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DESCRIPTION OF A DIGITAL COMPUTER SIMULATION OF AN ANNULAR MOMENTUM CONTROL DEVICE (AMCD) LABORATORY TEST MODEL

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SUMMARY

A description of a digital computer simulation of an Annular Momentum Control Device (AMCD) laboratory model is presented. The AMCD is a momentum exchange device which is under development as an advanced control effector for spacecraft attitude control systems.

The digital computer simulation of this device incorporates the following models: six degree-of-freedom rigid body dynamics, rim warp, controller dynamics, nonlinear distributed element axial bearings, as well as power driver and power supply current limits. An annotated FORTRAN IV source code listing of the computer program is included.

INTRODUCTION

Momentum exchange devices are in use on a number of spacecraft and have demonstrated their ability to perform attitude control reliably and efficiently for vehicles as large as SKYLAB. The Annular Momentum Control Device (AMCD) concept was an outgrowth of research at the NASA Langley Research Center (NASA-LARC) directed toward development of momentum exchange devices. Reference 1 presents a detailed description of the AMCD concept as well as potential applications.

In order to investigate any potential problems in implementing the AMCD concept, a laboratory model of the AMCD was designed and fabricated under contract. The laboratory model has been delivered to NASA-LARC and preliminary tests of the device have been performed. A detailed description of the laboratory model is presented in reference 2. Reference 3 presents the results of the static and low-speed dynamic tests which include spin motor torque characteristics as well as spin motor and magnetic bearing drag losses.

A digital computer simulation of the laboratory model AMCD has been developed as an analytical tool to investigate implementation problems with the laboratory model. This report presents a description of that simulation. The simulation incorporates six degree-of-freedom rigid body rim dynamics with rim warp superimposed, as well as power driver and power supply current limits. Equations of motion of the rim are not developed in this report but are taken from reference 4. Similarly, the mathematical model of the nonlinear axial bearing element is taken from reference 5.

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This description includes source code for the simulation computer program which is written in FORTRAN IV. An annotated listing of the program is contained in appendix A.

SYMBOLS

CNG	negative current limit hit counter
CPS	positive current limit hit counter
CR	instantaneous power supply current
CRBAR	average power supply current
CRL	interval minimum power supply current
CRLIM	power supply current limit
CRSM	interval sum of power supply current
CRU	interval maximum power supply current
DEG	radian to degree conversion factor
DELT	integration step size
DELTPR	output print interval
DIV1, DIV2	temporary variables in data collection block
FA, FB, FC	axial force at stations A, B, C
FA1, FA2, FA3, FA4	segment axial forces at station A
FB1, FB2, FB3, FB4	segment axial forces at station B
FC1, FC2, FC3, FC4	segment axial forces at station C
FCNY	axial force function in initialization block
FRA, FRB, FRC	radial force at stations A, B, C
F1, F2, F3	X, Y, Z bearing force components
GAA, GAB, GAC	total axial gap at stations A, B, C
GAAC, GABC, GACC	total axial command at stations A, B, C
GAACP, GABCP, GACCP	GAAC, GABC, GACC, delayed by DELT
GAA1, GAA2, GAA3, GAA4	segment axial gap at station A
GAB1, GAB2, GAB3, GAB4	segment axial gap at station B
GAC1, GAC2, GAC3, GAC4	segment axial gap at station C
GPBAR	interval average axial gap at station A
GPL	interval minimum axial gap at station A
GPPP	interval range of axial gap at station A
GPRMS	interval root mean square axial gap at station A
GPSM	interval sum of axial gap at station A
GPSQSM	interval sum of square of axial gap at station A
GPU	interval maximum axial gap at station A
GRA, GRB, GRC	total radial gap at stations A, B, C
GRAP, GRBP, GRCP	GRA, GRB, GRC, delayed by DELT
H1, H2, H3	X, Y, Z rim angular momentum components
H1DT, H2DT, H3DT	time derivatives of H1, H2, H3
H1DTP, H2DTP, H3DTP	H1DT, H2DT, H3DT, delayed by DELT
IAA, IAB, IAC	axial bearing control current at stations A, B, C
IBIAS	equivalent permanent magnet bias current
INA1, INA2	transverse moments of inertia of rim
INA3	polar moment of inertia of rim
IRA, IRB, IRC	radial bearing control currents at stations A, B, C
KAA, KAR	axial controller position and rate gain
KRA, KRR	radial controller position and rate gain

