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AN INTERACTIVE COMPUTER PROGRAM FOR SIZING SPACECRAFT MOMENTUM STORAGE DEVICES

F. J. Wilcox, Jr.

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Langley Research Center
Hampton, Virginia 23665
AN INTERACTIVE COMPUTER PROGRAM FOR SIZING SPACECRAFT
MOMENTUM STORAGE DEVICES

Floyd J. Wilcox, Jr.
Langley Research Center

SUMMARY

An interactive computer program has been developed which computes the sizing requirements for nongimbled reaction wheels, control moment gyros (CMG), and dual momentum control devices (DMCD) used in Earth-orbiting spacecraft. The program accepts as inputs the spacecraft's environmental disturbance torques, rotational inertias, maneuver rates, and orbital data. From these inputs, wheel weights are calculated for a range of radii and rotational speeds. The shape of the momentum wheel may be chosen to be either a hoop, solid cylinder, or annular cylinder. The program provides graphic output illustrating the trade-off potential between the weight, radius, and wheel speed. A number of the intermediate calculations such as the X-, Y-, and Z-axis total momentum, the momentum absorption requirements for reaction wheels, CMG's, DMCD's, and basic orbit analysis information are also provided as program output.

INTRODUCTION

Earth-orbiting spacecraft utilize nongimbled reaction wheels, control moment gyros (CMG), and dual momentum control devices (DMCD) for momentum storage and control, and the development of accurate momentum wheel sizing requirements is essential for effective spacecraft design. As part of the Langley Research Center's Computer-Aided Spacecraft Design effort, an interactive computer program has been developed to size momentum wheels. The program accepts as input the spacecraft's environmental disturbance torques, rotational inertias, maneuver rates, vehicular orientation, and orbital data. Momentum wheel weights are calculated for a range of wheel radii and rotational speeds, and are provided as graphical output to illustrate the trade-off potential between the weight, radius, and wheel speed. Intermediate calculations such as the X-, Y-, and Z-axis total momentum, the momentum absorption requirements for reaction wheels, CMG's, DMCD's, and basic orbit analysis information are also provided as output.

The momentum wheel sizing computer program listing is given in the appendix.

PROGRAM DESCRIPTION

The momentum wheel sizing computer program provides an interactive graphics technique for determining the wheel size and weight for various momentum storage
and control devices on Earth-orbiting spacecraft. The program is written in ANSI standard FORTRAN on a Control Data Corporation (CDC) CYBER 173 computer. The graphics output is generated using Tektronix Plot 10 software routines in conjunction with a Tektronix 4014/15 graphic terminal. The program should be easily adapted to and can be executed on any host computer with this graphics package and remote terminal.

A simplified flow diagram of the momentum wheel sizing program is shown in figure 1.

**Inputs and Assumptions**

The user provides the following inputs: spacecraft environmental disturbance torques, rotational inertias, maneuver rates, orbit altitudes and inclination, vehicle orientation, and celestial orientation. These inputs are provided as outputs from two other Langley Research Center Computer-Aided Spacecraft Design programs, (1) the Spacecraft Design and Cost Model (SDCM), reference 1, and (2) the Large Area Space System (LASS), reference 2. The orbital equations of motion were obtained from reference 3. The relationship between the orbital reference frames and the vehicle reference frames is shown in figure 2. The input parameters are:

**INOSE - Vehicle Pointing Orientation**
1. Sideways
2. Nose Down
3. Nose Forward

**ISATOR - Celestial Orientation**
1. Earth
2. Solar
3. Inertial

**XNNN - Number of Gimbled Configurations for CMG**

**A - Apoapsis Altitude**

**P - Periapsis Altitude**

**ORBINC - Orbit Inclination**

**TL - Number of Orbits Between Wheel Unloading**

**TACCEL - Maneuver Acceleration Time**
PDOTR \[ \{X \} \] - X-, Y-, Z-Axis Spacecraft Maneuver Rate

UPSILN - Angular Pivoting for DMCD

TA \[ \{X \} \] - X-, Y-, Z-Axis Atmospheric Disturbance Torque

TG \[ \{X \} \] - X-, Y-, Z-Axis Gravity Gradient Disturbance Torque

TS \[ \{X \} \] - X-, Y-, Z-Axis Solar Disturbance Torque

\[ \{X \} J \] - X-, Y-, Z-Axis Spacecraft Rotational Inertia

A major assumption of the program is that the X-axis is the spin axis while the Y- and Z-axes are transverse. Also, the spacecraft's orbit may be either circular or elliptical. Although all the momentum control wheels are normally the same size, the X-, Y-, and Z-axes momentum absorption requirements are not identical, therefore, it is necessary to determine the wheel weight for the axis with the largest momentum absorption requirement.

**Orbit Analysis**

The first step of the orbit analysis portion of the program is to analyze the ellipse representing the orbit, as shown in figure 3.

From the figure, the semimajor axis, \( a \), is calculated by

\[
a = \frac{(2R + A + P)}{2}
\]

The radius at periapsis, \( RP \), is calculated by

\[ RP = R + P \]

the focus of the ellipse, \( c \), is calculated by

\[ c = a - RP \]
and the eccentricity, \( e \), is calculated by

\[
e = \frac{c}{a}
\]

where \( R \) is the radius of the Earth.

In the case of a circular orbit, the semimajor axis becomes the circle's radius which is also the radius at periapsis.

\[
a = RP
\]

This forces both the focus and eccentricity to zero

\[
c = 0
\]

\[
e = 0
\]

The orbital period, \( T \), is then calculated using Kepler's 3/2 Law

\[
T = \frac{2a^{3/2}}{\sqrt{u}}
\]

where \( u \) is Earth's gravitational constant.

The mean orbital motion, \( N \), is calculated using

\[
N = \sqrt{\frac{u}{a^3}}
\]

and the eccentric anomaly, \( E \), by

\[
E = N + c \sin (N) + \frac{1}{2} e^2 \sin (2N)
\]

In the case of a circular orbit, the last two terms of the preceding equation are forced to zero and the eccentric anomaly becomes

\[
E = N
\]
Using the above calculations, the maximum orbital angular rate of change, $\dot{\theta}$, which is at perigee, is determined from

$$\dot{\theta} = \frac{N\sqrt{1-e^2}}{[1-e\cos(E)]^2}$$

For a circular orbit, the maximum rate of change is the mean orbital motion such that

$$\dot{\theta} = N$$

**Total Momentum**

To calculate the total momentum in each of the three spacecraft's body axes, three different momentums are taken into account: (1) maneuver momentum, (2) environmental disturbance torque momentum, and (3) orientation tracking momentum.

The maneuver momentums, $H_{XMAN}$, $H_{YMAN}$, and $H_{ZMAN}$, in all three axes are calculated using the following equations:

$$H_{XMAN} = \frac{XJ(\text{PDOTRX})}{57.3}$$

$$H_{YMAN} = \frac{YJ(\text{PDOTRY})}{57.3}$$

$$H_{ZMAN} = \frac{ZJ(\text{PDOTRZ})}{57.3}$$

To compute the disturbance torque momentum, the total disturbance torques, $XDT$, $YDT$, and $ZDT$, are first calculated by summing the atmospheric, solar, and gravity gradient torques by

$$XDT = T_{AX} + T_{SX} + T_{GX}$$

$$YDT = T_{AY} + T_{SY} + T_{GY}$$

$$ZDT = T_{AZ} + T_{SZ} + T_{GZ}$$
Using these totals, the disturbance torques, $HTX$, $HTY$, and $HTZ$, are then computed using

$$HTX = XDT (TL) (T)$$

$$HTY = YDT (TL) (T)$$

$$HTZ = ZDT (TL) (T)$$

To compute the orientation tracking momentums, $HTRAKX$, $HTRAKY$, and $HTRAKZ$, the program first determines whether the spacecraft is solar oriented, inertial oriented, or Earth oriented. If the spacecraft is either solar or inertially oriented, there is no orientation tracking momentum and the following assignments are made:

$$HTRAKX = 0.0$$

$$HTRAKY = 0.0$$

$$HTRAKZ = 0.0$$

If the spacecraft is Earth oriented, the program will determine whether its body axis is sideways, nose down, or nose forward with respect to the orbital velocity vector (fig. 2). The following assignments are made if its body axis is

