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(Supersedes IMR No. 678)

ANALYSIS OF MAN-IN-THE-LOOP CONTROL
SYSTEMS IN THE PRESENCE OF NONLINEARITIES

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June 1981

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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<td>The BRL and HEL are jointly investigating the effects of system nonlinearities on the accuracy of turret control systems with human operators in the loop. The system response at very low rates (one milliradian per second and less) is degraded because of the increased relative importance of nonlinear elements such as coulomb friction, backlash, and dead space. Good low rate response is necessary for accurate tracking of long range targets with laser designators and guided missile directors. This report describes the first phase of the BRL contribution to the joint project — (Cont’d on reverse side)</td>
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Item 20. ABSTRACT (Continuation)

This phase developed a simplified simulation of a turret control with a human transfer function. There is an adaptive algorithm to adjust the coefficients of the human transfer function to account for changes in the system characteristics. Backlash, coulomb friction, and dead space are introduced and their effects on system response and loop performance are documented.

The next phase will adjust the simulation to agree with the system response of a concurrent turret measurement program. It will compare the loop performance to a concurrent experiment with a real man-in-the-loop. It will relate loop performance (tracking accuracy) to system response at low rates.
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I. STATEMENT OF THE PROBLEM

The goal of this project is to improve the accuracy of rate control systems. The traditional direct-fire gun-type turret has an accuracy requirement on the order of 0.2 milliradians which is sufficient for ranges of from one to two kilometers. Laser designators and guided missile directors are designed for twice the range and therefore require twice the accuracy, i.e., approximately 0.1 milliradians. Even the best modern turret systems have trouble achieving this order of accuracy all the time. This effort attempts to determine which system characteristics are limiting tracking accuracy. It will then be possible to write specifications in terms of hardware characteristics rather than in terms of system performance goals.

The premise of this approach is that the solution can be found in the nonlinear behavior of the turret systems at very low rates. The tracking rates of interest and changes in rate that are called for to achieve precise tracking are very small. A 30-kilometer-per-hour target, for example, at a range of 4 kilometers and a heading of 30 degrees would result in a 1-milliradian-per-second crossing rate. The gunner will command small changes about this nominal rate in an attempt to reduce the tracking error. We can infer the magnitude of these changes to be less than 0.3 milliradians per second (referred to the output) by the following logic. Since the desired error tolerance is on the order of 0.1 milliradians the gunner should have the ability to make commands at his bandwidth (3 radians per second) which would result in amplitudes of 0.1 milliradian. Assuming a sinusoidal input of 0.3-milliradian-per-second amplitude and 3-radian-per-second frequency the output would be a sinusoid with 0.1-milliradian amplitude.

The nonlinear elements in the turret, i.e., backlash, coulomb friction, and deadspace, will have more effect on the turret response at low rates and for small commands. The gunner will notice a decrease in gain and an increase in phase lag. He will attempt to compensate for the turret changes within limits, but eventually the tracking error will increase above what it would be for a linear system. Moreover, the human's ability to compensate will vary considerably with training and between people. The result will be unpredictable system performance due to operator differences rather than hardware differences.

Traditionally the turret specifications for low rate tracking have been system performance specifications with a human operator in the loop, e.g., 0.1-milliradian root-mean-square error when tracking a 1.0-milliradian-per-second target for 10 seconds. It would probably be better to specify the accuracy requirements against sinusoidal inputs and better still to specify the system characteristics without a human operator in the loop. Enough analysis of linear control systems with human operators has been done to relate accuracy to system characteristics (gain and phase lag) and input power spectra at
least for linear control systems. This report addresses the system performance at low rates when the nonlinear system characteristics are important. Ultimately this work should lead to specifications of system characteristics which are required to achieve any specified degree of accuracy.

II. APPROACH

The overall solution to the problem requires three distinct tasks to be carried out by three different organizations.

a. First, there is the characterization of a typical turret control system at very low rates. An M60A3 turret control is being used because it is available now and in the future and it is typical of current military turret control systems. Frequency response and transient response will be measured at various amplitudes from low rates near or below threshold up to high rates in the linear region. This work is being done under contract by General Electric, Pittsfield, Massachusetts.

b. Second, there are experiments with humans in the loop and with computer simulated turret response. These tests will characterize the human operator and they will allow for some limited parameter variations of turret response. Human Engineering Laboratory is doing this work.

c. Third, there is an analysis task with both the turret response and the human operator simulated by a computer. This task allows for parametric variations of turret response just as with the human experiments; but the computer allows for almost unlimited parameter variations because the trials are faster and they are without random human variation. This report describes the Phase I effort on the third task.

The Phase I effort develops the methods and computer codes based on assumed system characteristics. The Phase II effort will do it all again but with accurate system data from the other tasks.

The main task of Phase I was to develop a self-optimizing human operator model. The model must minimize root mean square (rms) tracking error, subject to constraints on human behavior, in a consistent and rational manner. This model was then used to determine the effects of various kinds of nonlinearities on system performance.
III. PROCEDURE FOR MAN-MODEL OPTIMIZATION

The Phase I effort had a goal of developing techniques for evaluating nonlinearities. This included the man model, the adaptive algorithm for the man model, models of nonlinearities and some limited data to show how well the models work. Complicated turret dynamics were not important at this stage; consequently a very simplified model of turret response was incorporated. Figure 1 shows a block diagram of the control loop and the linear models that were used for the man and turret. The reference signal was either white noise, a sinusoid, or a maneuvering tank. The human model was a conventional linear model from Sheridan\(^1\) to which a noise remnant was added for reasons that will be explained later. The turret response was given a time constant of 0.1 seconds and a gain of 0.01 radians per second per radian. These parameters are about right for a tank turret at very low rates. Nonlinearities were introduced in the digital simulation at the points shown in Figure 1.

The notation in Figure 1 was chosen to be consistent with the digital simulation shown in its entirety in the Appendix. The linear transfer functions were simulated by the step invariant zeta transform\(^2\) method.

\[
Y_H = e^{-7S} \cdot \frac{1}{1 + 6S}
\]

![Block Diagram of Control Loop](image)

Figure 1. Block Diagram of Control Loop.

\(^1\)Man-Machine Systems, Sheridan and Ferrell, 1974, MIT Press.