KRB	radial electromagnet gain
KRM	radial equivalent permanent magnet stiffness
K1	axial electromagnet gain
M	mass of rim
NILIM, PILIM	current limits of power driver
NP	interval iteration counter
OMG1, OMG2, OMG3	X, Y, Z rim body rate components
OMG1P, OMG2P, OMG3P	OMG1, OMG2, OMG3, delayed by DELT
P1, P2, P3	X, Y, Z rim linear momentum components
P1DT, P2DT, P3DT	time derivative of P1, P2, P3
P1DTP, P2DTP, P3DTP	P1DT, P2DT, P3DT, delayed by DELT
RAD	degree to radian conversion factor
RATIO	peak-to-peak axial gap to warp amplitude ratio
RB	axial displacement of rim center of mass
RBBAR	average of RB
RBL	interval minimum of RB
RBSM	interval sum of RB
RBU	interval maximum of RB
RM	radius of rim
RPM	rim rotation rate
RPMI	initial rpm for simulation
RPMF	final rpm for simulation
SPA, SPB, SPC	position set points for stations A, B, C
TEMP1, TEMP2	temporary variables in magnetic bearing block
TH1, TH2, TH3	angular displacement of rim about X, Y, Z axes
TIME	simulation elapsed time
TIMEPR	print interval
T1, T2, T3	bearing torque components about X, Y, Z axes
WAA, WAB, WAC	axial warp at stations A, B, C
WAA1, WAA2, WAA3, WAA4	segment axial warp at station A
WAB1, WAB2, WAB3, WAB4	segment axial warp at station B
WAC1, WAC2, WAC3, WAC4	segment axial warp at station C
WAL	axial rim warp amplitude
WEIGHT	rim weight
WR	radial rim warp at all stations
WRL	radial rim warp amplitude
X	temporary variable in initialization block
XBARO	equivalent nominal magnetic bearing gap
X1, X2, X3	X, Y, Z rim displacement components
X30	initial rigid body axial displacement
X30P	temporary variable in initialization block
X1DT, X1DT, X3DT	time derivative of X1, X2, X3
X1DTP, X2DTP, X3DTP	X1DT, X2DT, X3DT, delayed by DELT
Y, YO, YOP	temporary variables in initialization block
Z	function argument used for FCNY

AMCD DESCRIPTION

An AMCD is a spacecraft attitude control effector that provides control torques by exchanging spacecraft angular momentum with an internal momentum storage device. The storage device is a large spinning rim and the exchange mechanism is a set of three noncontacting magnetic bearings which exert forces on the spinning rim. A brief description of each of the system components as well as the physical layout of the laboratory model follows.

Orientation of components in the AMCD is shown in figure 1. Three magnetic bearing stations, labeled A, B, and C, in the figure, are spaced equidistant about the circumference of the rim. At each bearing station, four groups of electromagnets are placed about the rim at -14.5, -6, +6, and +14.5 degrees of arc relative to the station center. Each group contains two axial and one radial bearing element. At each station center, proximity sensors are installed to measure the displacement of the rim within the bearing gap. Proximity sensor signals and external command signals are input to the controller electronics. The controller maintains the rim position by regulating the flow of current in the electromagnet coil windings, thereby causing forces to be produced by the electromagnets.

SIMULATION DESCRIPTION

Figure 2 shows a block diagram of the simulation. The blocks divide the simulation into segments according to function. In the following text, the function of each of the blocks is described. Appendix A contains a program listing to which annotation has been added to enable one to identify the sections of code which correspond to the functional blocks.

Rigid Body and Rim Warp Models

Models for the rigid body displacements and for axial and radial rim warp are contained in the first block. Rim warp is defined as a deformation of the rim from an ideal shape due to manufacturing defects or plastic creep due to storage and handling.

Laboratory measurements have indicated that the axial warp may be approximated by a sinusoid with two periods per rim revolution (this may be visualized as the shape that a large flexible ring would assume if the weight were supported by two diametrically opposed points). The amplitude of the sinusoid is adjusted to make the model agree with measured data. Axial rim warp at each electromagnet and sensor location, 15 points in all, is computed using station A center point as zero reference.

Similar laboratory measurements of the radial rim warp have indicated that it may be approximated by a sinusoid with three periods per rim revolution. As in the axial case, the amplitude of the sinusoid is adjusted to make the model agree with measured data. Radial rim warp is computed at the center of each bearing station using station A as zero reference. Since the bearing stations are 120 degrees apart, it may be shown that all the radial rim warp components are in phase and, thus, they may be generated from a single model.

Axial and radial rigid body angular and translational displacements at each of the same 15 points mentioned above are derived from figure 1 under the assumption of small displacements of the rim in the radial and axial directions.

Finally, the warp and rigid body contributions to the rim displacements are summed for each of the axial and radial components to generate the total rim displacement in the bearing gaps. It is this displacement which is measured by the proximity sensors and transmitted to the controller.

Controller Model

In this simulation, perfect sensors are assumed, therefore, the computed bearing gaps are passed directly to the controller and considered to be the measured gaps.

The controller is a proportional plus derivative type which is expressed in discrete equation form. Gains are derived from reference 2 and converted to equivalent gains for the discrete controller. Simulated proximity sensor measurements are combined with set point commands for input to the controller equations. Outputs from the controller are voltages which are proportional to the required control currents.

A power amplifier converts the voltage control commands into currents which energize each electromagnet circuit. The power amplifiers are modelled as having ideal transfer characteristics, with a limit on the maximum available output current for that particular bearing segment. The power supply effects are modelled as a limit on the total current demanded from all of the power amplifiers. After the power amplifier model has processed the command current, the total current commanded is computed as the sum of the unsigned magnitudes (the sign determines only the direction of the current flow in the electromagnet coil windings). If the upper limit has been reached or exceeded, all commands are ratioed to the maximum available current.

Magnetic Bearing Models

Each of the twelve nonlinear axial magnetic actuators is an implementation of equation 42 in reference 5. An axial magnetic actuator consists of a pair of opposed electromagnets, each of which can exert an attractive force. This force is proportional to the square of the current flowing through the coil windings and inversely proportional to the square of the distance from the rim to the magnet pole face. After the forces produced by each of the twelve actuators are computed, they are resolved into the rim coordinate system to yield two torque components and one force component which will be applied to the rigid body dynamics equations.

Each of the three radial stations is modelled as a linear system which is an implementation of equation 43 in reference 5. A radial station is represented by a single electromagnet which exerts an attractive force against the inner surface of the rim. Each radial station is opposed by a component of the force generated by the other two stations. The forces produced by the three radial actuators are resolved into the rim coordinate system to yield two force components which will be applied to the rigid body dynamics equations.