1. **Sideways:**
   - $HTRAKX = XJ(\dot{\theta})$
   - $HTRAKY = 0.0$
   - $HTRAKZ = 0.0$

2. **Nose down:**
   - $HTRAKX = 0.0$
   - $HTRAKY = YJ(\dot{\theta})$
   - $HTRAKZ = 0.0$

3. **Nose forward:**
   - $HTRAKZ = 0.0$
   - $HTRAKY = YJ(\dot{\theta})$
   - $HTRAKZ = 0.0$

The total momentum in each axis is computed by summing the maneuver, disturbance torque, and orientation tracking momentums.
Control Device's Momentum Absorption Requirements

The momentum absorption requirements for the reaction wheel, CMG, and DMCD are calculated to determine the wheel weight. The maximum momentum in any axis, $H_{MAX}$, is used for the calculation of nongimbled reaction wheel weight. Using an intrinsic FORTRAN function, $H_{MAX}$ is determined by

$$H_{MAX} = \text{AMAX1} \left( H_X, H_Y, H_Z \right)$$

Here $H_{MAX}$ will be assigned the largest value between $H_X$, $H_Y$, and $H_Z$. To compute the CMG momentum for computing wheel weight, the minimum momentum in any axis, $H_{MIN}$, is first calculated using another intrinsic FORTRAN function

$$H_{MIN} = \text{AMIN1} \left( H_X, H_Y, H_Z \right)$$

Here $H_{MIN}$ will be assigned the smallest value between $H_X$, $H_Y$, and $H_Z$. From this, the CMG slew angle, $\Gamma$, is calculated from

$$\Gamma = \tan^{-1} \left( \frac{H_{MIN}}{(XNNN) H_{MAX}} \right)$$

Then using the preceding $H_{MIN}$ and $\Gamma$ calculations, the CMG wheel momentum, $H_{CMG}$, is calculated using

$$H_{CMG} = \frac{H_{MIN}}{(XNNN) \sin(\Gamma)}$$

The peak gimble rate, $\Delta\dot{\theta}$, is computed by

$$\Delta\dot{\theta} = \frac{H_{CMG}}{57.3 \times \text{TACCEL}}$$
and the peak torquer torque, $TCMG$, by

$$TCMG = \frac{(HCMG) \text{AMAX1 } (PdotRX, PdotRY, PdotRZ)}{57.3}$$

To compute the DMCD momentum for computing wheel weight, the spin and transverse axis momentum absorption requirements must be calculated. The DMCD configuration for both the spin and transverse axes is shown in figure 4.

The spin axis absorption momentum, $DELTHU$, is calculated by

$$DELTHU = \frac{HX}{2}$$

and the transverse axis absorption momentum by

$$HU = \frac{\text{AMAX1 } (HY, HZ)}{2 \left( \frac{\text{UPSLN}}{2} \right)}$$

From these calculations, the total DMCD wheel momentum, $HTDMCD$, is computed by summing the spin and transverse axes absorption momentums

$$HTDMCD = DELTHU + HU$$

Wheel Weight

The final step of the program is to calculate the wheel weight. The wheel mass is calculated from the relationship between the rotational inertia of the wheel and its radius,

$$I = MR^2$$

Since the angular momentum, $L$, is equal to the rotational inertia of the wheel, $I$, multiplied by its angular velocity (wheel speed),

$$L = I\omega$$
Then

\[ L = MR^2 \omega \]

and

\[ M = \frac{L}{R^2 \omega} \]

For a solid cylinder:

\[ I = \frac{MR^2}{2} \]

and

\[ L = \frac{MR^2}{2} \omega \]

and

\[ M = \frac{2L}{R^2 \omega} \]