\(^2\)Digital Signal Analysis, Stearns, 1975, Hayden Book Company Inc.
An algorithm for optimizing the human transfer function was developed while using white noise for a reference signal. It minimized rms tracking error but with a penalty for open loop gain margin less than 6 db and open loop phase margin less than 45 degrees. Secant functions accomplished the penalty by giving a cost factor of one at 6 db and 45 degrees and a cost factor of infinity at 0 db and 0 degrees.

\[
\text{secant } [15 \text{ (Gain Margin } -6\text{)}, \text{ secant } [2 \text{ (Phase Margin } -45\text{)]}
\]

The loop was warmed up for a few seconds, run for 52 seconds at a time step of 0.01 seconds, and sampled every .05 seconds till 1024 samples of input to the man and output from the plant were stored. A fast fourier transform was taken of the input and output. The open loop gain and phase were calculated from zero to ten radians per second at intervals of one radian per second by adding the complex numbers in every eight cells and then dividing the absolute values to get gain and subtracting the angles to get phase. The computer program plots the resulting gain and phase and it calculates the cost. It selects new values for the human transfer function and then repeats the simulation and cost calculations until a minimum is established.

The human transfer function optimization algorithm worked fine with a white noise input. There was enough power at every frequency of interest to make good calculations of gain and phase. The gain calculation becomes noisy when the input (the denominator) gets near zero. The phase calculation gets noisy when either the input or output power gets too small to make an accurate phase measurement. The algorithm requires smooth monotonically-decreasing gain and phase for at least one frequency band beyond 180 degree phase lag. Such data were obtained with a white noise input with and without nonlinearities in the loop. Unfortunately real targets do not present a white noise tracking spectrum.

A realistic target motion was constructed from the following considerations:

a. The algorithm wants as much power as possible and so does the maneuvering target; therefore a course made of segments of 0.2g turns was used.

b. The target wants to move forward rather than go in a circle; therefore the turns were limited to plus and minus 45 degrees from the line of sight between the target and tracker.
c. The algorithm wants power in each one-radian-per-second frequency band, therefore the turning radius and speed were selected to produce a fundamental frequency at 0.5 radian per second so that the harmonics would fall at 1.5, 2.5, 3.5, ..., radians per second. The relationships for radial acceleration were used.

$$\text{radial acceleration} = rw^2 = \frac{v^2}{r} = 0.2g$$
$r = \text{radius} = 8 \text{ meters}$
$w = \text{angular rate} = 0.5 \text{ radians per second}$
$g = \text{acceleration of gravity} = 10 \text{ meters per second squared}$

d. The range to target was set at four kilometers to reduce the angular tracking rates to the low rates of interest.

Maximum rate $= 4 \text{ m/s} \cdot \frac{\sin 45}{4 \text{ km}} = 0.7 \text{ mrad/s}$

These considerations resulted in a course which was roughly sinusoidal at 0.5 radians per second. The abrupt changes in radial acceleration every 90 degrees of turn gave strong enough harmonics to allow the algorithm to calculate gain and phase when there were no nonlinearities in the loop, although it did require double precision in the calculations. When nonlinearities were introduced the gain and phase curves became noisy and the optimization algorithm would not work.

Additional power was required at both the input and output at frequencies of interest (1.5 through 8.5) to make the optimization algorithm work properly. Fortunately the addition of noise power is justified as the so-called remnant term of the human transfer function ($Y_H$). Although it can be added either before or after the linear portion of $Y_H$, here it is added before $Y_H$ to enhance the optimization algorithm operation, but after the rms calculation to avoid improperly affecting it. The appropriate amount of noise was calculated by the following steps:

a. Sheridan page 241 shows the noise power to be 20 percent of the total power at the output of the man. Page 242 shows it to be uniform with frequency.

b. The $Y_H$ can be approximated by a pure gain for power calculations, because the transportation delay does not affect power and the lead-lag terms are very small.

c. Sample trials have shown the rms error to be approximately 0.3 milliradians.

d. There are approximately eight bands of interest.
Therefore power from a sinusoid with an rms amplitude of 0.05 milliradians should be introduced at each frequency band.

\[ 0.3 \sqrt{0.2/8} = 0.05 \]

This additional power helped but sooner or later as the magnitude of the nonlinearities was increased the algorithm would become too noisy. There are still a couple of tricks to try, i.e., longer running time and extrapolation of the phase curve to 180 degrees lag rather than interpolation as was done here. These will be tried in the Phase II effort. The current effort was finished by using the simple expedient of minimizing rms error and forgetting about the phase and gain calculations. This procedure raised the gain until the system went unstable. It is a consistent method but it is probably not typical of human operation.

IV. EFFECTS OF NONLINEARITIES ON THE TURRET RESPONSE

Three nonlinearities were added one at a time. Deadspace was added at G3 on Figure 1. It corresponds to the deadspace in a gunner's control for the first couple of degrees of rotation. Coulomb friction was added at G4. It corresponds to the friction on the turret itself. Backlash was applied to the output at H and it can also be applied to the input at G3.

Figure 2 through Figure 6 show the effects of these nonlinearities on the gain and phase characteristics of the turret, i.e., from G3 to H. Figure 2 shows the turret with no nonlinearities for a comparison. The turret parameters were \( B = 10, \ KB = 1.0, \) and \( J = 1.0 \). These curves were generated by using a single sinusoid by itself at each frequency. The family of curves in Figure 3 through Figure 6 represents successive doubling.

![Figure 2. Turret Response Without Nonlinearities.](image-url)
of the ratio of the nonlinearity to the input. It was done by changing the input rather than the turret. This procedure is equivalent to the way the test data would be collected on a turret. The input amplitudes were 0.125, 0.25, 0.5, 1, 2, 4 and 8 milliradians.

The phase lag shown in Figure 2 points out a limitation of this methodology. A quick calculation would predict a lag of 135 degrees at 10 radians per second. The figure shows a lag of 150 degrees. The difference of 15 degrees must be due to the analysis technique which uses the Zeta transform and the Fast Fourier Transform. The time step used with the simulation can account for 6 degrees of error (0.01 seconds x 10 radians per second x 60 degrees per radian). The rest is either due to the FFT or it is unknown.