Rigid Body Dynamics

The rigid body dynamics of the rim are computed by the momentum method as described in reference 6. The first step in the computation is to determine the rim body rates by dividing the momentum states by the moment of inertia of the rim about the respective body axis (the inertia matrix of the rim is diagonal). Then, these body rates are used in the dynamics equation to determine the derivative with respect to time of the rim momentum. The momentum derivatives are found by solving for the partial derivatives with respect to time from the expression for the total derivatives of momentum in the body coordinate system. Initially, all cross product terms were incorporated, but subsequent simulation data showed that only the terms currently used are significant.

Data Collection

In the data collection section of the program, the bearing gap at station A, the total required bearing current, and the average displacement of the rim along the Z-axis are sampled at each computation interval. Maximum, minimum, and average values are computed from these parameters over a time segment defined as the print interval. Additionally, the RMS gap, the maximum peak-to-peak gap, and a measure of the fraction of the time segment in which the axial bearing power amplifier at station A is in a saturated state are computed. These data together with the simulation elapsed time and rim RPM are printed at the end of each print interval.

Numerical Integration

An Adam's second order integrator was selected from a brief comparison study of candidate integration schemes wherein speed and error control were used as critical selection criteria. At the beginning of the simulation, all parameters must be initialized and the steady state conditions of the rim dynamics prior to the first computation step must be found. An iterative technique is used to solve the rim dynamic and kinematic relationships to yield the equilibrium condition. This allows all initial conditions to be established. At that point, the simulation begins and proceeds until the final rim RPM value, as selected by the user, has been reached.

CONCLUDING REMARKS

This paper has described a digital computer simulation of a laboratory model of an Annular Momentum Control Device (AMCD). The digital computer simulation of this device incorporates the following models: six degree-of-freedom rigid body dynamics, rim warp, controller dynamics, nonlinear distributed element axial bearings, as well as power driver and power supply current limits. Annotated FORTRAN IV source code of the computer program is included in appendix A. The simulation can be used in the analysis of advanced control systems approaches for the laboratory model AMCD.

REFERENCES

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5. Groom, Nelson J.: Analytical Model of an Annular Momentum Control Device (AMCD) Laboratory Test Model Magnetic Bearing Actuator. NASA TM-80099, 1979.

6. Russell, W. J.: Dynamic Analysis of the Communication Satellites of the Future. AIAA Paper 76-261, AIAA/CASI Sixth Communications Satellite Systems Conference, Montreal, Canada, April 5-8, 1976.

