2)-3 .GE. 0 ) GO TO 550
C
WITH BOOST CONTROL, FILTER OUT IN COAST
T1P=PC(2)+PC(3)
T2P=PC(2)+PC(4)+T2FLX
T1Y=YC(2)+YC(3)
T2Y=YC(2)+YC(4)+T2FLX
CALL CYCLE (THEDDA, PC(5), PC(6), PC(7), T1P, T2P, DCP, AT, NERR1, PCFCT)
NERC+NERC+NERR1
CALL CYCLE (PSDDA, YC(5), YC(6), YC(7), T1Y, T2Y, DCY, AT, NERR1, YCFCT)
NERC+NERC+NERR1
WDCST=(DCR*RC(7)*2.+DCP*PC(8)+DCY*YC(8))/BT(5)
C TEST FOR COAST OPTION 1-COAST TIME 2-COAST FUEL AND RETRO TIME
IF (IO(3)-2 .GE. 0 ) GO TO 540
C COMPUTE COAST TIME
TCOAST(ITER)=DELT+(A(12)-WBOOST(ITER)-WFILT)/WDCST
STC=STC+TCOAST(ITER)
GO TO 600
C COMPUTE COAST FUEL AND BOOST+COAST FUEL
C COAST TIME IS ONLY PORTION WITH FILTER SWITCHED OUT; COAST FUEL
C INCLUDES FILTER IN AND FILTER OUT COAST TIMES
540 WCOAS(ITER)=A(11)*WDCST+WFILT
SUC=SUC+WCOAS(ITER)
WTOT(ITER)=WBOOST(ITER)+WCOAS(ITER)
SWT=SWT+WTOT(ITER)
GO TO 600
C STAGE 3 OPTION
C SEPARATE COAST CONTROL FILTER OUT IN COAST AND YAW-ROLL MIXING
C 2 ROLL MOTORS FOR YAW; 2 ROLL MOTORS FOR ROLL
550 THEDDA=THEDDA*PDC(2)/PC(8)
PSDDA=PSDDA*2.*PDC(6)/YC(8)
PHIDD=PHIDD*PDC(6)/RC(7)
T1P=PC(2)+PDC(3)
T2P=PC(2)+PDC(4)+T2FLX
T1Y=YC(2)+PDC(7)
T2Y=YC(2)+PDC(8)+T2FLX
T1R=RC(1)+PDC(7)
T2R=RC(1)+PDC(8)
C COMPUTE PITCH, YAW, ROLL TORQUEING AND DEADBAND REDUCTION FUEL
PRTRW=(PDC(2)*(2.*T2P+ABS{(PTRC+57.3*AP+2.*(PC(6)-PDC(1)))/PC(5)}/(509
157.3*THEDDA))))
YRTRU=2.*PDC(6)*(2.*T2Y+ABS((YTRC+57.3*AY+2.*(YC(6)-PDC(9))/YC(5)))/ (57.3*PSDDA))
RRTRU=2.*PDC(6)*(2.*T2R+ABS((57.3*AR+2.*(RC(5)-PDC(5))/RC(4))/(57.5))

C TEST COAST SYSTEM IO(7) = 0 YAW-ROLL MIXING, =1 NO MIXING
IF (IO(7)-1 .LT. 0 ) GO TO 560
C NO YAW-ROLL MIXING, SEPARATE PITCH AND YAW MOTORS
PSDDA=PSDDA*YCF1/(2.*PDC(6))
T1Y=YC(2)+YCT1
T2Y=YC(2)+YCT2+T2FLX
YRTRU=YCF1*(2.*T2Y+ABS((YTRC+57.3*AY+2.*(YC(6)-PDC(9))/YC(5))/(57.5))

C TEST FOR COAST CONTROL SYSTEM 0=YAW-ROLL MIXING, 1= NO MIXING
IF (IO(7)-1 .GE. 0 ) GO TO 570
C YAW-ROLL MIXING
UDCST=(PDC(2)*DCP+2.*PDC(6)*(DCY+DCR))/PDC(10)
GO TO 580

C TEST FOR COAST OPTION 1-COAST TIME 2-COAST FUEL AND RETRO TIME
IF (IO(7)-2 .GE. 0 ) GO TO 590
C COAST TIME OPTION
TCOAST(ITER)=DELT+(A(12)-WBOOST(ITER)-WFLT-TRDRW-(PC(8)+YC(8)+RC(5))

C STAGE 3 COAST FUEL, RETRO TIME, TOTAL FUEL WITH INPUT RETRO TIME
UPDATE COUNTER ON NUMBER OF DEADBAND OVERSHOOT CASES

600 IF (NER1-1 .LT. 0 ) GO TO 610
MER1=MER1+1
610 IF (NRR1-1 .LT. 0 ) GO TO 620
MRER1=MRER1+1
620 IF (NERC-1 .LT. 0 ) GO TO 630
MERC=MERC+1
C TEST FOR COAST FILTER OPTION 1-COAST FILTER OUT 2-COAST FILTER IN
630 IF (IO(4)-2 .GE. 0 ) GO TO 750
C TEST PRINT OPTION 1-INDIVIDUAL SAMPLE RESULTS, 2-ONLY STATISTICAL
IF (IO(1)-2 .GE. 0 ) GO TO 750
C TEST FOR STAGE OPTION 2-BOOST CONTROL COAST 3-COAST CONTROL
IF (IO(2)-3 .GE. 0 ) GO TO 690
C TEST FOR COAST OPTION 1-COAST TIME 2-COAST FUEL AND RETRO TIME
IF (IO(3)-2 .GE. 0 ) GO TO 660
C PRINT COAST TIME
640 NPAGE=NPAGE+1
CALL PAGEHD (NRUN,NPAGE,NLINE)
WRITE( 6,980 )
WRITE( 6,1050 )
NLINE=NLINE+6
NPK1=1
650 IF (NLINE+3-62 .GT. 0 ) GO TO 640
WRITE( 6,1000 ) ITER,CAPI,RTI,BIMP,TWEB,TTO,WBOOST(ITER),BT(5)
WRITE( 6,1060 ) TCOAST(ITER),WDFILT,WDCST,NER1,NRR1
NLINE=NLINE+3
GO TO 750
C PRINT COAST FUEL AND RETRO TIME
660 IF (NPK1 .NE. 0 ) GO TO 680
670 NPAGE=NPAGE+1
   CALL PAGEHD (NRUN,NPAGE,NLINE)
   WRITE( 6,980)
   WRITE( 6,1070)
   NLINE=NLINE+6
   NPK1=1
680 IF (NLINE+3-62 .GT. 0 ) GO TO 670
   WRITE( 6,1000) ITER,CAPIMP,RTI,BIMP,TWEB,TTO,WBOOST(ITER),BT(5)
   WRITE( 6,1080) WCOAS(ITER),WDFILT,WDCST,NER1,NRR1,NERC,WTOT(ITER)
   NLINE=NLINE+3
   GO TO 750
C TEST FOR COAST OPTION 1-COAST TIME 2-COAST FUEL AND RETRO TIME
690 IF (IO(3)-2 .GE. 0 ) GO TO 720
   IF (NPK1 .NE. 0 ) GO TO 710
700 NPAGE=NPAGE+1
   CALL PAGEHD (NRUN,NPAGE,NLINE)
   WRITE( 6,980)
   WRITE( 6,1090)
   NLINE=NLINE+6
   NPK1=1
710 IF (NLINE+3-62 .GT. 0 ) GO TO 700
   WRITE( 6,1000) ITER,CAPIMP,RTI,BIMP,TWEB,TTO,WBOOST(ITER),BT(5)
   WRITE( 6,1100) TCOAST(ITER),WDFILT,TRDRW,WDCST,NER1,NRR1,NERC
   NLINE=NLINE+3
   GO TO 750
C PRINT COAST FUEL AND RETRO TIME
720 IF (NPK1 .NE. 0 ) GO TO 740
730 NPAGE=NPAGE+1
   CALL PAGEHD (NRUN,NPAGE,NLINE)
   WRITE( 6,980)
WRITE( 6,1110)
NLINE=NLINE+6
NPK1=1
740 IF (NLINE+3-62 .GT. 0 ) GO TO 730
WRITE( 6,1000) ITER,CAPIMP,RTI,BIMP,TWEB,TTO,WBOOST(ITER),BT(5)
WRITE( 6,1120) WCOAS(ITER),WDFILT,TRDRW,WDCST,TRET(ITER),NER1,NRR1
1,NERC,WTOT(ITER)
NLINE=NLINE+3
750 CONTINUE