![Figure 3. Turret Response with Coulomb Friction.](image)

Figure 3 shows the effect of coulomb friction applied to G4. The magnitude was 0.1 pound-foot applied to a turret of one slug-foot-squared polar moment. The ratio is about right since a tank has a 22,000 slug-feet-squared polar moment and about 2000 pound-feet of coulomb friction referred to the turret. The gain decreased as the input was decreased but the phase lag decreased as well.
Figure 4 shows the effect of deadspace applied at G3. The magnitude of the deadspace was 0.1 milliradians. A typical turret might have 0.04 radians deadspace at the turret control handle. The turret gain during these turret response runs was 0.1 compared to a typical turret gain of 0.02 radians per second per radian. Obviously the problem will require new coefficients for a quantitative analysis but these figures show the trends.
Figure 5 shows the effect of backlash applied at the turret control. The magnitude of the backlash was 0.04 milliradians. Once again, the level chosen was not necessarily representative of real turrets, however it does show the relative effects of backlash on gain and phase. Backlash at the control handle will cause a phase lag without changing the gain substantially.
Figure 6 shows the effect of 0.001 milliradian of backlash on the output. Here the backlash can be seen to have a greater effect at higher frequencies as compared to backlash on the input. The reduction in amplitude with increased frequency at the output causes this effect.

The objective of presenting these figures is to indicate that it will be possible to shape the gain-phase characteristics of the turret model. This will be done when the test data from the tank turret become available.
V. EFFECTS OF NONLINEARITIES ON LOOP RESPONSE

The intent at this point was to calculate the rms error for the closed-loop system when tracking the target course developed earlier. The gain-phase plots for the open-loop response of the man and turret were also of interest, but as explained earlier the gain-phase plots were usable only for the condition with low levels of nonlinearities. Figure 7 shows these plots for a condition with no nonlinearities. This condition had a phase margin of 41 degrees, a gain margin of 4.8 db and an rms error of 0.31 milliradians. The cross-over frequency (0 db gain) was 3.0 radians per second.

![Gain-Phase Plot Without Nonlinearities](image)

Figure 7. Gain-Phase Plot Without Nonlinearities.

When the nonlinearities were added the loop was optimized for minimum rms error. The rms error for no nonlinearities dropped to 0.26 milliradians but the loop was not nearly as stable. The phase margin was only 13 degrees and the gain margin was 1.4 db. The growth in rms error with increased levels of nonlinearities is shown in Figures 8, 9, and 10. The deadspace in Figure 8 is at the control handle. The turret gain was changed to 0.01 (BK = 0.10, B = 100) for these runs. The coulomb friction in Figure 9 was applied to C4. The backlash in Figure 10 was applied to the control handle.
Figure 8. Tracking Error with Dead Space at the Control Handle.

Figure 9. Tracking Error with Coulomb Friction at the Turret Output.
Figure 10. Tracking Error with Backlash at the Control Handle.

The only conclusion that can be reached at this time regarding Figures 8, 9, and 10 is that the level of nonlinearities that were used did have an influence on tracking error. It remains to be seen if these are the appropriate levels. The turret measurement tests will determine the appropriate levels to use. It also remains to be proven that the man-model used here is appropriate for this task. The human tracking tests will determine that.

VI. SUMMARY

A control loop with a man-model and with provision for nonlinearities was developed. An optimization algorithm for the adaptive man-model worked well for low levels of nonlinearities, but it had to be simplified to work for high levels of nonlinearities. Nonlinearities were shown to influence tracking error.

The next phase of this effort will have the benefit of quantitative descriptions of the turret response. The turret will be simulated in more detail and the correct parameter values will be used for nominal conditions. Another attempt will be made to improve the adaptive man-model to work with the appropriate nonlinearities.
PROGRAM CTRL

THIS PROGRAM SIMULATES A TANK GUNNER TRACKING A TARGET.
ON DEMAND IT WILL ADJUST THE PARAMETERS OF THE MAN
TO GIVE THE LOWEST COST OR ERROR.
IT WILL ALSO PRODUCE BODE PLOTS ON PRINTER AND IN A
FILE FOR USE BY A PLOTTER.

THE PROGRAM IS INTERACTIVE, AND PROMPTS ALL INPUTS.
A CARRIAGE RETURN IS SUFFICIENT FOR AN ANSWER OF
ZERO OR NO.

TWO PROMPTS REQUIRE MULTIPLE INPUTS
ON ONE LINE, SEPERATED BY COMMAS.

FIRST SET:
TRAILING ZERO VALUES MAY BE IGNORED.
COMMAS ARE SUFFICIENT FOR NONTRAILING ZERO FIELDS.
TAU TRANSPORT DELAY IN SECONDS
B VISCOUS FRICTION
BK PLANT GAIN
BKLSH BACKLASH AT OUTPUT IN RADIANS
CF COULOMB FRICTION
DEDSPC DEADSPACE AT INPUT IN RADIANS

SECOND SET:
TI INTEGRATION TIME IN SECONDS
K GAIN OF MAN
TL LEAD TIME IN SECONDS

INSTEAD OF THE SECOND SET, DEFAULTS OF
TI = .01, K = 2.5 * B, AND TI = TI + 1/B
MAY BE CALLED BY A CARRIAGE RETURN.

THE PLANT IS NORMALIZED TO A MASS OF 1.

SUBROUTINES IN THE PACKAGE:

THE MAIN PART OF THE PROGRAM DOES ALL THE INTERACTIVE
CONVERSATION AND CALLS PLANTO, AUTO, FUN, AND MACHINE.

SUBROUTINE AUTO
SETS UP THE AUTOMATIC OPTIMIZATION
CALLS FUN AND FNMIN.
THE PARAMETER ACCURACY IN AUTO TELLS FNMIN
THE PRECISION DESIRED.
THE AUTOMATIC MINIMIZATION ALSO TERMINATES IF TI
BECOMES LESS THAN .005

SUBROUTINE FNMIN
DOES THE AUTOMATIC OPTIMIZATION
CALLS FUN
IF AUTOMATIC MINIMIZATION IS CHOSEN
FNMIN SYSTEMATICALLY VARIES
X( 1 ) = 1 / TI, X( 2 ) = K, AND X( 3 ) = TL
TO MINIMIZE THE COST RETURNED BY FUNCTION FUN.
X(1) IS INVERTED TO AVOID NEGATIVE VALUES.

FUNCTION FUN
MODELS THE CONTROL LOOP
COMPUTES THE COST OF TRACKING
CALLS MAN0, PLANT1, STATS0, MAN1, TCTS, STATS1, PLANT2,
STATS2, STATSW, AND FFT.

THE PARAMETER NN IS USED AS A FLAG IN FUN:
NN > 0, AUTOMATIC REDUCTION, NO BODE PLOT.
NN = 0, BODE PLOT OF MAN-MACHINE SYSTEM
USING THE MODEL TARGET AS INPUT.
NN = -1, BODE PLOT OF MACHINE WITH MODEL TARGET
AS INPUT TO MAN.
NOTE THAT IN THIS CASE THE TARGET IS FILTERED THRU
THE MAN AND THE PLOT IS THEREFORE AN IMPLICIT FUNCTION
OF THE MAN.
NN < -1, BODE PLOT OF MACHINE WITH SINE WAVE INPUT.