APPENDIX A

```
C******************************************************
C****      INITIALIZATION BLOCK  1000             *****
C******************************************************
      PROGRAM AMCD
      REAL IAA,IAB,IAC,IBIAS,INA1,INA2,INA3
      REAL IRA,IRB,IRC
      REAL K1,KAA,KAR,KRA,KRB,KRM,KRR
      REAL M,NILIM
      DOUBLE PRECISION X,X30,X30P,Y,YO,YOP,Z,FCNY
      LOGICAL FLAG
 1000 PI=4.*ATAN(1.)
      RAD=PI/180.
      DEG=180./PI
C****      SYSTEM PARAMETERS
      M=1.54
      WEIGHT=M*32.2
      INA1=5.306
      INA2=INA1
      INA3=2.*INA1
      RM=2.625
      KAA=5.965E+3
      KAR=2.02E+1
      KRA=351.*12.
      KRR=1.3*12.
      KRB=1.55
      KRM=170.*12.
      K1=3.4476E-3/144.0/16.0
      PILIM=13.33
      NILIM=-PILIM
      CRLIM=30.
      IBIAS=14.96999297
      XBARO=.14/12.
      SPA=.025/12.
      SPB=SPA
      SPC=SPA
      WRL=.002/12.
C****      INPUT CASE DATA
 1100 WRITE(5,1200)
 1200 FORMAT(' SELECT DELTA T (END PROGRAM IF NEGATIVE)')
      ACCEPT 1300,DELT
 1300 FORMAT(F12.3)
      IF(DELT.LE.0.)  GOTO 9999
      WRITE(5,1400)
 1400 FORMAT(' SELECT CASE PARAMETERS ...'/
     1 ' PRINT INTERVAL,INIT SPIN RPM,FINAL SPIN RPM,WARP AMPLITUDE')
      ACCEPT 1300,DELTPR,RPMI,RPMF,WAL
C****      DETERMINE STEADY STATE BEARING GAP
      FCNY(Z)=12.*K1*(((IBIAS+KAA*(SPA-Z))/(XBARO-Z))**2
     1 -((IBIAS-KAA*(SPA-Z))/(XBARO+Z))**2)-WEIGHT
      X30P=.010/12.
      YOP=FCNY(X30P)
      X30=.020/12.
      YO=FCNY(X30)
 1500 X=(X30P*YO-X30*YOP)/(YO-YOP)
      Y=FCNY(X)
```

```
      X30P=X30
      Y0P=Y0
      X30=X
      Y0=Y
      IF(ABS(Y).GT.1.E-10)  GOTO 1500
      TH3=0.
      WAA=WAL*SIN(2.*TH3)
      WAB=WAL*(SIN(2.*TH3)*COS(240.*RAD)+COS(2.*TH3)*SIN(240.*RAD))
      WAC=WAL*(SIN(2.*TH3)*COS(120.*RAD)+COS(2.*TH3)*SIN(120.*RAD))
      GAA=-WAA+X30
      GAB=-WAB+X30
      GAC=-WAC+X30
      TH1=(GAA-GAB)/(RM*SQRT(3.))
      TH2=(2.*GAC-(GAA+GAB))/(RM*3.)
      X1=0.
      X2=0.
      X3=(GAA+GAB+GAC)/3.
      GAACP=X30-SPA
      GABCP=X30-SPB
      GACCP=X30-SPC
      WR=WRL*SIN(3.*TH3)
      GRA=X1*SIN(30.*RAD)+X2*COS(30.*RAD)+WR
      GRB=X1*SIN(30.*RAD)-X2*COS(30.*RAD)+WR
      GRC=-X1+WR
      GRAP=GRA
      GRBP=GRB
      GRCP=GRC
C****       COMPUTE INITIAL CONDITIONS
      TIME=0.
      TIMEPR=-DELT/2.
      OMG1=0.
      OMG2=0.
      OMG3=RPMI*2.*PI/60.
      X1DT=0.
      X2DT=0.
      X3DT=0.
      H1=OMG1*INA1
      H2=OMG2*INA2
      H3=OMG3*INA3
      P1=X1DT*M
      P2=X2DT*M
      P3=X3DT*M
      T1=0.
      T2=0.
      T3=1.1
      H1DT=T1-OMG2*H3
      H2DT=T2+OMG1*H3
      H3DT=T3-OMG1*H2+OMG2*H1
      P1DT=0.
      P2DT=0.
      P3DT=0.
      H1DTP=H1DT
      H2DTP=H2DT
      H3DTP=H3DT
      P1DTP=P1DT
      P2DTP=P2DT
      P3DTP=P3DT
      OMG1P=OMG1
      OMG2P=OMG2
```

```
      OMG3P=OMG3
      X1DTP=X1DT
      X2DTP=X2DT
      X3DTP=X3DT
C****      CLEAR STATISTICAL VARIABLES
      GPSM=0.
      GPSQSM=0.
      GPL=X30
      GPU=GPL
      CRSM=0.
      CRL=KAA*(ABS(GAACP)+ABS(GABCP)+ABS(GACCP))
      CRU=CRL
      RBSM=0.
      RBL=(GAACP+GABCP+GACCP)/3.
      RBU=RBL
      CNG=0.
      CPS=0.
      NP=0
      FLAG=.FALSE.
```

```
C*******************************************************
C****      RIGID BODY AND RIM WARP BLOCK  2000    *****