C
END OF INDIVIDUAL SAMPLE CALCULATION LOOP
C
BEGIN PART 2 STATISTICAL ANALYSIS
AVI=IT
VI=AVI+1.
VIB=AVI-1.
WBMEAN=SWB/AVI
C TEST FOR COAST OPTION 1-COAST TIME 2-COAST FUEL AND RETRO TIME
IF (I0(3)-2 .GE. 0 ) GO TO 790
C COAST TIME OPTION
TCMEAN=STC/AVI
C CALL SUBROUTINE FOR REARRANGING ARRAYS
CALL ASCEND (IT,WBOOST,0)
CALL ASCEND (IT,TCOAST,1)
SDXWB=0.
SDXTC=0.
C COMPUTE DISCRETE SAMPLE PROBABILITY LEVEL,SUM VALUES AND SQUares
DO 780 KAB=1,IT
XKAB=KAB
PROB=XKAB/VI
DXWB=(WBMEAN-WBOOST(KAB))**2
DXTC=(TCMEAN-TCOAST(KAB))**2
SDXWB=SDXWB+DXWB
SDXTC=SDXTC+DXTC
C PRINT ELEMENTS OF REARRANGED ARRAY AS COMPUTED
IF (NPK2 .NE. 0 ) GO TO 770
760 NPAGE=NPAGE+1
CALL PAGEHD (NRUN, NPAGE, NLINE)
WRITE ( 6,1130)
NLINE=NLINE+4
NPK2=1
770 IF (NLINE+1-62 .GT. 0 ) GO TO 760
WRITE ( 6,1140) PROB, WBOOST(KAB), TCOAST(KAB)
NLINE=NLINE+1
780 CONTINUE
C PRINT MEAN, SIGMA, LAST RANDOM SEQUENCE INTEGER, NO. OF DEADBAND OVER
C SHOOT CASES
SIGB=SQRT(SDXWB/UIB)
SIGT=SQRT(SDXTC/UIB)
NPAGE=NPAGE+1
CALL PAGEHD (NRUN, NPAGE, NLINE)
WRITE ( 6,1150)
WRITE ( 6,1160) WBMEAN, TCMEAN
WRITE ( 6,1170) SIGB, SIGT
C FIND LAST RANDOM SEQUENCE INTEGER, CDC RANF RANDOM NUMBER GENERATOR
C CALL RANGET (K)
WRITE ( 6,1180) K
WRITE ( 6,1190)
WRITE ( 6,1200) MER1
WRITE ( 6,1210) MRER1
WRITE ( 6,1220) MERC
GO TO 10
C OPTION FOR FUEL CONSUMPTION
790 WCMEAN=SUC/AUI
WTOTM=SUT/AUI
C TEST FOR STAGE OPTION 2-COAST WITH CONTROL 3-COAST CONTROL
IF (IO(2)-3 .LT. 0 ) GO TO 870
C SEPARATE COAST CONTROL OPTION
TREATMENT/AVI
CALL ASCEND (IT,WBOOST,0)
CALL ASCEND (IT,UCOAS,0)
CALL ASCEND (IT,UTOT,0)
CALL ASCEND (IT,TRET,1)
SDXWB=0.
SDXFC=0.
SDXWT=0.
SDXRT=0.
C CALCULATE PROBABILITIES OF FUEL CONSUMPTION AND RETRO TIME
DO 820 KAB=1,IT
  XKAB=KAB
  PROB=XKAB/VI
  DXWB=(UBMEAN-WBOOST(KAB))**2
  DXFC=(UCMEAN-UCOAS(KAB))**2
  DXUT=(UTOTM-UTOT(KAB))**2
  DXRT=(TRETM-TRET(KAB))**2
  SDXWB=SDXWB+DXWB
  SDXFC=SDXFC+DXFC
  SDXWT=SDXWT+DXUT
  SDXRT=SDXRT+DXRT
C PRINT ELEMENTS OF REARRANGED ARRAY AS COMPUTED
  IF (NPK3 .NE. 0 ) GO TO 810
  800 NPAGE=NPAGE+1
  CALL PAGEHD (NRUN,NPAGE,NLINE)
  WRITE( 6,1230)
  NLINE=NLINE+4
  NPK3=1
  810 IF (NLINE+1-62 .GT. 0 ) GO TO 800
  WRITE( 6,1240) PROB,WBOOST(KAB),UCOAS(KAB),TRET(KAB),UTOT(KAB)
  NLINE=NLINE+1
  820 CONTINUE
  SIGB=SQRT(SDXWB/VI)
  SIGUC=SQRT(SDXFC/VI)
SIGWT=SQRT(SDXWT/VIB)
SIGRT=SQRT(SDXRT/VIB)
IF (IT-100 .LT. 0 ) GO TO 850
ANI=0.995*UI
NI=ANI
ANIP=NI
IF (.5-(ANI-ANIP) .GT. 0 ) GO TO 840
NI=NI+1
840 CONTINUE
C COMPUTE UPPER 95% CONFIDENCE LEVEL ON 99.5% PROBABILITY LEVEL
DEN=SQRT(1.-1.96*SQRT(2./(AVI-1.)))
XK=1./DEN
XWB95=WBMEAN+XK*(WBOOST(NI)-WBMEAN)
XWC95=WCMEAN+XK*(WCOAS(NI)-WCMEAN)
XWT95=WTOTM+XK*(WTOT(NI)-WTOTM)
XRET95=TRETM+XK*(TRET(NI)-TRETM)
850 NPAGE=NPAGE+1
CALL PAGEHD (NRUN,NPAGE,NLINE)
WRITE( 6,1340)
WRITE( 6,1350)
WRITE( 6,1340)
WRITE( 6,1250)
WRITE( 6,1260) WBMEAN,WCMEAN,TRETM,WTOTM
WRITE( 6,1270) SIGB,SIGUC,SIGRT,SIGWT
IF (IT-100 .LT. 0 ) GO TO 860
WRITE( 6,1310) XWB95,XWC95,XRET95,XWT95
860 CONTINUE
C RETRIEVE LAST RANDOM SEQUENCE INTEGER
CALL RANGET (K)
WRITE( 6,1180) K
WRITE( 6,1190)
WRITE( 6,1200) MER1
WRITE( 6,1210) MRER1
WRITE( 6,1220) MERC
C COMPUTE STATISTICS AND COMPARE WITH NORMAL, LOG-NORMAL, AND WEIBULL