SUBROUTINE MACHINE
MAKE BODE PLOTS OF THE MACHINE
CALLS FUN AND PLOT.

SUBROUTINE PLOT
PRODUCES A PRETTY BODE PLOT IN A FILE READY FOR PLOTTING
PLOT ASSUMES THE PLOTTING PACKAGE
TIC (TERMINAL INDEPENDENT GRAPHICS) WHICH WAS
WRITTEN IN C AND REQUIRES A C COMPILER.

SUBROUTINE FFT
FAST FOURIER TRANSFORM

THE MAN:

SUBROUTINE MAN0
INITIALIZES THE MAN
CALLS TCTA0

SUBROUTINE MAN1
THE MAN'S PART OF THE CONTROL LOOP
CALLS TCTA1

THE PLANT:

SUBROUTINE PLANT0
INITIALIZES THE PLANT

SUBROUTINE PLANT1
RESets PLANT AT START OF EACH RUN

SUBROUTINE PLANT2
THE MACHINERY'S PART OF THE CONTROL LOOP

THE STATS:
SUBROUTINE STATS0
INITIALIZES STATISTICS PACKAGE

SUBROUTINE STATS1
COLLECTS THE DATA

SUBROUTINE STATS2
FINDS RMS ERROR, MEAN INPUT OFFSET, ETC

SUBROUTINE STATSW
WRITES THE STATS

THE TARGET:

SUBROUTINE TCTA0
SETS UP TARGET

SUBROUTINE TCTA1
RUNS TARGET

SUBROUTINE TCTS
SINE WAVES FOR BODE PLOTS

THE PROGRAM WAS WRITTEN TO BE RUN ON A PDP 11/70
USING THE CULC F4P COMPILER AND THE UNIX OPERATING
SYSTEM.
THE PROGRAM IS IMPLICIT DOUBLE PRECISION,
AND USES COMPLEX ARITHMETIC.
GENERIC NAMES HAVE BEEN USED FOR FUNCTIONS, IE ABS,
AND THE F4P COMPILER SELECTS THE PROPER FUNCTION,
IE ABS, CABS, DABS, ETC.

common b, delta, deltat,
+ Jmax, Jmaxt, Jmod, k, nc, nt, pi, tmax, unlin
common /x/ x(10)
external fun
real * 8 JJ, kk
write ( 6, 5 )
format ( 'NOW TYPE VALUES FOR TAU, B, BK, BACKLASH, ' /
+ ' COULOMB FRICTION, AND DEAD SPACE ' )
accept 10, tau, b, bk, bklsh, cf, dedspc
5 format ( 7f10.0 )
unlin = abs( bklsh ) + abs( cf ) + abs( dedspc )
k = 10
Jmod = 5
Jmax = 2 ** k
Jmaxt = Jmax * Jmod
tstep = 2.
pi = 3.1415926535
nc = 8
nn = 0
fno = no
tmax = fno * 2. * pi
delta = tmax / float( jmax )
deltat = tmax / float( jmaxt )
write ( 6, 15 ) tau, delta, b, bk, bklsh, of, dedsp, jmax
nt = tau / deltat + 5
call plant0( b, bk, bklsh, bklsh, of, dedsp, deltat )
write ( 6, 20 )
20 format ( ' DO YOU WANT TO LOOK AT THE MACHINERY? ' + ' TO ANSWER, TYPE 1 FOR YES, 0 FOR NO. ' )
accept 30, m
write ( 6, 25 )
25 format ( / ' DO YOU WANT AUTOMATIC REDUCTION? ' + ' TYPE 1 FOR YES, OR 0 FOR NO ' )
accept 30, n
30 format ( 110 )
35 write ( 6, 40 )
40 format ( / ' NOW TYPE VALUES FOR TI, K, AND TL ' )
accept 10, ti, kk, tl
if ( ti .gt. 0. ) go to 45
   ti = .01
   kk = 2.5 * b
   tl = ti + 1. / b
45 x( 1 ) = 1. / ti
   x( 2 ) = kk
   x( 3 ) = tl
if ( n .gt. 0 ) call auto
   cost = fun( x, nn )
if ( m .eq. 1 ) call machine
if ( n .le. 0 ) go to 35
stop
end

subroutine auto

implicit double precision ( a-h, o-z )
common b, delta, deltat,
+ jmax, jmaxt, jmod, kj, nc, nt, pi, tmax, unlin
dimension eps( 10 )
common / x / x( 10 )
real * 8 kk
external fun

k = 1
nn = 0
cost = fun( x, nn )
   ti = 1. / x( 1 )
   kk = x( 2 )
   tl = x( 3 )
write ( 6, 15 ) cost, ti, kk, tl
15 format ( / ' THE INITIAL COST WAS ', 3pf6.3 / )
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+ ' FOR TI = ', 0pf7.4, ' KK = ', f5.1, ', TL = ', f7.4 //
+ ' TI  KK  TL  RMS  PHASMR  GAINMR  COST  SLOPE' //

acrcy = .05
e = 5.
n = 3
do 5 i = 1, n
      eps( i ) = acrcy * x( i )
call fnmin( n, x, cost, fun, e, eps, k )
ti = 1. / x( 1 )
kk = x( 2 )
tl = x( 3 )
write ( 6, 10 ) cost, ti, kk, tl
5      format ( 6, 10 ) cost, ti, kk, tl
+ ' FOR TI = ', 0pf7.4, ', KK = ', f5.1, ', TL = ', f7.4 
return
end

function fun( x, nn )
implicit double precision ( a-h, o-z )
common b, delta, deltat,
+ jmax, jmaxt, jmod, k, nc, nt, pi, tmax, unlin
common / gp / gann( 10, 7 ), phas( 10, 7 )
dimension gain( 81 ), phase( 81 )
dimension gl( 100 ), flin( 1024 ), frout( 1024 )
+ flout( 1024 )
dimension x( 10 )
complex cin, cout, crin, crou, scin, scrou, cxx, cyy
real*4 flini, flouti, frini, frouti
data costmn / 1. /