C*******************************************************
C****      AXIAL WARP
 2000 CONTINUE
      WAA1=WAL*(SIN(2.*TH3)*COS(-29.*RAD)+COS(2.*TH3)*SIN(-29.*RAD))
      WAA2=WAL*(SIN(2.*TH3)*COS(-12.*RAD)+COS(2.*TH3)*SIN(-12.*RAD))
      WAA =WAL* SIN(2.*TH3)
      WAA3=WAL*(SIN(2.*TH3)*COS( 12.*RAD)+COS(2.*TH3)*SIN( 12.*RAD))
      WAA4=WAL*(SIN(2.*TH3)*COS( 29.*RAD)+COS(2.*TH3)*SIN( 29.*RAD))
      WAB1=WAL*(SIN(2.*TH3)*COS(211.*RAD)+COS(2.*TH3)*SIN(211.*RAD))
      WAB2=WAL*(SIN(2.*TH3)*COS(228.*RAD)+COS(2.*TH3)*SIN(228.*RAD))
      WAB =WAL*(SIN(2.*TH3)*COS(240.*RAD)+COS(2.*TH3)*SIN(240.*RAD))
      WAB3=WAL*(SIN(2.*TH3)*COS(252.*RAD)+COS(2.*TH3)*SIN(252.*RAD))
      WAB4=WAL*(SIN(2.*TH3)*COS(269.*RAD)+COS(2.*TH3)*SIN(269.*RAD))
      WAC1=WAL*(SIN(2.*TH3)*COS( 91.*RAD)+COS(2.*TH3)*SIN( 91.*RAD))
      WAC2=WAL*(SIN(2.*TH3)*COS(108.*RAD)+COS(2.*TH3)*SIN(108.*RAD))
      WAC =WAL*(SIN(2.*TH3)*COS(120.*RAD)+COS(2.*TH3)*SIN(120.*RAD))
      WAC3=WAL*(SIN(2.*TH3)*COS(132.*RAD)+COS(2.*TH3)*SIN(132.*RAD))
      WAC4=WAL*(SIN(2.*TH3)*COS(149.*RAD)+COS(2.*TH3)*SIN(149.*RAD))
C****      RADIAL WARP
      WR=WRL*SIN(3.*TH3)
C****      AXIAL BEARING GAPS
      GAA1=RM*(TH1*COS(15.5*RAD)-TH2*SIN(15.5*RAD))+X3+WAA1
      GAA2=RM*(TH1*COS(24.*RAD)-TH2*SIN(24.*RAD))+X3+WAA2
      GAA=RM*(TH1*COS(30.*RAD)-TH2*SIN(30.*RAD))+X3+WAA
      GAA3=RM*(TH1*COS(36.*RAD)-TH2*SIN(36.*RAD))+X3+WAA3
      GAA4=RM*(TH1*COS(44.5*RAD)-TH2*SIN(44.5*RAD))+X3+WAA4
      GAB1=RM*(-TH1*COS(44.5*RAD)-TH2*SIN(44.5*RAD))+X3+WAB1
      GAB2=RM*(-TH1*COS(36.*RAD)-TH2*SIN(36.*RAD))+X3+WAB2
      GAB=RM*(-TH1*COS(30.*RAD)-TH2*SIN(30.*RAD))+X3+WAB
      GAB3=RM*(-TH1*COS(24.*RAD)-TH2*SIN(24.*RAD))+X3+WAB3
      GAB4=RM*(-TH1*COS(15.5*RAD)-TH2*SIN(15.5*RAD))+X3+WAB4
      GAC1=RM*(-TH1*SIN(14.5*RAD)+TH2*COS(14.5*RAD))+X3+WAC1
      GAC2=RM*(-TH1*SIN(6.*RAD)+TH2*COS(6.*RAD))+X3+WAC2
      GAC=RM*TH2+X3+WAC
      GAC3=RM*(TH1*SIN(6.*RAD)+TH2*COS(6.*RAD))+X3+WAC3
      GAC4=RM*(TH1*SIN(14.5*RAD)+TH2*COS(14.5*RAD))+X3+WAC4
C****      RADIAL BEARING GAPS
      GRA=X1*SIN(30.*RAD)+X2*COS(30.*RAD)+WR
      GRB=X1*SIN(30.*RAD)-X2*COS(30.*RAD)+WR
      GRC=-X1+WR
```

```
C******************************************************
C****      BEARING CONTROLLER BLOCK  3000         *****
C******************************************************
C****      AXIAL CONTROLLER
      GAAC=GAA-SPA
      IAA=-KAA*GAAC-KAR*(GAAC-GAACP)/DELT
      GAACP=GAAC
      GABC=GAB-SPB
      IAB=-KAA*GABC-KAR*(GABC-GABCP)/DELT
      GABCP=GABC
      GACC=GAC-SPC
      IAC=-KAA*GACC-KAR*(GACC-GACCP)/DELT
      GACCP=GACC
C****      RADIAL CONTROLLER
      IRA=-KRA*GRA-KRR*(GRA-GRAP)/DELT
      GRAP=GRA
      IRB=-KRA*GRB-KRR*(GRB-GRBP)/DELT
      GRBP=GRB
      IRC=-KRA*GRC-KRR*(GRC-GRCP)/DELT
      GRCP=GRC
C****      CURRENT LIMITER
 3100 IF(IAA.GT.NILIM)  GOTO 3200
      CNG=CNG+1.
      IAA=NILIM
      GOTO 3300
 3200 IF(IAA.LT.PILIM)  GOTO 3300
      CPS=CPS+1.
      IAA=PILIM
 3300 IF(IAB.GT.NILIM)  GOTO 3400
      IAB=NILIM
      GOTO 3500
 3400 IF(IAB.LT.PILIM)  GOTO 3500
      IAB=PILIM
 3500 IF(IAC.GT.NILIM)  GOTO 3600
      IAC=NILIM
      GOTO 3700
 3600 IF(IAC.LT.PILIM)  GOTO 3700
      IAC=PILIM
 3700 CONTINUE
C****      POWER SUPPLY LIMITER
      CR=ABS(IAA)+ABS(IAB)+ABS(IAC)+ABS(IRA)+ABS(IRB)+ABS(IRC)