C STATISTICAL DISTRIBUTION FUNCTIONS
CALL WBL (IT, WBOOT, NUMCHI, FWB)
CALL WBL (IT, WCOAS, NUMCHI, FWC)
CALL WBL (IT, WTOT, NUMCHI, FWT)
WRITE (6, 1400)
WRITE (6, 1410) (FWB(J), FWC(J), FWT(J)), J=1,4, FWB(9), FWC(9), FWT(9)
WRITE (6, 1410) (FWB(J), FWC(J), FWT(J)), J=5,8, FWB(10), FWC(10), FWT(15)
WRITE (6, 1410) (FWB(J), FWC(J), FWT(J)), J=11,17, FWB(18), FWC(18), FWT(18)
WRITE (6, 1410) (FWB(J), FWC(J), FWT(J)), J=18, FWB(19), FWC(19), FWT(19)
WRITE (6, 1410) (FWB(J), FWC(J), FWT(J)), J=19, FWB(20), FWC(20), FWT(20)
WRITE (6, 1420)
WRITE (6, 1430) (FWB(J), FWC(J), FWT(J)), J=1,4, FWB(9), FWC(9), FWT(9)
WRITE (6, 1430) (FWB(J), FWC(J), FWT(J)), J=5,8, FWB(10), FWC(10), FWT(15)
WRITE (6, 1430) (FWB(J), FWC(J), FWT(J)), J=11,17, FWB(18), FWC(18), FWT(18)
WRITE (6, 1430) (FWB(J), FWC(J), FWT(J)), J=18, FWB(19), FWC(19), FWT(19)
WRITE (6, 1430) (FWB(J), FWC(J), FWT(J)), J=19, FWB(20), FWC(20), FWT(20)
WRITE (6, 1430) (FWB(J), FWC(J), FWT(J)), J=20

C TEST FOR HISTOGRAM OUTPUT OPTION IO(9)=0 HISTOGRAMS, =1 NONE
IF (IO(9), EQ, 1) GO TO 10
C CALCULATE AND PLOT HISTOGRAMS
NDX = 30
C COMPUTE RANGE OF VARIABLES AND PLOT HISTOGRAM FOR RETRO TIME
CALL RANGE (TRET, IT, GREAT, SMALL, DX, NDX, ERRTB)
IF (ERRTB .GT. 0 ) GO TO 950
WRITE (6, 1390)
CALL HISTO (TRET, IT, GREAT, SMALL, DX)
GO TO 950
C STAGE 3- SEPARATE COAST CONTROL OPTION
870 CALL ASCEND (IT, WBOOT, 0)
CALL ASCEND (IT, WCOAS, 0)
CALL ASCEND (IT, WTOT, 0)
SDXWB = 0.
SDXFC = 0.
SDXWT = 0.
C COMPUTE PROBABILITY DISTRIBUTION AND SUM OF SQUARES
DO 900 KAB = 1, IT
XKAB = KAB
PROB = XKAB / VI
900 CONTINUE
IN  

DXWB= (UBMEAN-WBOOST(KAB))**2     783  
DXFC= (UCMEAN-WCOAS(KAB))**2     784  
DXWT= (WTOTM-WTOT(KAB))**2     785  
SDXWB= SDXWB+DXWB     786  
SDXFC= SDXFC+DXFC     787  
SDXWT= SDXWT+DXWT     788  
C PRINT ELEMENTS OF REARRANGED ARRAY AS COMPUTED     789  
  IF (NPK4 .NE. 0 ) GO TO 890     790  
880 NPAGE=NPAGE+1     791  
  CALL PAGEHD (NRUN,NPAGE,NLINE)     792  
  WRITE( 6,1280)     793  
    NLINE=NLINE+4     794  
NPK4=1     795  
890 IF (NLINE+1-62 .GT. 0 ) GO TO 880     796  
  WRITE( 6,1290) PROB,WBOOST(KAB),WCOAS(KAB),WTOT(KAB)     797  
    NLINE=NLINE+1     798  
900 CONTINUE     799  
C COMPUTE STANDARD DEVIATION     800  
  SIGB=SQRT(SDXWB/VIB)     801  
  SIGWC=SQRT(SDXFC/VIB)     802  
  SIGWT=SQRT(SDXWT/VIB)     803  
  IF (IT-100 .LT. 0 ) GO TO 930     804  
ANI=0.995*VI     805  
NI=ANI     806  
ANIP=NI     807  
  IF (.5-(ANI-ANIP) .GT. 0 ) GO TO 920     808  
NI=NI+1     809  
920 CONTINUE     810  
C COMPUTE UPPER 95% CONFIDENCE LEVEL, 99.5% PROBABILITY LEVEL     811  
  DEN=SQRT(1.-1.96*SQRT(2./(AVI-1.)))     812  
  XK=1./DEN     813  
  XWB95=UBMEAN+XK*(WBOOST(NI)-UBMEAN)     814  
  XWC95=UCMEAN+XK*(WCOAS(NI)-UCMEAN)     815  
  XWT95=WTOTM+XK*(WTOT(NI)-WTOTM)     816
930 NPAGE=NPAGE+1
CALL PAGEHD (NRUN,NPAGE,NLINE)
WRITE( 6,1340)
WRITE( 6,1350)
WRITE( 6,1340)
WRITE( 6,1300)
WRITE( 6,1260) WBMEAN,WCMEAN,UTOTM
WRITE( 6,1270) SIGB,SIGWC,SIGUT
IF (IT-100 .LT. 0 ) GO TO 940
WRITE( 6,1310) XWB95,XWC95,XWT95
940 CONTINUE
C FIND LAST RANDOM SEQUENCE INTEGER
CALL RANGET (K)
WRITE( 6,1180) K
WRITE( 6,1190)
WRITE( 6,1200) MER1
WRITE( 6,1210) MRER1
WRITE( 6,1220) MERC
C COMPUTE STATISTICAL PARAMETERS AND FIT TO NORMAL, LOG-NORMAL, AND
C WEIBULL DISTRIBUTION FUNCTIONS
CALL WBL (IT,WBOOST,NUMCHI,FWB)
CALL WBL (IT,WCOAS,NUMCHI,FWC)
CALL WBL (IT,WTOT,NUMCHI,FWT)
WRITE( 6,1400)
WRITE( 6,1410) ((FWB(J),FWC(J),FWT(J)),J=1,4),FWB(9),FWC(9),FWT(9)
1,FWB(18),FWC(18),FWT(18)
WRITE( 6,1420)
WRITE( 6,1410) ((FWB(J),FWC(J),FWT(J)),J=5,8),FWB(10),FWC(10),FWT(10)
110),FWB(19),FWC(19),FWT(19)
WRITE( 6,1430) ((FWB(J),FWC(J),FWT(J)),J=11,17),FWB(20),FWC(20),FWT(20)
110)
C TEST FOR HISTOGRAM OUTPUT IO(9)=0 GIVES HISTOGRAMS, -1 NONE
IF (IO(9).EQ.1) GO TO 10
C CALCULATE AND PLOT HISTOGRAMS OF BOOST, COAST, AND TOTAL FUEL
NDX = 30
CONTINUE
CALL RANGE (WBOOST, IT, GREAT, SMALL, DX, NDX, ERRTB)
IF (ERRTB .GT. 0) GO TO 960
WRITE (6, 1360)
CALL HISTO (WBOOST, IT, GREAT, SMALL, DX)
CALL RANGE (WCOAS, IT, GREAT, SMALL, DX, NDX, ERRTB)
IF (ERRTB .GT. 0) GO TO 970
WRITE (6, 1370)
CALL HISTO (WCOAS, IT, GREAT, SMALL, DX)
CALL RANGE (WTOT, IT, GREAT, SMALL, DX, NDX, ERRTB)
IF (ERRTB .GT. 0) GO TO 10
WRITE (6, 1380)
CALL HISTO (WTOT, IT, GREAT, SMALL, DX)
GO TO 10