      if ( x( 1 ) .le. 0. .or. x( 2 ) .le. 0. .or. x( 3 ) .le. 0. )
      + cost = 1.e+2
      if ( x( 1 ) .le. 0. .or. x( 2 ) .le. 0. .or. x( 3 ) .le. 0. )
      + go to 900
      call man( deltat, nt, x )
call plan( h )
points = jmax
      if ( nn .eq. 0 ) write ( 6, 55 )
      format ( / 27x, 'SEC REF IN OUT +1', 4( 9x, 1h+ ) )
55
      if ( nn .eq. -1 ) write ( 6, 56 )
      format ( 27x, 'SEC REF IN OUT +1', 4( 9x, 1h+ ) )
56
      call statsO( delta, jmax )
jem = 2
jmx = jmaxt
jec = jem
      if ( nn .ge. -1 ) jci = 1
      if ( nn .ge. 0 ) jci = 0
      NOW MODEL THE CONTROL LOOP
do 101 jct = jctl, jcm
   Jm = 0
   if ( jct .eq. jcm ) jmx = jmax
   do 100 J = 1, Jmx
      if ( nn .ge. -1 ) call manl( h, J, nt, diffdt, diff, g3 )
      if ( nn .lt. 1 ) call tgts( J, g3 )
      if ( jct .lt. jcm ) go to 90
      if( mod( J, jmod ) .ne. 0 ) go to 90
      Jm = Jm + 1
      if ( nn .ge. 0 ) frin( Jm ) = diffdt
      if ( nn .lt. 0 ) frin( Jm ) = g3
      frout( Jm ) = h
      fin( Jm ) = 0.
      frout( Jm ) = 0.
      if ( nn .ge. -1 )
         + call stats1( diffdt, frin( Jm ), frout( Jm ), Jm )
   90         call plant2( g3, h )
   100        continue
101        continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
      + call stats2( avein, aveout, rms )
      do 120 J = 1, Jmax
         tJ = J
         frin( J ) = frin( J ) - avein
         frout( J ) = frout( J ) - aveout
      120     continue
frini = frin(1)
fiini = fin(1)
cin = complex( frini, fiini )
frouti = frount(1)
flouti = fout(1)
cout = complex( frouti, flouti )
crin = cin * conjg( cin )
crout = cout * conjg( cin )
if ( abs( crin ).le. 1.e-10 + .or. nn .lt. -1 .or. nn .gt. 0 + .or. i .gt. 80 ) go to 391
exx = crout / crin
cyy = abs( exx )
gan = 20. * log10( real( cyy ) )
faz = aTan2( imag( crout ), real( crout ) )
faz = 180. * faz / pi
enl = real( enl )
eni = sqrt( oei )
cyy = abs( cout )
enn = real( cyy )
if ( abs( eno ) .gt. 1.e-10 ) write ( 6, 390 )
+ 1, frin(1), fin(1), frount(1), fout(1),
+ gan, faz, enl, oni
390 format ( 15, 4f8.4, 2f8.2, 2fM.4 )
391 continue
serin = serin + crin
scrout = scrout + crout
400 continue
if ( scrout .eq. 0. ) write ( 6, 450 )
if ( abs( scrout ) .gt. 1.e+10 ) write ( 6, 451 )
+ 1./x(1), x(2), x(3)
451 format ( /f7.4, f7.2, f7.4, ' UNSTABLE ' / )
450 format ( / ' INPUT TOO SMALL ' / )
if ( scrout .eq. 0. .or. abs( scrout ) .gt. 1.e+10 )
+ cost = 1.e+1
if ( scrout .eq. 0. .or. abs( scrout ) .gt. 1.e+10 )
+ go to 900
exx = 0.
if ( abs( serin ) .gt. 1.e-30 ) exx = scrout / serin
cyy = abs( exx )
ynl( lrad ) = real( cyy )
phase( lrad ) = aTan2( imag( scrout ), real( scrout ) )
if ( phase( lrad ) .gt. 0. )
+ phase( lrad ) = phase( lrad ) - 2. * pi
500 continue
if ( nn .gt. 0 .or. nn .lt. -nc ) go to 540
if ( nn .eq. 0 ) idbmn = -10
if ( nn .eq. -1 ) idbmn = -60
if ( nn .lt. -1 ) idbmn = -70
idbmn = idbmn + 30
write ( 6, 510 ) ( idb, idb = idbmn, idbmx, 10)
510 format ( / 20x, 'PHASE SHIFT', 20x, 7hDB GAIN /
+ ' FREQ PH GAIN -180', 15x, '-90',
+ ' 14, 3( 7x, 13 )')
write ( 6, 530 )
530 format ( lx, lh+ , 4( 8x, lh+ ), 3x, lh+, 3( 9x, lh+ ) )
540 xx = 180. / pi
radf = 2. * pi * float( nav ) / tmax
npm = 52
if ( nn .lt. 0 ) npm = nqm - idbmn - 10
11 = 1
im = 40
if ( nn .lt. -1 ) 11 = 1 - nn
if ( nn .lt. -1 ) im = 1 - nn
do 600 1 = 11, im
+ go to 590
phasmr = 180. + xx * ( phase( 1 ) -
+ ( phase( 1 ) - phase( i+1 ) )
+ * ( gain( 1 ) - 1. )
+ / ( gain( 1 ) - gain( i+1 ) )
if ( n.eq. 1 )
+ slope = 20. * log10( gain( 1 ) / gain( i+1 ) )
+ / log10( 1. / 3. )
if ( 1 .gt. 1 )
+ slope = 20. * log10( gain( 1-1 ) / gain( 1+2 ) )
+ /
+ ( log10( ( float( 1-1 ) - .5 )
+ / ( float( i+1 ) + .5 )
+ 590 n = 450
np = n / 5
gnm = 20. * log10( gain( 1 ) )
m = gnm
rf = radf * ( float( 1 ) - .5 )
if ( nn .lt. -1 ) rf = rf - .5 / float( no )
rf = rf + .001
if ( nn .eq. -no ) 11i = 11i + 1
if ( nn .ge. -1 .or. nrf .lt. 1 .or. np .lt. 1 ) go to 595
if ( nn .lt. -1 ) gaan( nrf, 11i ) = gnm
if ( nn .lt. -1 ) phasmat( nrf, 11i ) = phase( 1 ) * xx
595 continue
+ if ( nn .le. 0 .and. np .gt. -55 .and. m .gt. 2-npm )
+ write ( 6, 610 ) rf, a, gnm
if ( nn .le. 0 .and. ( np .le. -55 .or. m .le. 2-npm )
+ .and. gnm .gt. -100, )
+ write ( 6, 611 ) rf, a, gnm
if ( phase( 1 ) .gt. -pi .and. phase( i+1 ) .lt. -pi )
+ gainmat = - 20. * log10( gain( 1 )
+ - ( gain( 1 ) - gain( i+1 ) )
+ * ( phase( 1 ) + pi )
+ ( phase( 1 ) - phase( i+1 ) )
+ if ( nn .lt. -1 ) go to 600
if ( phase( 1 ) .lt. -pi .and. gain( 1 ) .lt. 1. ) go to 700
600 continue
610 format ( lx, f5.2, 15, f5.1, t<np+56>, 1h*, t<m+np>, 1h+ )
611 format ( lx, f5.2, 15, f5.1 )
620 format ( lx, f10.1, 11, f10.3 )
+ if ( nn .ge. -1 ) write ( 6, 630 )
630 format ( " FELL THRU 600 LOOP'")
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```
700   cost = rms
        go to 701
        if ( phasmr .ne. 0. )
+       cost = rms / sin( phasmr * pi / 90. )
        if ( gainmr .lt. 6. .and. gainmr .gt. 0. )
+       cost = cost / sin( gainmr / 6. * pi / 2. )
701  continue
        if ( nn .eq. 0 )
+       write ( 6, 750 ) phasmr, gainmr, cost, slope
750  format ( / ' THE PHASE MARGIN IS ', f5.0, ' DEGREES ',
+          ' THE GAIN MARGIN IS ', f6.1, ' DB ' ,
+          ' THE COST IS ', 3pf12.3 ,
+          ' THE SLOPE IS ', 3pf6.1 , ' DB PER DECADE. ' )
        ti = 1. / x( 1 )
        if ( nn .gt. 0 .and. cost .lt. 1. ) write ( 6, 800 )
+       ti, x( 2 ), x( 3 ), rms, phasmr, gainmr, cost, slope
800  format ( 17.4, 17.2, 17.4, 3pf7.3, 3pf7.3, 3pf7.3, 3pf7.2 )
        if ( ti .lt. .005 .and. cost .lt. costmn ) cost = - cost
        costmn = min( cost, costmn )
        fun = cost
    continue
900  return
end
```