      IF(CR.LT.CRLIM)  GOTO 3800
      IAA=IAA*CRLIM/CR
      IAB=IAB*CRLIM/CR
      IAC=IAC*CRLIM/CR
      IRA=IRA*CRLIM/CR
      IRB=IRB*CRLIM/CR
      IRC=IRC*CRLIM/CR
      CR=CRLIM
 3800 CONTINUE
```

```
C*******************************************************
C****       MAGNETIC BEARING MODEL BLOCK  4000     *****
C*******************************************************
      TEMP1=(IBIAS+IAA)/(XBARO-GAA1)
      TEMP2=(IBIAS-IAA)/(XBARO+GAA1)
      FA1=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAA)/(XBARO-GAA2)
      TEMP2=(IBIAS-IAA)/(XBARO+GAA2)
      FA2=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAA)/(XBARO-GAA3)
      TEMP2=(IBIAS-IAA)/(XBARO+GAA3)
      FA3=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAA)/(XBARO-GAA4)
      TEMP2=(IBIAS-IAA)/(XBARO+GAA4)
      FA4=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      FA=FA1+FA2+FA3+FA4
      TEMP1=(IBIAS+IAB)/(XBARO-GAB1)
      TEMP2=(IBIAS-IAB)/(XBARO+GAB1)
      FB1=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAB)/(XBARO-GAB2)
      TEMP2=(IBIAS-IAB)/(XBARO+GAB2)
      FB2=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAB)/(XBARO-GAB3)
      TEMP2=(IBIAS-IAB)/(XBARO+GAB3)
      FB3=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAB)/(XBARO-GAB4)
      TEMP2=(IBIAS-IAB)/(XBARO+GAB4)
      FB4=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      FB=FB1+FB2+FB3+FB4
      TEMP1=(IBIAS+IAC)/(XBARO-GAC1)
      TEMP2=(IBIAS-IAC)/(XBARO+GAC1)
      FC1=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAC)/(XBARO-GAC2)
      TEMP2=(IBIAS-IAC)/(XBARO+GAC2)
      FC2=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAC)/(XBARO-GAC3)
      TEMP2=(IBIAS-IAC)/(XBARO+GAC3)
      FC3=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      TEMP1=(IBIAS+IAC)/(XBARO-GAC4)
      TEMP2=(IBIAS-IAC)/(XBARO+GAC4)
      FC4=K1*(TEMP1*TEMP1-TEMP2*TEMP2)
      FC=FC1+FC2+FC3+FC4
C****        TRANSFORM BEARING FORCES INTO RIM SYSTEM
      T1=RM*((FA1-FB4)*COS(15.5*RAD)+(FA2-FB3)*COS(24.*RAD)
     1 +(FA3-FB2)*COS(36.*RAD)+(FA4-FB1)*COS(44.5*RAD)
     2 +(FC3-FC2)*SIN(6.*RAD)+(FC4-FC1)*SIN(14.5*RAD))
      T2=RM*((FC2+FC3)*COS(6.*RAD)+(FC1+FC4)*COS(14.5*RAD)
     1 -(FA4+FB1)*SIN(44.5*RAD)-(FA3+FB2)*SIN(36.*RAD)
     2 -(FA2+FB3)*SIN(24.*RAD)-(FA1+FB4)*SIN(15.5*RAD))
      F3=FA+FB+FC
C****        RADIAL BEARINGS
      FRA=KRB*IRA+KRM*GRA
      FRB=KRB*IRB+KRM*GRB
      FRC=KRB*IRC+KRM*GRC
      F1=(FRA+FRB)*SIN(30.*RAD)-FRC
      F2=(FRA-FRB)*COS(30.*RAD)
```

```
C******************************************************
C****      RIM DYNAMICS BLOCK  5000               *****
C******************************************************
      OMG1=H1/INA1
      OMG2=H2/INA2
      OMG3=H3/INA3
      X1DT=P1/M
      X2DT=P2/M
      X3DT=P3/M
      H1DT=T1-OMG2*H3
      H2DT=T2+OMG1*H3
      H3DT=T3-OMG1*H2+OMG2*H1
      P1DT=F1
      P2DT=F2
      P3DT=F3-WEIGHT
```

```
C******************************************************
C****       DATA COLLECTION AND I/O BLOCK  6000    *****
C******************************************************
      GPSM=GPSM+GAA
      GPSQSM=GPSQSM+GAA*GAA
      IF(GAA.GT.GPU)  GPU=GAA
      IF(GAA.LT.GPL)  GPL=GAA
      CRSM=CRSM+CR
      IF(CR.GT.CRU)  CRU=CR
      IF(CR.LT.CRL)  CRL=CR
      RB=(GAA+GAB+GAC)/3.