END OF MAIN ROUTINE

FORMAT (85H SMPL CAPT IMP ROLL TORQ BOOST IMP T(WEB))
1 T(TO) BOOST FUEL ISP/BX, 77H(LB-SEC) IMP(LB-SC) (LB-SB)
2SEC) (SEC) (SEC) (SEC)
FORMAT (BF10.3)
FORMAT (/I5,1P7E12.4)
FORMAT (8X,44HCST TIME FLOW RATE NO. OF DB OVERSHootS, /10X,39874
1H(SEC) FILTER IN BOOST P-Y ROLL)
FORMAT (5X,1P2E12.4, I8, I12)
FORMAT (8X,43HCST FUEL FLOW RATE NO. OF DB OVERSHootS, 3X,10HT0877
1ITAL FUEL, /, 10X, 40H(LBS) FILTER IN BOOST P-Y ROLL, 7X,5H(LB)
2BS), /
FORMAT (5X,1P2E12.4, I8, I12, 4X,1PE12.4)
FORMAT (8X,55HCST TIME FLOW RATE FLOW RATE NO. OF DB OVERSHOOT
10TS, /, 10X, 53H(SEC) FILTER IN COAST BOOST P-Y ROLL
2, /)
FORMAT (5X,1P3E12.4, I8, I12)
```plaintext
1290 FORMAT (5X,F10.5,F16.3,F16.4,F15.3)
1300 FORMAT (/22X, 'BOOST FUEL', COAST FUEL, 6X, 'TOTAL FUEL')
1310 FORMAT (/5X, '0.995 PROB', 5X, F11.3, F15.3, F16.4, F15.3, /, 5X, '0.95 CONF')
1320 FORMAT (I8)
1330 FORMAT (I15)
1340 FORMAT (/)
1350 FORMAT (72H)
1360 FORMAT (1H1, I11X, 'BOOST FUEL CONSUMPTION HISTOGRAM', /)
1370 FORMAT (1H1, I11X, 'COAST FUEL CONSUMPTION HISTOGRAM', /)
1380 FORMAT (1H1, I11X, 'TOTAL FUEL CONSUMPTION HISTOGRAM', /)
1390 FORMAT (1H1, I11X, 'RETRO TIME HISTOGRAM', /)
1400 FORMAT (1H1, I5X, 'DISTRIBUTION FUNCTION FIT', /, 34X, 'BOOST COAST TOTAL', /, 5X, 'NORMAL DISTRIBUTION', /)
1410 FORMAT (10X, 'MEAN', 16X, 3F10.3, /, 10X, 'STANDARD DEV', 8X, 3F10.3, /, 10X, '0.995 PROB 0.995 CONF')
1420 FORMAT (/, 5X, 'WEIBULL DISTRIBUTION', /, 6X, '(VALUES OF LOG)')
1440 FORMAT (3(E10.3))
1450 FORMAT (E15.5)
1460 FORMAT (2(E15.5))
1470 FORMAT (I5/(6F10.3))
END
```
*DECK ALTI
SUBROUTINE ALTI (ALTO,VO,QO)
C THIS SUBROUTINE COMPUTES THE ALTITUDE(ALTO) FROM THE
C VELOCITY AND DYNAMIC PRESSURE USING THE ALTITUDE-DENSITY TABLE
DIMENSION DUM(18)
COMMON/DRH/RHO(18),MR
MR=1
RHI=ALOG(VO*VO/(2.*QO))
C EXCHANGE THE ORDINATES AND ABCISSAS IN THE ALTITUDE-DENSITY TABLE
DO 10 J=1,18,2
   DUM(J)=RHO(J+1)
   DUM(J+1)=RHO(J)
10   CALL TBLU (18,ALTO,RHI,DUM,MR)
RETURN
END
*DECK ASCEND

SUBROUTINE ASCEND (L, VAL, M)

C SUBROUTINE FOR REARRANGING ARRAY IN ASCENDING ORDER

C OR DESCENDING ORDER IF M=1

DIMENSION VAL(1)

DO 40 J=1, K

IF(M) 10, 10, 20

10 IF (VAL(J)=VAL(JL) .LE. 0) GO TO 40

GO TO 30

20 IF((VAL(JL)=VAL(J) .LE. 0) GO TO 40

30 TEMP=VAL(J)

VAL(J)=VAL(JL)

VAL(JL)=TEMP

40 CONTINUE

RETURN

END
*DECK CALCU

SUBROUTINE CALCU

C THIS SUBROUTINE COMPUTES THE STATE VARIABLES AND THE FIRST
C DERIVATIVES FOR USE WITH THE RUNGE SUBROUTINE

COMMON/DDI/TBL2(90),TBL3(90),NTHT,NWT,CDS,M2,M3,WBO

COMMON/DDY/YDOT(4),Y(4),T,DT

COMMON/DRH/RHO(18),MR

DATA GO,RO,CON/32.174,20919668.,57.29577951/

CALL TBLU (NTHT,TH,T,TBL2,M2)

CALL TBLU (NWT,WT,T,TBL3,M3)

ALT=V(2)

CALL TBLU (18,RHI,ALT,RHO,MR)

Y(4)=0.5*Y(1)*Y(1)/EXP(RHI)

G=GO/(1.+Y(2)/RO)**3

GAMA=Y(3)/CON

YDOT(1)=GO*(TH-CDS*Y(4))/(WT+WBO)-G*SIN(GAMA)

YDOT(3)=-CON*(G*COS(GAMA))/Y(1)

YDOT(2)=Y(1)*SIN(GAMA)

RETURN

END
*DECK CHISQ

SUBROUTINE CHISQ (N,A,CR,NG,AM,AS,WA,WB,WC,LD)

C THIS SUBROUTINE TEST THE SAMPLE DISTRIBUTION FOR GOODNESS

C OF FIT TO A NORMAL, LOG-NORMAL, AND WEIBULL DISTRIBUTION FUNCTION

DIMENSION A(100),JCEL(100),Z(47),C(47)