```
subroutine machine
    implicit double precision ( a-h, o-z )
    common b, delt, deltat,
+   Jmax, Jmaxt, Jmod, kj, nc, nt, pi, tmax, ur.lin
    common / gp / gann( 10, 7 ), phasm( 10, 7 )
    common / mark / mark( 8 )
    common / tgts / a, w
    common / x / x( 10 )
    byte or
    data mark / '+', '*', 'x', 'o', 'n', '*', '.', 'n' /
    or = '015
    write ( 6, 5 )
5  format ( / ' HOW LOOK AT MACHINE ONLY ' )
    n = -1
    cost = fun( x, n )
    write ( 6, 10 )
10  format ( / ' BODE PLOTS FOR SINUSOIDAL DRIVING FUNCTIONS ' )
    do 200 k = 1, 7
        a = .1 / 2 ** ( k-1 )
        write ( 6, 20 ) a
20  format ( / 'x, 3pf6.2, ' MILLIRADIANS PER SECOND AMPLITUDE. ' )
    km = k
    do 100 l = 1, 10
        w = deltat * float( i )
        n = - nc * 1
        cost = fun( x, n )
        if ( cost .gt. 1. ) go to 300
700  continue
```

31
if ( unlin .eq. 0 ) go to 300

continue

write ( 6, 320 )

format ( ' // CONSOLIDATED PLOT ' /
+ ' 20x, ' PHASE SHIFT ', 20x, ' DB GAIN ' /
+ '/ FREQ -225 -180 -135 -90 ' /
+ ' -70 -60 -50 -40 ' /
+ ' 10x, 1h+, 3( 6x, 1h+ ), 3x, 1h+, 3(9x, 1h+ ) ' )
do 400 i = 1, 10

write ( 6, 330 ) i

format ( 15, 1 )

itpm = uwrite ( 1, or, 1 )
do 350 k = 1, km

m = gaan( 1, k )
np = phasa( 1, k ) / 5.
if ( m .gt. -100 .and. np .ge. -54 + .and. m .lt. 0 .and. np .lt. 0 ) + write ( 6, 340 ) mark( k ), mark( k )

format ( t<np+56>, al, t<m+12>, al, $ )

itpm = uwrite( 1, or 1 )
do 350 continue
write ( 6, 360 )

format ( 1x )
do 400 continue

call plot( km )
return

end

subroutine plot( n )
imPLICIT double precision ( a-h, o-z )
common / gp / gaan( 10, 7 )
common / mark / mark( 8 )
dimension lxP( 10 ), lyp( 10 ), lyG( 10 )
byte dev( 4 ), file( 10 )
external ffaxis, ffline, ffnworigin, ffoutput
data dev / 'v', 't', 'c', 0 /
data file / 'd', 'n', 't', 'n', 'p', 'l', 'o', 't', + ' 2 * 0 /
call callc( ffoutput, file, 0 )
call callc( ffnworigin, 1000, 1000 )
call callc( ffaxis, ' FREQUENCY IN RADIANS PER SECOND ' , + 0, 0, 6000, 0.0, 0.0, 1.0 ), 600 )
call callc( ffaxis, ' PHASE IN RADIANS == GAIN IN DB ' , + 0, 0, -6000, 90.0, 0.0, -200.0, 20.0, 600 )
jmx = 10
do 100 j = 1, n
do 90 j = 1, 10
lyg( j ) = gaan( j, 1 ) * 30. + 6000.
lyp( j ) = phasa( j, 1 ) * 30. + 6000.
lxp( j ) = j * 600

90 continue
SUBROUTINE TGTA0

IMPLICIT DOUBLE PRECISION (A-H, O-Z)
COMMON B, DELTA, DELTAT,
+ JMAX, JMAXT, JMOD, K, NO, NT, PI, TMAX, UNLIN
COMMON / TGT0 / DT, H, HTL, HLM, OOD, POS, VDT

DIST0 = 4000.
DT = DELTAT
HLM = PI / 5.
POS = 0.
H = HLM
VEL = 10.
HDT = VEL / 50.
HLM = HDT * DELTAT
OOD = 1. / DIST0
VDT = VEL * DELTAT
RETURN

END

SUBROUTINE TGTAL(J, DITHER, G)

IMPLICIT DOUBLE PRECISION (A-H, O-Z)
COMMON / TGT0 / DT, H, HDT, HLM, OOD, POS, VDT

IF ( ABS(H) .GE. HLM .AND. H * HDT .GT. 0. )
+ HDT = -HDT
H = H + HDT
POS = POS + SIN(H) * VDT
DTF = DT * FLOAT(J)
ANGLE = OOD * POS
DITHER = OOD * (.1 * SIN(1.5 * DTF)
+ + .1 * SIN(1. + 2.5 * DTF)
+ + .1 * (SIN(2. + 3.5 * DTF)
+ + SIN(3. + 4.5 * DTF) + SIN(4. + 5.5 * DTF)
+ + SIN(5. + 6.5 * DTF) + SIN(6. + 7.5 * DTF)))
G = ANGLE
RETURN

END

SUBROUTINE TGTS(J, G)

IMPLICIT DOUBLE PRECISION (A-H, O-Z)
COMMON / TGT0 / A, W
g = a * sin( w * float( j ) )
return
end

subroutine fnmin(a,x,fx,fun,e,eps,k)
implicit double precision ( a-h, o-z )
dimension x(10),eps(10),e(10),q(10),h(10,10),xi(10) ,xo(I0)
real*8 mJ,lmda,11,12,13, 1min,
mjfcet = 2,
reduced from 20. in BRL version to tame subroutine
m=n
do 1 i=1,m
se(i)=eps(i)
q(i)=se(i)*e
xi(i)=x(i)
xo(i)=x(i)
do 2 j=1,m
2 h(i,j)=0.0
do 1 ic=0
1 ic=1
jc=0
lr3=5
go to 112
3 imax=20*m
fmin=fbar
f0=fbar
fj=fbar
de=0.0
assign 30 to irl
begin iteration
50 do 41 j=1,m
qj=q(j)
mj= mjfcet *qj
go to 100
30 q(j)=max(se(j),abs(lmda))
if(abs(de1).gt.abs(fj-fbar))goto 41
de1=fj-fbar
jd=j
41 fj=fbar
check convergence