      RBSM=RBSM+RB
      IF(RB.GT.RBU)  RBU=RB
      IF(RB.LT.RBL)  RBL=RB
      NP=NP+1
C****       PREPARE DATA FOR OUTPUT
      IF(TIME.LT.TIMEPR)  GOTO 6300
      TIMEPR=TIMEPR+DELTPR
      RPM=30.*OMG3/PI
      WRITE(6,6000) TIME,RPM
 6000 FORMAT(' TIME  ='F10.3,2X,'RPM   ='F10.3)
      IF(FLAG)  GOTO 6100
      WRITE(6,6010) H1DT,H2DT,H3DT,P3DT
 6010 FORMAT(' H1DT  ='1PE10.3,2X,'H2DT  ='E10.3,2X,'H3DT  ='E10.3,2X,
     1        'P3DT  ='E10.3)
      WRITE(6,6020) H1,H2,H3,P3
 6020 FORMAT(' H1    ='1PE10.3,2X,'H2    ='E10.3,2X,'H3    ='E10.3,2X,
     1        'P3    ='E10.3)
      WRITE(6,6030) OMG1,OMG2,OMG3,X3DT
 6030 FORMAT(' OMG1  ='1PE10.3,2X,'OMG2  ='E10.3,2X,'OMG3  ='E10.3,2X,
     1        'X3DT  ='E10.3)
      WRITE(6,6040) TH1,TH2,TH3,X3
 6040 FORMAT(' TH1   ='1PE10.3,2X,'TH2   ='E10.3,2X,'TH3   ='E10.3,2X,
     1        'X3    ='E10.3)
      WRITE(6,6050) T1,T2,F3
 6050 FORMAT(' T1    ='1PE10.3,2X,'T2    ='E10.3,2X,'F3    ='E10.3)
      WRITE(6,6060) FA,FB,FC
 6060 FORMAT(' FA    ='1PE10.3,2X,'FB    ='E10.3,2X,'FC    ='E10.3)
      WRITE(6,6070) IAA,IAB,IAC
 6070 FORMAT(' IAA   ='1PE10.3,2X,'IAB   ='E10.3,2X,'IAC   ='E10.3)
C****       COMPUTE GAP STATISTICS
 6100 DIV1=0.
      IF(NP.GT.0)  DIV1=1./NP
      GPBAR=GPSM*DIV1
      CRBAR=CRSM*DIV1
      RBBAR=RBSM*DIV1
      DIV2=0.
      IF(NP.GT.1)  DIV2=1./(NP-1)
      GPRMS=SQRT((GPSQSM-NP*GPBAR*GPBAR)*DIV2)
      GPBAR=12.*GPBAR
      GPRMS=12.*GPRMS
      GPU=12.*GPU
      GPL=12.*GPL
      RBU=12.*RBU
      RBL=12.*RBL
      RBBAR=12.*RBBAR
      GPPP=ABS(GPU-GPL)
      CNG=100.*CNG*DIV1
      CPS=100.*CPS*DIV1
```

```
      RATIO=GPPP/(WAL*24.)
      WRITE(6,6200) GPBAR,GPRMS,GPL,GPU
 6200 FORMAT(' GPBAR ='1PE10.3,2X,'GPRMS ='E10.3,2X,'GPL    ='E10.3,2X,
     1         'GPU   ='E10.3)
      WRITE(6,6210) GPPP,CRBAR,CRL,CRU
 6210 FORMAT(' GPPP  ='1PE10.3,2X,'CRBAR ='E10.3,2X,'CRL    ='E10.3,2X,
     1         'CRU   ='E10.3)
      WRITE(6,6220) CNG,CPS,RBL,RBU
 6220 FORMAT(' CNG   ='1PF10.3,2X,'CPS   ='F10.3,2X,'RBL    ='E10.3,2X,
     1         'RBU   ='E10.3)
      GPSM=0.
      GPSQSM=0.
      GPL=GPBAR/12.
      GPU=GPL
      CRSM=0.
      CRL=CRBAR
      CRU=CRL
      RBSM=0.
      RBL=RBBAR/12.
      RBU=RBL
      CNG=0.
      CPS=0.
      NP=0
      FLAG=.TRUE.
 6300 CONTINUE
```

```
C*****************************************************
C****      NUMERICAL INTEGRATION BLOCK  7000      *****
C*****************************************************
      H1=H1+DELT*(3.*H1DT-H1DTP)/2.
      H2=H2+DELT*(3.*H2DT-H2DTP)/2.
      H3=H3+DELT*(3.*H3DT-H3DTP)/2.
      P1=P1+DELT*(3.*P1DT-P1DTP)/2.
      P2=P2+DELT*(3.*P2DT-P2DTP)/2.
      P3=P3+DELT*(3.*P3DT-P3DTP)/2.
      TH1=TH1+DELT*(3.*OMG1-OMG1P)/2.
      TH2=TH2+DELT*(3.*OMG2-OMG2P)/2.
      TH3=TH3+DELT*(3.*OMG3-OMG3P)/2.
      X1=X1+DELT*(3.*X1DT-X1DTP)/2.
      X2=X2+DELT*(3.*X2DT-X2DTP)/2.
      X3=X3+DELT*(3.*X3DT-X3DTP)/2.
      H1DTP=H1DT
      H2DTP=H2DT
      H3DTP=H3DT
      P1DTP=P1DT
      P2DTP=P2DT
      P3DTP=P3DT
      OMG1P=OMG1
      OMG2P=OMG2
      OMG3P=OMG3
      X1DTP=X1DT
      X2DTP=X2DT
      X3DTP=X3DT
      IF(TH3.GT.360.*RAD)  TH3=TH3-360.*RAD
      TIME=TIME+DELT
      IF(RPM.LT.RPMF)  GOTO 2000
      GOTO 1100
C***       TERMINATE PROGRAM
 9999 CONTINUE
      END
```