Finally, for an annular cylinder

\[ I = M \frac{R_1^2 + R_2^2}{2} \]

and

\[ L = M \frac{R_1^2 + R_2^2}{2} \omega \]

and

\[ M = \frac{2L}{\omega(R_1^2 + R_2^2)} \]
where \( R_1 \) is the wheel's inner radius and \( R_2 \) is the outer radius. The acceleration of gravity, \( ACC \), at the spacecraft's altitude is then calculated by

\[
ACC = \frac{u}{R^2_p^2}
\]

The wheel masses are next multiplied by the acceleration of gravity to determine the wheel weight at the spacecraft's altitude. Thus, the equations used in computing wheel weight are

1. For a hoop \( W = \frac{L \cdot (ACC)}{R^2 \cdot \omega} \)

2. For a solid cylinder \( W = \frac{2L \cdot (ACC)}{R^2 \cdot \omega} \)

3. For an annular cylinder \( W = \frac{2L \cdot (ACC)}{\omega \left( R_1^2 + R_2^2 \right)} \)

**Trade-Off and Output**

Calculated wheel weight curves are shown in figures 5 through 7 for wheel radii varying from 1 inch (2.54 cm) to 10 inches (25.4 cm) and wheel speeds of 500 to 5000 rpm's in increments of 500 rpm's to illustrate the trade-off potential between weight, radius, and wheel speed. Weights of hoop, solid cylinder, and annular cylinder momentum wheels are presented for the nongimbled, CMG, and DMCD systems. Calculations were made in U.S. Customary Units. Conversion factors for values used in this report are given in table 1. The program's input default values, which were used to generate the weight curves (figs. 5 to 7), are given in figure 8.

In addition to the weight curves, values of 22 calculated parameters are outputted, including the maximum torque in any axis which is calculated by

\[
T_{MAX} = \frac{A_{MAX1 \text{ (HXMAN, HYMAN, HZMAN)}}}{T_{ACCEL} + A_{MAX1 \text{ (XDT, YDT, ZDT)}}}
\]
These other calculated parameters are

RP - Radius at periapsis

\( \dot{\theta} \) - Maximum orbital rate of change

T - Orbital period

\[
H \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \text{ MAN} - X-, Y-, Z-axis maneuver momentum
\]

\[
HT \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - X-, Y-, Z-axis disturbance torque momentum
\]

\[
HTRAK \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - X-, Y-, Z-axis orientation tracking momentum
\]

\[
H \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - X-, Y-, Z-axis total momentum
\]

HMAX - Maximum momentum, any axis

HCMG - CMG wheel momentum

HTDMCD - DMCD wheel momentum

DELDOT - Peak gimble rate

TCMG - Peak torquer torque

TMAX - Maximum torque in any axis

Calculated values of the output parameters are given in figure 9 for the weight curves illustrated.
CONCLUDING REMARKS

An interactive computer program has been developed at the Langley Research Center to size momentum wheels for various momentum storage and control devices for orbiting spacecraft. The program considers hoop, solid cylinder, and annular cylinder wheels.

Wheel weights are calculated and are shown for a series of wheel radii and wheel rotational speeds. Intermediate calculated parameters are also presented.
APPENDIX