if(ic.ge.imax)goto 91
lr2=1
kl=1
ps1l=0.0
cmin=200.
do 63 l=1,m
12=abs(xi(l)-xo(l))
if(t2.eq. 0.) go to 63

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if(t2.ge.0.01) ir2=2
psill=psill+t2*t2

if(t2(1:em-in) em-in=0.0
continue

goto (90,70),ir2

check desirability of new direction

70 do 73 i=1,m
73 x(1)=x(1)+x(1)-xo(1)
ir3=0

goto 112

75 f1=f1

psill=sqrt(psill)
emin=emin*psill
li=-psill
f2=fmin

if((f1-f2-f3)*f3*del**2.ge..5*del*(f1-f3)**2)goto 72

compute new direction and use directions

1=1,2,3,...,jd-1,jd+1,...,n,new

j,j+=1

do 82 j=jd,jj

if(jd-m)81,83,81

81 do 82 j=1,jd,jj

q(j)=q(j+1)
do 82 j=1,jd,jj

h(i,j)=x(i,j)/psill

se(m)=emin

84 q(m)=psill

if((f1-f2-f3)*f3*del**2.ge..5*del*(f1-f3)**2)goto 72

assign 72 to ir1

go to 400

prepare for new iteration

72 do 71 i=1,m
71 xo(i)=x(i)

if(k)93,96,93

90 do 92 i=1,m
92 x(i)=x(i)

if(k)93,96,93

prepare to return
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93  k=k1
97  return
96  if(k1-1)94,97,94
94  write(6,95) imax,k1
95  format(24h funmin--not converged --,i3,15h iterations,k =,i2)
stop

o  find minimum along a line (initial steps)
100  i2=0
101  f2=fmin
102  lmda=qj
103  ir3=1
104  go to 110
105  l3=lmda
106  f3=fbar
107  go to 400
108  l3=lmda
109  f3=fbar
110  lmda=-qj
111  ir3=3
112  go to 110
113  l1=lmda
114  f1=fbar

o  find minimum along a line
400  t1=i2-13
401  t2=i3-11
402  t3=i1-12
403  t4=t1*t2*t3
404  t5=t1*t1+t2*t2+t3*t3
405  t4=t5/t4
406  t1=t1/t4
407  t2=t2/t4
408  t3=t3/t4
409  lmda=.5*((t2-t3)*f1+(t3-t1)*f2+(t1-t2)*f3)/t5
410  if(t4).401,402,402
411  if(abs(lmda)-mj).403,403,402
412  if(f1.lt.f3)goto 404
413  if(f1.lt.f3)goto 405
414  if(f1.lt.f3)goto 406
415  lmda=mj
416  go to 403
417  lmda=-mj
418  if(f1.lt.f3)goto 405
419  if(f3.lt.f1)goto 406
420  lmin=12
421  fmin=f2
422  if(abs(lmda-lmin).lt.0.001) go to 471
423  if(lmda.eq.0.0)goto 408
424  if(abs((lmda-lmin)/lmda).lt.0.03)goto 471
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408 ir3=4
   go to 110
409 lmin=11
   fmin=f1
   go to 407
406 lmin=13
   fmin=f3
   go to 407
480 if(lmda.gt.12)goto 481
   if(lmda.lt.11)goto 482
   if(fbar.lt.f2)goto 483
486 l1=lmda
   f1=fbar
   go to 400
481 if(lmda.gt.13)goto 484
   if(fbar.lt.f2)goto 485
487 l3=lmda
   f3=fbar
   go to 400
482 l3=12
   f3=f2
   l2=11
   f2=f1
   go to 486
483 l3=12
   f3=f2
488 l2=lmda
   f2=fbar
   go to 400
484 l1=12
   f1=f2
   l2=13
   f2=f3
   go to 487
485 l1=12
   f1=f2
   go to 488
471 lmda=lmin
   fbar=fmin
   do 473 i=1,m
   473 xi(i)=xi(i)+lmda*ho(j,i)
   go to irl. (30,72)
   prepare to evaluate function
110 do 111 i=1,m
111 xi(i)=xi(i)+lmda*ho(j,i)
112 je=je+1
   fbar=fun(x,m)
   c special for control c c c c c c c c
   if ( fbar .le. 0. ) go to 91
   c special for control c c c c c c c c
   go to (102,105,104,480,3,75 ),ir3
end

37
subroutine fft( fr, fi, k )

implicit double precision ( a-h, o-z )

dimension fr( 1024 ), fi( 1024 )

n = 2**k
mr = 0
nn = n - 1
do 2 m = 1, nn
1 = n
l = 1 / 2
if ( mr + 1 .gt. nn ) go to 1
mr = mod( mr, n ) + 1
if ( mr .lt. m ) go to 2
tr = fr( m + 1 )
fr( m + 1 ) = fr( mr + 1 )
fr( mr + 1 ) = tr
ti = fi( m + 1 )
fi( m + 1 ) = fi( mr + 1 )
fi( mr + 1 ) = ti
continue
2 = 1
3 = 1
if ( 1 .ge. n ) return
istep = 2 * 1
ol = 1
do 4 m = 1, n
n = 3.1415926535 * float( 1 - m ) / cl
wr = cos( n )
wl = sin( n )
do 4 i = m, n, istep
j = i + 1
tr = wr * fr( j ) - wl * fi( j )
ti = wr * fi( j ) + wl * fr( j )
fr( j ) = fr( i ) - tr
fi( j ) = fi( i ) - ti
fr( i ) = fr( i ) + tr
fi( i ) = fi( i ) + ti
4 = 1
continue
1 = istep
go to 3
end

subroutine man0( delta, nt, x )

implicit double precision ( a-h, o-z )
reset 8 kk
common / man / g1( 320 ), g2, g3, kk, expt, tiii, ttime
dimension x( 10 )
c

kk = x( 1 )
ti = x( 2 )
38
expt = exp( -tlt1 )