COMMON/CZ/Z,C

DATA (Z(I),I=1,47)/
1-1000.,-5.,-4.,-3.4,-3.2,-3.0,-2.9,-2.8,-2.7,-2.6
2,-2.5,-2.3,-2.1,-2.0,-1.8,-1.6,-1.4,-1.2,-1.0,-0.8,-0.6,-0.4,-0.2,0.0,0.2,0.4,0.6,0.8,1.0,1.2,1.4,1.6,1.8,2.0,2.1,2.2,2.3,2.5,2.6,2.7,2.8,3.0,3.2,3.4,4.0,5.0,1000.0/

DATA (C(I),I=1,47)/
1 0.0,0.0000006,0.00006,0.0003,0.0007,0.0013,0.0019
2 0.0026,0.0035,0.0047,0.0062,0.0107,0.0179,0.0228,0.0359,0.0548
3 0.0808,0.1151,0.1587,0.2119,0.2743,0.3446,0.4207,0.5000,0.5793
4 0.6554,0.7257,0.7881,0.8413,0.8849,0.9192,0.9452,0.9641,0.9772
5 0.9821,0.9893,0.9938,0.9953,0.9965,0.9974,0.9981,0.9987,0.9993
6 0.9997,0.99994,0.9999994,1.0/

PN-N

NPARM=4

IF(LD.LE.0) NPARM=3

XN=NG

AB=A(10)

AT=A(N-9)

DV=(AT-AB)/(XN-2.)

DO 10 J=1,NG

10 JCEL(J)=0

JCEL(1)=10

JCEL(NG)=10

NR=N-10

C COUNT THE NUMBER OF VALUES IN EACH GROUP

DO 40 J=11,NG

X=A(J)-AB

IF(X)20,30,30

1028

1029

1030

1031

1032

1033

1034

1035
20  IC=1
GO TO 40
30  IC=X/DV+2
   IF(IC.GT.NG) IC=NG
   JCEL(IC)=JCEL(IC)+1
C   CALCULATE PROBABILITIES WITH EACH GROUP AND COMPAR WITH EX
C   SPECTED FREQUENCY AND COMPUTE CHI-SQUARED VALUE CS
C   COMPUTE LOWER CELL PROBABILITY
   XL=-1.E10
   XU=AB
   M=1
   FE=PN*PZC(XL,XU,AM,AS,WA,WB,WC,LD,M)
   FA=JCEL(1)
   CS=((FA-FE)*(FA-FE))/FE
C   COMPUTE UPPER CELL PROBABILITY
   XL=AT
   XU=1.E10
   M=46
   FE=PN*PZC(XL,XU,AM,AS,WA,WB,WC,LD,M)
   FA=JCEL(NG)
   CS=CS+((FA-FE)*(FA-FE))/FE
   NL=NG-1
   XL=AB
   M=1
   DO 50  J=2,NL
      XU=XL+DV
      FE=PN*PZC(XL,XU,AM,AS,WA,WB,WC,LD,M)
      FA=JCEL(J)
      CS=CS+((FA-FE)*(FA-FE))/FE
50  XL=XU
C   TEST CHI-SQUARED VALUE FOR LEVEL OF SIGNIFICANCE
   F=NG-NPARM
   B=2./(9.*F)
   ZT=(1.-B-(CS/F)**0.3333333333)/SQRT(B)
M=1
CALL TBLN(CR,ZT,Z,C,47,M)
RETURN
END
*DECK CYCLE
SUBROUTINE CYCLE (THEC, GR, DR, H, T1, T2, DC, A, NDOVER, FCT)

C SUBROUTINE FOR COMPUTING THE LIMIT CYCLE
C THEC-CONTROL ACCELERATION
C GR-RATE TO DISPLACEMENT GAIN RATIO
C DR-DEADBAND HALFWIDTH
C H-HYSTHERSIS
C T1-EFFECTIVE TURN ON DELAY TIME
C T2=EFFECTIVE TURN OFF DELAY TIME
C DC=DUTY CYCLE
C A=LIMIT CYCLE RATE
C NDOVER=0 FOR NO DEADBAND OVERSHOOT
C =1 FOR DEADBAND OVERSHOOT CONDITION
C IF FCT IS GREATER THAN ZERO, PULSE WIDTH IS ESTIMATED AND USED
C TO ESTIMATE EFFECTIVE CONTROL ACCELERATION

NDOVER=0
FK=1.0
D=DR/57.3
TDD=ABS(THEC)
K=0
IF (FCT .LE. 0) GO TO 10
K=1
10 A=(TDD*T2*(GR-T2/2.)+D*H)/(2.*GR-T1-T2)
ALPHA=D*(2.*GR-T1-T2-H*(GR-T1/2.))/(T2*(GR-T2/2.)*(GR-T1/2.))
IF (TDD-ALPHA .LE. 0) GO TO 20
NDOVER=1
C DUTY CYCLE APPROXIMATION FOR DEADBAND OVERSHOOT
H=H/2.
AD=2.*D*(1.0-H)/(TDD*GR)
DNOM=(T1-T2+AD)/(2.*T2-AD+((AD/2.+T2-AD)*(T1-T2+AD)/GR))
DC=1./((1.+DNOM)
GO TO 30
C COMPUTE DUTY CYCLE WITHOUT DEADBAND OVERSHOOT
20 DC=FK/(1.+TDD*(D/A+T1-GR)/A)
IF (K LE. 0) GO TO 30
PU = 2 * A/TDD
FK = 1 + FCT/PU
TDD = ABS (THEC*FK)
K = 0
GO TO 10
30 RETURN
END
*DECK HISTO

SUBROUTINE HISTO (X,N,XMAX,XMIN,DX)

C THIS SUBROUTINE Sorts AND Plots A Histogram ON THE Line PRINTER

C X=ARRAY OF SAMPLES
C N=NUMBER OF SAMPLES IN ARRAY
C XMAX=MAXIMUM VALUE
C XMIN=MINIMUM VALUE
C DX=INCREMENT FOR EACH CELL
C K=NUMBER OF SAMPLES IN EACH CELL

DIMENSION X(1),KAXIS(94)
DATA ISTAR,IBLANK/1H*,1H /

C PRINT NUMBER OF SAMPLES, MIN AND MAX VALUES
WRITE( 6,110) N,X(1),X(N)
L=1
K=0
AX1=XMIN
10 AX2=AX1+DX
DO 20 J=L,N
   IF (X(J)-AX2 .GE. 0 ) GO TO 30
   K=K+1
20 CONTINUE
30 IF (K-94 .GE. 0 ) GO TO 50
   K1=K+1
   DO 40 J=K1,94
   40 KAXIS(J)=IBLANK
   K2=K
   IF (K .LE. 0 ) GO TO 80
   GO TO 60
50 K2=94
60 DO 70 J=1,K2
    70 KAXIS(J)=ISTAR
80 WRITE( 6,100) AX1,AX2,K,(KAXIS(J),J=1,94)
   IF (AX2-XMAX .GE. 0 ) GO TO 90
   L=L+K
1116
1117
1118
1119
1120
1121
1122
1123
1124
1125
1126
1127
1128
1129
1130
1131
1132
1133
1134
1135
1136
1137
1138
1139
1140
1141
1142
1143
1144
1145
1146
1147
1148
1149
K=0
AX1-AX2
GO TO 10
90 RETURN
100 FORMAT (1X,F6.2,* TO*,F7.2,I5,* I*,94A1,*I*)
110 FORMAT (1X,*NO OF SAMPLES-*I5,* MIN=*,F6.2,* MAX=*,F7.2,/4X,*RA
1
INGE NUMBER 0 5 10 15 20 25 30 35 40 45
2 50 55 60 65 70 75 80 85 90 95*,/23X,*I....I....I....I....I....I....I....I....I....I....I
3I....I....I....I....I....I....I....I....I....I....I....I....I....I....I
4....I....I....I....I*)
END
*DECK OURF
C THIS SUBROUTINE COMPUTES A FACTOR(FAC) ON CONTROL MOTOR
C THRUST FOR SHORT PULSES OF AN OVERSPEED RESPONSE
C T = TIME FROM ZERO THRUST TO FIRST OVERSPEED PEAK
C OR= THRUST OVERSPEED RATIO FMAX/FPEAK
SUBROUTINE OURF (T,OR,FAC)
A=0.31831*ALOG(1.0/(OR-1.0))
P=ATAN(1.0/A)
W=6.2832/T
FAC=(1.570796-0.5*P-SIN(2.*P))/W
RETURN
END
*DECK PAGEHD