MOMENTUM WHEEL SIZING PROGRAM

The momentum wheel sizing program listing is given in this appendix.

```plaintext
PROGRAM WHEEL(INPUT,OUTPUT,TAPE1,TAPE2,TAPE3)
REAL N
COMMON INPUT,LOC,REAL,EXP
COMMON /WEIR/ WEIGHT,WEIGH2,WEIGH3,WEIGH4,WEIGH5,
*WEIGH6,WEIGH7,WEIGH8,WEIGH9,WEIGH0,R
COMMON /URPI/U,RP,PI
DIMENSION R(122),WEIGH1(122),WEIGH2(122)
DIMENSION WEIGH3(122),WEIGH4(122),WEIGH5(122)
DIMENSION WEIGH6(122),WEIGH7(122),WEIGH8(122)
DIMENSION WEIGH9(122),WEIGH0(122)
DIMENSION LOC(5),REAL(9),EXP(12),INPUT(277)
C RADIUS OF EARTH
DATA RE/3441.66/
C EARTH'S GRAVITATIONAL CONSTANT
DATA U/1.407850464E16/
DATA PI/3.141592654/
DATA WEIGHT(1),WEIGH2(1),WEIGH3(1),WEIGH4(1),WEIGH5(1),
*WEIGH6(1),WEIGH7(1),WEIGH8(1),WEIGH9(1),WEIGH0(1),
*R(1)/11*101./
CALL INITT(120)
CALL FEET(RE)
20 PRINT *,"ENTER 1 FOR DEFAULT VALUES"
PRINT *,"ENTER 2 FOR VALUES FROM LAST RUN"
PRINT *,"ENTER 3 FOR PERMANENTLY SAVED VALUES"
PRINT *,"ENTER 4 TO STOP"
READ *,IVALUE
PRINT 5025
IF (IVALUE.EQ.1) GOTO 40
IF (IVALUE.EQ.2) GOTO 60
IF (IVALUE.EQ.3) GOTO 70
IF (IVALUE.EQ.4) GOTO 999
GOTO 20
40 READ (1,5000) (LOC(J),J=1,3)
READ (1,5005) (REAL(J),J=1,9)
READ (1,5010) (EXP(J),J=1,12)
READ (1,5015) (INPUT(J),J=1,277)
RENEW 1
CALL REPLACE
GOTO 80
60 READ (2,5000) (LOC(J),J=1,3)
READ (2,5005) (REAL(J),J=1,9)
READ (2,5010) (EXP(J),J=1,12)
READ (2,5015) (INPUT(J),J=1,277)
RENEW 2
```

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APPENDIX

CALL REPLACE
GOTO 80
70 READ (3,5000) (LOC(J),J=1,3)
READ (3,5005) (REAL(J),J=1,9)
READ (3,5010) (EXP(J),J=1,12)
READ (3,5015) (INPUT(J),J=1,277)
REWIND 3
CALL REPLACE
80 INOSE= LOC(1)
ISATOR= LOC(2)
XIII= LOC(3)
APOA= REAL(1)
PER= REAL(2)
ORBINC= REAL(3)
TL= REAL(4)
TACCEL= REAL(5)
PDOTRX= REAL(6)
PDOTRY= REAL(7)
PDOTRZ= REAL(8)
UPSIH= REAL(9)
TAX= EXP(1)
TGX= EXP(2)
TSX= EXP(3)
TAY= EXP(4)
TGY= EXP(5)
TSY= EXP(6)
TAZ= EXP(7)
TGZ= EXP(8)
TSZ= EXP(9)
XJ= EXP(10)
YJ= EXP(11)
ZJ= EXP(12)
WRITE (2,5000) (LOC(J),J=1,3)
WRITE (2,5005) (REAL(J),J=1,9)
WRITE (2,5010) (EXP(J),J=1,12)
WRITE (2,5015) (INPUT(J),J=1,277)
REWIND 2
PRINT *, "DO YOU WANT TO SAVE NEW VALUES PERMANENTLY?"
PRINT *, "ENTER 1 FOR YES"
PRINT *, "ENTER 2 FOR NO"
READ *,JOE
PRINT 5040
IF (JOE.EQ.1) 90,95
90 WRITE (3,5000) (LOC(J),J=1,3)
WRITE (3,5005) (REAL(J),J=1,9)
WRITE (3,5010) (EXP(J),J=1,12)
WRITE (3,5015) (INPUT(J),J=1,277)
REWIND 3
95 CALL FEET(APOA)
CALL FEET(PER)
APPENDIX

C COMPUTE SEMIMAJOR AXIS OF ELLIPSE
A = (2.*RE+APOA+PER)*0.5

C COMPUTE ORBITAL PERIOD
T = 2.*PI*A**(1.5)/SQRT(U)

C COMPUTE RADIUS OF PERIAPSIS
RP = RE+PER

C COMPUTE FOCUS OF ELLIPSE
C = A-RP

C COMPUTE ECCENTRICITY
ECC = C/A

C COMPUTE MEAN ORBITAL MOTION
N = SQRT(U/A**3)