tlt1 = ti / ti
ltlme = t1 - tlt1 - expt
50 do 50 n = 1, nt
   g1( n ) = 0.
g2 = 0.
g3 = 0.
call tgta0
return
end

subroutine manl( h, j, nt, diffdt, diffdt, gm )

implicit double precision ( a-h, o-z )
real*8 kk
common / man / gl( 320 ), g2, g3, kk, expt, tltl, ltlme

do 60 n = 1, nt-1
   g1( n ) = g1( n+1 )
call tgtal( j, dither, g )
diffdt = g - h
diffdt = g + dither - h
g1( nt ) = diffdt
g2 = g2
   g2 = kk * g1( 1 )
g3 = expt * g3 + ltlme * g2 + tlti * g2
gm = g3
return
end

subroutine plant0( b, kb, bk, bklshi, cf, ds, dt )

implicit double precision ( a-h, o-z )
real*8 jj, kb
common / plant / expb, bdxpb, bklsh, bklshi, cfdt, dedspc, +
   delta, g3b, g4, hn, hnb1

jj = 1.
delta = dt
tj = delta / jj
expb = exp( -b * kb * tj )
bdxpb = ( 1. - expb ) / b
bklsh = bk
bklshi = bkl
cfdt = cf * tj
dedspc = ds
return
end

subroutine plant1( h )

39
implicit double precision ( a-h, o-z )
common / plant / expb, bdxpb, bksh, bklshi, cfdt, dedspo,
+ delta, g3b, g4, hn, hnb1
  g3b = 0.
g4 = 0.
h = 0.
hn = 0.
hnb1 = 0.
return
end

subroutine plant2( g3, h )
  implicit double precision ( a-h, o-z )
  common / plant / expb, bdxpb, bksh, bklshi, cfdt, dedspo,
  + delta, g3b, g4, hn, hnb1
  g3bl = g3b
  g3b = 0.
  if ( abs( g3 ) .gt. dedspo )
    g3b = g3 - sign( dedspo, g3 )
  if ( abs( g3b - g3bl ) .gt. bklshi )
    g3b = g3b - sign( bklshi, g3b - g3bl )
  g4 = expb * g4 + bdxpb * g3bl
  g4 = g4 - sign( min( cfdt, abs( g4 ) ), g4 )
  hnb1 = hnb1 + delta * g4
  if ( abs( hnb1 - hn ) .gt. bklshi )
    hnb1 = hnb1 - sign( bklshi, hnb1 - hn )
  h = hn
  return
end

subroutine stats0( dt, jmax )
  implicit double precision ( a-h, o-z )
  common / stats / delta, points, tmax,
  + sum, sumsq, sumin, sumout, sum12, sumo2,
  + sumt, sumt2, sumit, sumot
  delta = dt
  points = jmax
  tmax = points * delta
  sum = 0.
  sumsq = 0.
  sumin = 0.
  sumout = 0.
  sum12 = 0.
  sumo2 = 0.
  sumt = 0.
  sumt2 = 0.
  sumit = 0.
subroutine stats1 ( difft, frin, frout, j )
implicit double precision ( a-h, o-z )
common / stats / delta, points, tmax,
+ sum, sumsq, sumin, sumout, sumi2, sumo2,
+ sumt, sumt2, sumit, sumot

dt = difft
sum = sum + dt * delta
sumsq = sumsq + dt * dt * delta
sumin = sumin + frin
sumout = sumout + frout
sumi2 = sumi2 + frin * frin
sumo2 = sumo2 + frout * frout
tj = j
sumt = sumt + tj
sumt2 = sumt2 + tj * tj
sumit = sumit + frin * tj
sumot = sumot + frout * tj
return

end

subroutine stats2 ( avin, avout, rmsd )
implicit double precision ( a-h, o-z )
common / stats / delta, points, tmax,
+ sum, sumsq, sumin, sumout, sumi2, sumo2,
+ sumt, sumt2, sumit, sumot
common / stntw / rms, avein, aveout,
+ devin, devout, devid, devod, al, bl, ao, bo
rms = sqrt( sumsq / tmax )
rmsd = rms
avein = sumin / points
avout = sumout / points
avin = avein
aveout = avout
s12 = sumi2 - sumin * avein
so2 = sumo2 - sumout * aveout
pts1 = points - 1.
devin = sqrt( s12 / pts1 )
devout = sqrt( so2 / pts1 )
avet = sumt / points
st2 = sumi2 - sumt * avet
sit = sumit - sumin * avet
sot = sumot - sumout * avet
bl = sit / st2
bo = sot / st2
Jan 2 10:41

\[ a_l = \text{avein} - b_l \times \text{avet} \]
\[ a_o = \text{aveout} - b_o \times \text{avet} \]
\[ \text{pts2} = \text{points} - 2 \]
\[ \text{devid} = \sqrt{\frac{(s_l^2 - b_l \times s_l t)}{\text{pts2}}} \]
\[ \text{devod} = \sqrt{\frac{(s_o^2 - b_o \times s_o t)}{\text{pts2}}} \]
return
end

subroutine statsw

\[ \text{implicit double precision (a-h, o-z)} \]
common /statw/rms, avein, aveout, devin, devout, + devid, devod, al, bi, ao, bo

write (6, 100) rms, avein, aveout, devin, devout, + devid, devod, al, bi, ao, bo
100 format (' RMS AVEIN AVEOUT DEVIN DEVOUT', + ' DEVID DEVOD AI BI AO BO', + '/3pllf6.3/')
return
end
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