SUBROUTINE PAGEHD (NRUN,NPAGE,NLINE)

C THIS SUBROUTINE EJECTS AN OUTPUT PAGE AND PRINTS RUN NO.
C AND PAGE NO. AT THE TOP OF EACH NEW PAGE

WRITE ( 6,10)
WRITE ( 6,20) NRUN,NPAGE
NLINE=5
RETURN

10 FORMAT (1H1)
20 FORMAT (5X,7HRUN NO.,I5,54X,8HPAGE NO.,I5)
END
*DECK PZC

FUNCTION PZC(XL,XU,AM,AS,WA,WB,WC,LD,M)
COMMON/CZ/Z(47),C(47)

C THIS FUNCTION SUBPROGRAM COMPUTES THE PROBABILITY OF A VALUE
BETWEEN A LOWER AND UPPER LIMIT FOR A NORMAL OF WEIBULL

C DISTRIBUTION
IF(LD.GT.0) GO TO 10

NORMAL DISTRIBUTION PROBABILITY
SF=(XL-AM)/AS
CALL TBLN(P1,SF,Z,C,47,M)
SF=(XU-AM)/AS
CALL TBLN(P2,SF,Z,C,47,M)
PZC=P2-P1
RETURN

WEIBULL DISTRIBUTION PROBABILITY
10 P1=0.
IF(XL-WA) 20,20,15
15 AG=((XL-WA)/WB)**WC
P1=1.-EXP(-AG)
20 P2=0.
IF(XU-WA) 30,30,25
25 AG=((XU-WA)/WB)**WC
P2=1.
IF(AG.GT.100) GO TO 30
P2=1.-EXP(-AG)
30 PZC=P2-P1
RETURN
END
**DECK RANGE**

SUBROUTINE RANGE (X,N,XMAX,XMIN,DX,NDX,ERRTB)

C THIS SUBROUTINE DIVIDES THE RANGE OF A TABLE OF NUMBERS INTO
C N OR GREATER EQUAL PARTS WITH ESTHETICALLY PLEASING SCALES
C TEST FOR INCREASING OR DECREASING FUNCTION. IF DECREASING
C THE TABLE IS CHANGED TO AN INCREASING ARRANGEMENT
C X = INPUT ARRAY
C N = NUMBER OF VALUES IN ARRAY
C XMAX= UPPER END OF LAST CELL
C XMIN= LOWEST VALUE
DIMENSION X(I)

ERRTB=0

C TEST FOR ASCENDING OR DESCENDING ARRAY
IF (X(1)-X(N)) 40,10,20
    10 ERRTB=-1
    RETURN

C DECREASING ARRAY, CHANGE TO ASCENDING ORDER
LN=N/2
DO 30 J=1,LN
    Z=X(J)
    NF=N+1-J
    X(J)=X(NF)
    30 X(NF)=Z

C COMPUTE AESTHETICALLY PLEASING INCREMENTS OVER RANGE
40 XMIN=X(1)
    XMAX=X(N)
    DELT=XMAX-XMIN
    ZDX=NDX
    XINC=DELT/ZDX
    XLIN=ALOG10(XINC)
    LIN=XLIN
    IF (XLIN .GE. 0 ) GO TO 50
    LE=-LIN+1
    GO TO 60

1212 1213 1214 1215 1216 1217 1218 1219 1220 1221 1222 1223 1224 1225 1226 1227 1228 1229 1230 1231 1232 1233 1234 1235 1236 1237 1238 1239 1240 1241 1242 1243 1244 1245
C
50 LE=-LIN
60 MINC=XINC*(10.**LE)
    IF (MINC-5.LT.0) GO TO 70
    XINC=5./(10.**LE)
    GO TO 100
70 IF (MINC-4.LT.0) GO TO 80
    XINC=4./(10.**LE)
    GO TO 100
80 IF (MINC-2.GE.0) GO TO 90
    XINC=1./(10.**LE)
    GO TO 100
90 XINC=2./(10.**LE)
100 DX=XINC
C COMPUTE START AND FINISH XMIN AND XMAX
    R=XMIN/XINC
    KAR=ABS(R)
    KR=R
    XKAR=KAR
C TEST FOR FIRST CELL STARTING VALUE
    IF (KR.NE.0) GO TO 130
    IF (R.LT.0) GO TO 120
110 XMIN=0.
    GO TO 160
120 XMIN=-XINC
    GO TO 160
C COMPUTE NON-ZERO MINIMUM STARTING CELL LOCATION
130 IF (R) 140,110,150
140 XMIN=-(XKAR+1.)*XINC
    GO TO 160
150 XMIN=XINC*(XKAR-1.)
C END CELL LOCATION
160 XMAX=X(N)+XINC
    RETURN
END
SUBROUTINE RNDX (JK)

SUBROUTINE FOR COMPUTING THE RANDOM NORMAL DEVIATE
RANF IS CDC BUILT-IN PSUEDO-RANDOM NUMBER GENERATOR
K IS THE CURRENT RANDOM SEQUENCE INTEGER WHICH CHANGES
WITH EACH NEW RANDOM NUMBER GENERATION

COMMON K,RXD(30)
DO 30 1=1,JK
Q=RANF(K)

THE FOLLOWING CODING WILL GIVE A SUITABLE REPLACEMENT FOR RANF

KA=K*23
JJ=1.0E+7
N=KA/JJ
M=N*JJ
K=KA-M-N
AK=K
Q=1.0E-7*K
IN THE ABOVE OPTION K SHOULD BE A 7 DIGIT NUMBER

TRANSFORM 0-1 UNIFORM DISTRIBUTION TO -0.5 TO 0.5 UNIFORM
IF (Q-.5 .LE. 0 ) GO TO 10

Q=1.0-Q
AB=-1.0
GO TO 20
10 AB=1.0

TRANSFORM UNIFORM TO GAUSSIAN N(0,1)

20 XPT=-2.*ALOG(Q)
XRT=ABS(XPT)
Y=SQRT(XRT)
D=2.515517+.802853*Y+.010328*Y*Y
E=1.0+1.432788*Y+.189269*Y*Y+.001308*Y*Y*Y

COMPLETE TRANSFORMATION TO GET RANDOM NORMAL DEVIATE

30 RXD(I)=AB*(Y-(D/E))
RETURN
END
*DECK RUNGE

SUBROUTINE RUNGE (L,I)