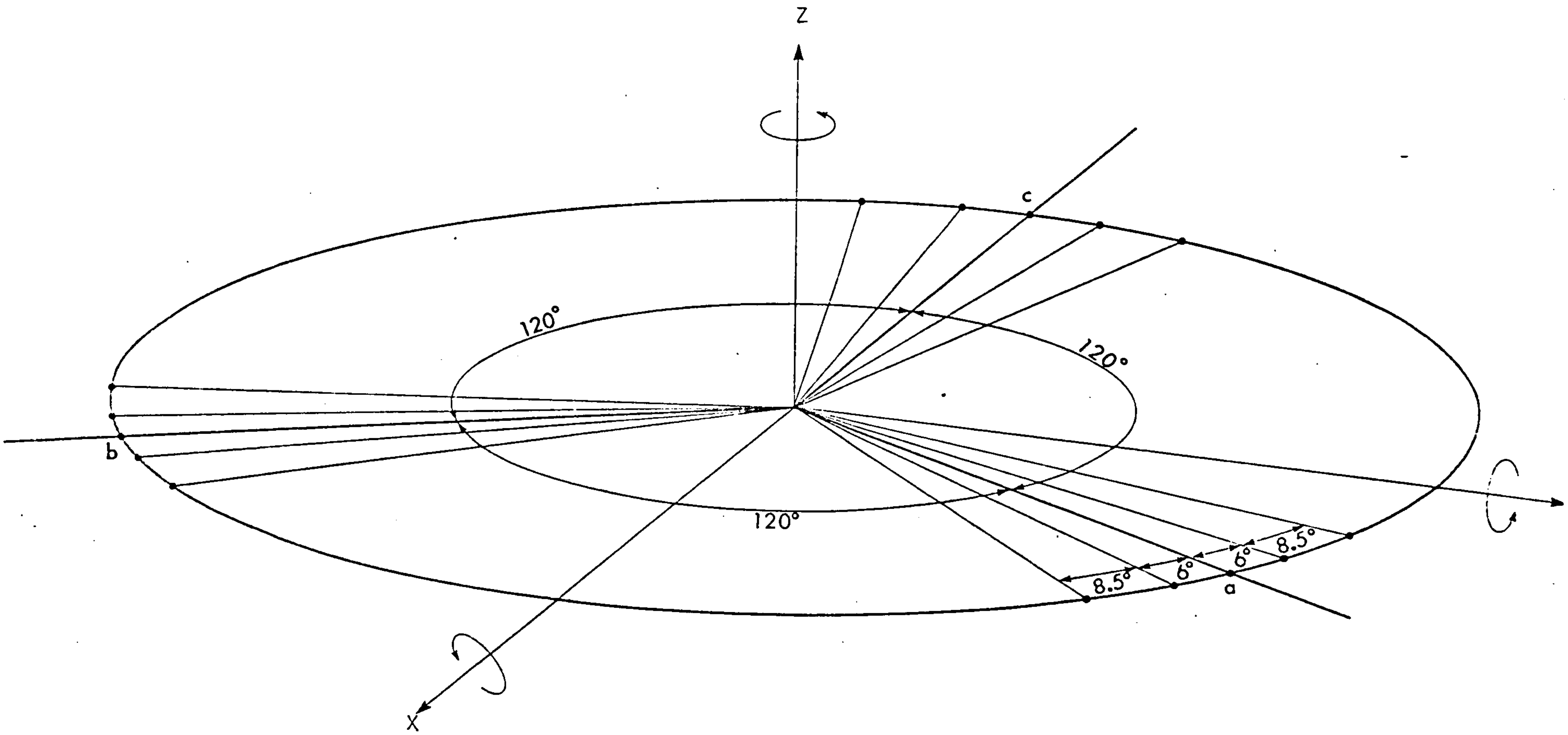

Figure 1.- AMCD Component Orientation

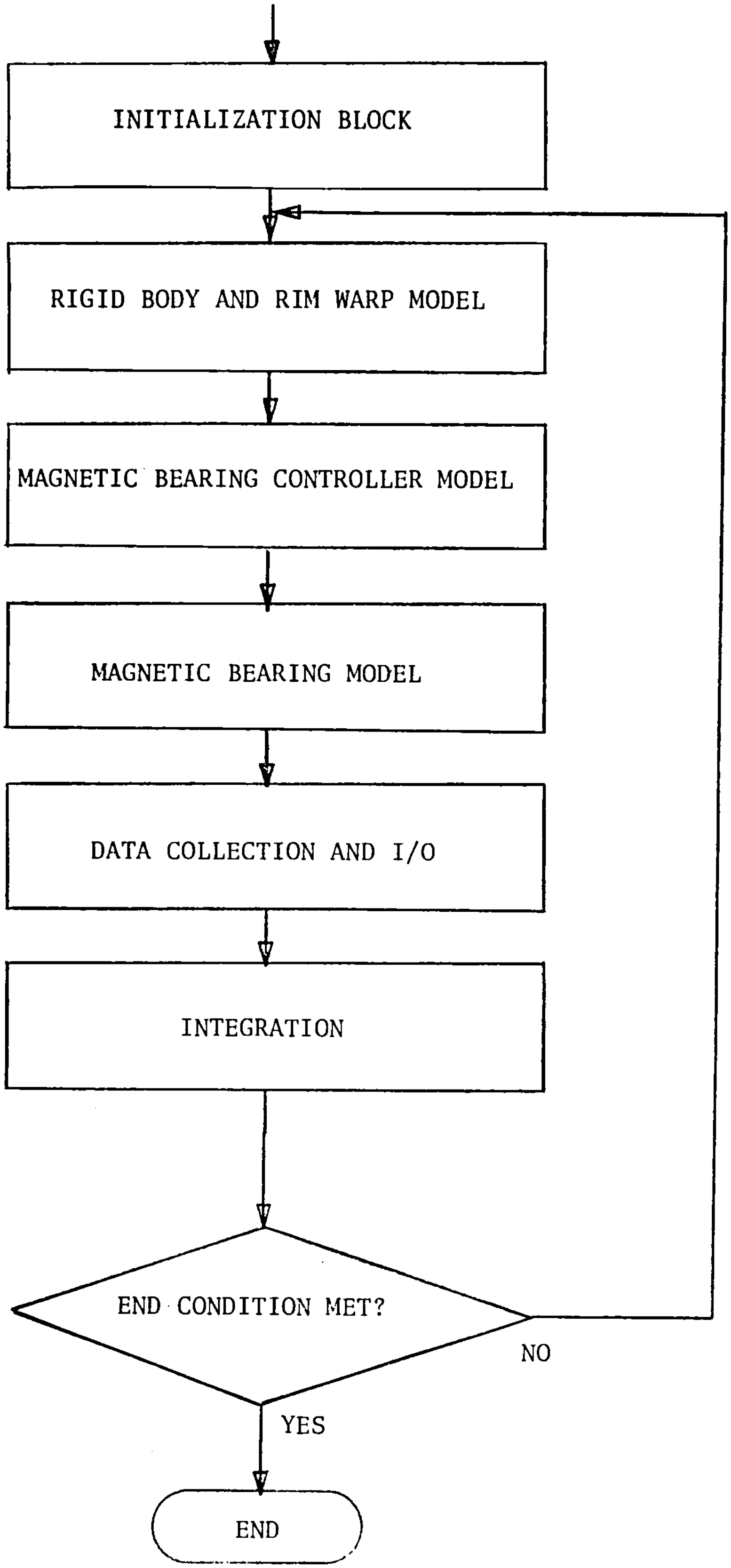

Figure 2.- Simulation Block Diagram

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15. Supplementary Notes

16. Abstract

A description of a digital computer simulation of an Annular Momentum Control Device (AMCD) laboratory model is presented. The AMCD is a momentum exchange device which is under development as an advanced control effector for spacecraft attitude control systems.

The digital computer simulation of this device incorporates the following models: six degree-of-freedom rigid body dynamics, rim warp, controller dynamics, non-linear distributed element axial bearings, as well as power driver and power supply current limits. An annotated FORTRAN IV source code listing of the computer program is included in appendix A.

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