C THIS SUBROUTINE PERFORMS THE RUNGE-KUTTA INTEGRATION IN

C COMBINATION WITH THE CALCULATION SUBROUTINE

DIMENSION RAT(4),SAV(4)
COMMON/DDY/YDOT(4),Y(4),T,DT

I=I+1
GO TO (10,20,40,60,80), I

10 L=1
RETURN

20 DO 30 J=1,3
  SAV(J)=Y(J)
  Y(J)=SAV(J)+0.5*DT*YDOT(J)
  RAT(J)=YDOT(J)
  V(J)=SAV(J)+0.5*DT*YDOT(J)
  T=T+0.5*DT
  L=1
  RETURN

30 DO 50 J=1,3
  Y(J)=SAV(J)+0.5*DT*YDOT(J)
  RAT(J)=RAT(J)+2.*YDOT(J)
  V(J)=SAV(J)+0.5*DT*YDOT(J)
  L=1
  RETURN

40 DO 50 J=1,3
  Y(J)=SAV(J)+0.5*DT*YDOT(J)
  RAT(J)=RAT(J)+2.*YDOT(J)
  V(J)=SAV(J)+0.5*DT*YDOT(J)
  L=1
  RETURN

50 DO 70 J=1,3
  Y(J)=SAV(J)+DT*YDOT(J)
  T=T+0.5*DT
  L=1
  RETURN

60 DO 70 J=1,3
  Y(J)=SAV(J)+DT*YDOT(J)
  T=T+0.5*DT
  L=1
  RETURN

70 Y(J)=SAV(J)+(DT/6.)*(RAT(J)+YDOT(J))
  L=2
  I=0
  RETURN

END
SUBROUTINE TABGEN(QO,VO,GAMO)

C THIS SUBROUTINE PROPAGATES THE TRAJECTORY PARAMETERS
C VELOCITY, DYNAMIC PRESSURE, GAMMA, AND ALTITUDE DURING
C A GRAVITY TURN BOOST. INITIAL VELOCITY AND DYNAMIC
C PRESSURE ARE USED TO DETERMINE ALTITUDE. THRUST, WEIGHT
C DRAG COEFFICIENT AND INITIAL FLIGHT PATH ANGLE (GAMMA) ARE
C USED TO SOLVE THE EQUATIONS OF MOTION USING THE RUNGE
C AND CALCUL SUBROUTINES. RETURNED TABLES ARE VIA COMMON DOUT

DIMENSION DUM(90)

COMMON/DOUT/NQT,TBL1(90),NUT,TBL5(90),NGT,TBL6(90),NHT,
1 TBL11(90),TF,NTC,TBL4(90)

COMMON/DRH/RHO(18),MRH

COMMON/DDI/TBL2(90),TBL3(90),NTHT,NUT,CD5,M2,M3,UB0

COMMON/DDY/YDOT(4),Y(4),T,DT

DATA DT,HP/0.5,41 C RHO

IS A TABLE OF Z,P,Z,P,Z,P VALUES WHERE
C Z = ALTITUDE IN FEET
C P = NATURAL LOG OF INVERSE ATMOSPHERIC DENSITY(SLUGS/FT3)
C ALOG(1/DENSITY)

DATA (RHO(J),J=1,18)/0.,6.042,100000.,10.3417,120000.,
1 11.271,140000.,12.1335,160000.,12.9239,200000.,14.3163,
2 240000.,15.8823,328000.,20.665,557700.,27.256/ 

DO 10 J=1,4

10 YDOT(J)=0.

MRH=1

M2=1

M3=1

C COMPUTE INITIAL ALTITUDE FROM VELOCITY AND DYNAMIC PRESSURE
CALL ALTI(ALTO,VO,QO)

T=0.

KP=NP

C SET INITIAL TRAJECTORY STATES

Y(1)=VO
BEGIN INTEGRATION LOOP AND FILLING OF TABLES

20 IF (KP-NP .LT. 0 ) GO TO 30

NQT=NQT+2
NTQ1=NQT-1
TBL1(NTQ1)=T
TBL5(NTQ1)=T
TBL6(NTQ1)=T
TBL11(NTQ1)=T
TBL11(NQT)=Y(2)
TBL6(NQT)=Y(3)
TBL5(NQT)=Y(1)
TBL1(NQT)=Y(4)
KP=0
30 KP=KP+1
I=0

CALL RUNGE-KUTTA INTEGRATION SUBROUTINE

40 CALL RUNGE (L,I)
   IF (L.EQ.2) GO TO 50

CALL STATE EQUATION UPDATE SUBROUTINE
CALL CALCU
GO TO 40

50 CONTINUE
   IF (T-TF .LE. 0 ) GO TO 20

END OF INTEGRATION LOOP

60 DO 70 J=2,NGT,2
   T=TBL6(J-1)

CHANGE INPUT TABLE OF THETA-GAMMA TO NEW THETA TABLE

MD=1
CALL TBLU (NTC, TH, T, TBL4, MD)
DUM(J-1)=T
60 DUM(J)=TH+TBL6(J)
   DO 70 J=1,NGT
70 TBL4(J)=DUM(J)
   NTC=NGT
RETURN
END
SUBROUTINE TBLN (Y,X,T,A,NT,M)

THIS SUBROUTINE IS A TABLE LOOKUP FROM ABSCISSA TABLE T
AND ORDINATE TABLE A. Y IS ORDINATE AT GIVEN ABSCISSA X.

NT IS LENGTH OF TABLES T AND A. MIS LOCATION OF LAST VALUE Sought

DIMENSION T(1),A(1)

10 IF (T(M)-X) 50,20,30
20 Y=A(M)
RETURN

30 IF (T(1)-X .LT. 0 ) GO TO 40
   M=1
   GO TO 20
40 M=M-1
   GO TO 10
50 MM=M+1
   IF (MM-NT .LE. 0 ) GO TO 60
   M=NT
   GO TO 20
60 IF (T(MM)-X .GT. 0 ) GO TO 70
   M=MM
   GO TO 50
70 M=MM-1
   DT=T(MM)-T(M)
   IF (DT .NE. 0 ) GO TO 80
   Y=A(M)
   RETURN
80 DY=A(MM)-A(M)
   DDT=X-T(M)
   Y=A(M)+DY*DDT/DT
RETURN
END
SUBROUTINE TBLU (NT,Y,X,T,M)
C SINGLE TABLE LOOKUP SUBROUTINE
C NT = NUMBER OF VALUES IN ARRAY
C Y = RETURNED ORDNATE
C X = ABSCISSA VALUE CALLED
C T = INPUT TABLE OF ALTERNATING ABSCISSAS AND ORDINATES
C ORDINATES MUST BE MONOTONICALLY INCREASING
C M = PREVIOUS INDEX USED IN THIS TABLE LOOKUP
C THIS INDEX GETS CHANGED TO CURRENT VALUE

DIMENSION T(1)
10 IF (T(M)-X) 50,20,30
20 Y=T(M+1)
   RETURN
30 IF (T(1)-X .LT. 0 ) GO TO 40
   M=1
   GO TO 20
40 M=M-2
   GO TO 10
50 MM=M+2
   IF (MM-NT-1 .LE. 0 ) GO TO 60
   M=NT-1
   GO TO 20
60 IF (T(MM)-X .GT. 0 ) GO TO 70
   M=MM
   GO TO 50
70 M=MM-2
   DT=T(MM)-T(M)
   IF (DT .NE. 0 ) GO TO 80
   Y=T(M+1)
   RETURN
80 DY=T(MM+1)-T(M+1)
   DDT=X-T(M)
   Y=T(M+1)+DY*DDT/DT
   RETURN
END
*DECK THEMIN

SUBROUTINE THEMIN (THEC,GR,DR,H,T1,T2,THMIN)
C
SUBROUTINE FOR COMPUTING THE MINIMUM DISTURBING ACCELERATION
C RESULTING IN ONE SIDED LIMIT CYCLE MOTION
C
THEC = CONTROL ACCELERATION
C GR = RATE TO DISPLACEMENT GAIN RATIO
C DR = DEADBAND HALFWIDTH
C H = HYSTERESIS
C T1 = EFFECTIVE TURN-ON DELAY TIME
C T2 = EFFECTIVE TURN-OFF DELAY TIME
C
THMIN = MINIMUM ACCELERATION (RETURNED)
D=DR/57.3
A=2.*GR-T1-T2
B=(GR-T1/2.)*T1
C=(GR-T2/2.)*T2
Z=GR-T1
ABC=(B-C)/A
CA=C/A
Z2=(D*H+C*THEC)/A
Z22=(D*H-C*THEC)/A
APR=B-Z*ABC-.5*(GR*GR+ABC*ABC)
BPR=2.*D-Z*Z2-ABC*CA*THEC
CPR=(.5*Z22*Z22+ABC*D*H/A)/APR
XPR=.5*BPR/APR
ZPR=ABS(XPR*XPR+CPR)
ZPR2=SQRT(ZPR)
THMIN1=ABS(XPR+ZPR2)
THMIN2=ABS(XPR-ZPR2)
IF (THMIN1-THMIN2 .GE. 0 ) GO TO 10
THMIN=THMIN1
GO TO 20
10 THMIN=THMIN2
20 RETURN
END
*DECK WBL
SUBROUTINE WBL (N,Y,NG,F)
C THIS SUBROUTINE COMPUTES THE STATISTICAL DISTRIBUTION PARAMETERS
C OF FIT TO NORMAL, LOG-NORMAL, AND WEIBULL
DIMENSION Y(1),Q(20),R(18),S(24),X(1000),F(20)
DATA (Q(I),I=1,20)/-0.95,3.46,
1-0.87,3.0,-0.64,2.3,-0.37,1.8,-0.09,1.39,0.16,1.1,0.63,0.7,0.93,
20.5,1.52,0.2,2.0,0.001/
DATA (R(I),I=1,18)/0.001,0.4,0.95,0.8,
1-1.7,1.2,-2.43,1.8,-3.48,2.4,-4.55,3.0,-5.65,3.66,-6.92,4.5,-8.5/
DATA (S(I),I=1,24)/0.2,0.932,0.4,0.902,0.6,0.888,0.8,0.886
1,1,1,0.893,1.8,0.9275,2.2,0.947,2.6,0.963,3.0,0.974,3.5,
20.984,4.5,0.994/
M=1
MR=1
MS=1
AVI=N-1
XK=1./SQRT(1.-1.96*SQRT(2./AVI))
NQ=20
NR=18
NS=24
AN=N
S1=0.
S2=0.
S3=0.
S4=0.
DO 10 J=1,N
X(J)=Y(J)
10 S1=S1+X(J)
C COMPUTE THE MEAN VALUE
XM=S1/AN
DO 20 J=1,N
DX=(X(J)-XM)
DS*DX*DX
S2=S2+DS
S3=S3+DS*DX
S4=S4+DS*DS

C COMPUTE THE VARIANCE, SKEWNESS, KURTOSIS, AND STANDARD DEVIATION

\begin{align*}
\text{VAR} &= \frac{S2}{AN} \\
\text{SKEW} &= \frac{S3}{AN} / (\text{VAR}^{1.5}) \\
\text{SKUR} &= \frac{S4}{AN} / (\text{VAR} \times \text{VAR}) \\
\text{SIG} &= \sqrt{\text{VAR}}
\end{align*}

C COMPUTE THE A, B, C PARAMETERS FOR A WEIBULL DISTRIBUTION FUNCTION

CALL TBLU (NQ, CL, SKEW, Q, MQ)
C = EXP(CL)
CALL TBLU (NR, BL, CL, R, MR)
B = SQRT(\text{VAR} / \text{EXP(BL)})
CALL TBLU (NS, A1, CL, S, MS)
A = XM - B*A1
OC = 1. / C
F(1) = XM
F(2) = SIG
F(3) = SKEW
F(4) = SKUR
F(5) = XM + XM*2.576*SIG
F(11) = A
F(12) = B
F(13) = C
F(14) = A + B*(0.694**OC)
F(15) = A + B*(4.6**OC)
F(16) = A + B*(5.3**OC)
F(17) = A + B*(6.9**OC)

C USE CHI-SQUARED GOODNESS OF FIT TEST TO ESTIMATE LEVEL OF SIGNIFICANCE (CR)
C TEST WEIBULL DISTRIBUTION
CALL CHISQ (N, X, CR, NG, XM, SIG, A, B, C, 1)
F(20) = CR
C TEST NORMAL DISTRIBUTION
CALL CHISQ (N,X,CR,NG,XM,SIG,A,B,C,0)
F(18)=CR
S1=0.
S2=0.
S3=0.
S4=0.
C COMPUTE THE LOGARITHM OF VALUES
DO 30 J=1,N
X(J)=ALOG(Y(J))
30 S1=S1+X(J)
XM=S1/AN
DO 40 J=1,N
DX=(X(J)-XM)
DS=DX*DX
S2=S2+DS
S3=S3+DS*DX
S4=S4+DS*DS
VAR=S2/AN
SIG=SQRT(VAR)
SKEW=S3/(AN*VAR**1.5)
SKUR=S4/(AN*VAR**VAR)
F(5)=XM
F(6)=SIG
F(7)=SKEW
F(8)=SKUR
F(10)=EXP(XM+XX*2.576*SIG)
C TEST LOG-NORMAL DISTRIBUTION FOR LEVEL OF SIGNIFICANCE
CALL CHISQ (N,X,CR,NG,XM,SIG,A,B,C,0)
F(19)=CR
RETURN
END
This report describes a FORTRAN coded computer program and method to predict the reaction control fuel consumption statistics for a three axis stabilized rocket vehicle upper stage. It uses a Monte Carlo approach which is made more efficient by using closed form estimates of impulse usage. It includes effects of rocket motor thrust misalignment, static unbalance, aerodynamic disturbances, and deviations in trajectory, mass properties and control system characteristics. This routine has been used for over a decade to accurately predict the control fuel consumption statistics for the Scout launch vehicle second and third-stage reaction control systems.

By selection of input data and options this routine can be applied to many types of on-off reaction controlled vehicles.

The pseudo random number generation and statistical analyses subroutines including the output histograms can easily be used for other Monte Carlo analyses problems.

A typical run of 200 samples requires 2 seconds of central processor time on a CDC CYBER 175 computer.
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