C COMPUTE ECCENTRIC ANOMALLY
E = N+ECC*SIN(H)+0.5*ECC**2*SIN(2*H)

C COMPUTE MAX ORBITAL ANGULAR RATE
THETAD = (N*SQR(1.-ECC**2))/((1.-ECC*COS(E))**2)

C COMPUTE MOMENTUM REQUIREMENTS FOR SIZING NON-GIMBALLED

C MOMENTUM WHEELS

C MANEUVER MOMENTUM
HXMAH = XJ*PDOTRX/57.3
HYMAH = YJ*PDOTRY/57.3
HZMAH = ZJ*PDOTRZ/57.3

C COMPUTE DISTURBANCE TORQUES
XDT = TAX+TGX+TSX
YDT = TAY+TGY+TSY
ZDT = TAZ+TGY+TSZ

C COMPUTE DISTURBANCE TORQUE MOMENTUM
HTX = XDT*TL*T
HTY = YDT*TL*T
HTZ = ZDT*TL*T

C COMPUTE ORIENTATION TRACKING MOMENTUM REQUIREMENTS
GOTO (120,100,100) ISATOR

C INERTIAL AND SOLAR ORIENTATION

100 HTRAKX = 0.0
HTRAKY = 0.0
HTRAKZ = 0.0
GOTO 200

C EARTH ORIENTATION
120 GOTO (140,160,180) INOSE

C SIDWAYS
140 HTRAKX = XJ*THETAD
HTRAKY = 0.0
HTRAKZ = 0.0
GOTO 200

C NOSE DOWN
160 HTRAKX = 0.0
HTRAKY = YJ*THETAD
HTRAKZ = 0.0
GOTO 200

C NOSE FORWARD
APPENDIX

180 HTRAKX= 0.0
HTRAKY= YJ*THETAD
HTRAKZ= 0.0
C COMPUTE TOTAL MOMENTUM PER ORBIT
200 HX= (HXMN+HTX+HTRAX)
HY= (HYIN+HTY+HTRAY)
HZ= (HZMN+HTZ+HTRAZ)
C COMPUTE MAX MOMENTUM ANY AXIS
HMAX= AMAX1(HX,HY,HZ)
C COMPUTE MAX TORQUE ANY AXIS
TMAX= AMAX1((HXMN,HYIN,HZMN+HYIN)/(TACCEL+AMAX1(XDT,YDT,ZDT))
C COMPUTE MINIMUM MOMENTUM
HMIN= AMIN1(HX,HY,HZ)
C COMPUTE SKEW ANGLE
GAMMA= ATAN((XMINN-2.)*HMIN/(XMINN*HMAX))
C COMPUTE CMG WHEEL MOMENTUM
HC MG= HMIN/(XMINN*sin(GAMMA))
C COMPUTE PEAK GIMBLE RATE
DELTDOT= HC MG/TACCEL*57.3
C COMPUTE PEAK TORQUER TORQUE
TCMG= HC MG*AMAX1(PDOTRX,PDOTRY,PDOTRZ)/57.3
C COMPUTE SPIN AXIS ABSORPTION REQUIREMENT
DELTHU= nX/2.
C COMPUTE TRANSVERSE AXIS ABSORPTION REQUIREMENT
HU= AMAX1(HX,HZ)/(2.*UPSILN/57.3)
C COMPUTE TOTAL DRCD WHEEL MOMENTUM
HTDCHD= DELTHU+HU
PRINT 5030,(INPUT(J),J=163,167),APOA
PRINT 5030,(INPUT(J),J=160,172),RP
PRINT 5030,(INPUT(J),J=173,177),THETAD
PRINT 5030,(INPUT(J),J=178,182),T
PRINT 5025
PRINT 5035,(INPUT(J),J=273,277)
PRINT 5025
PRINT 5030,(INPUT(J),J=183,187),HXMN
PRINT 5030,(INPUT(J),J=188,192),HYIN
PRINT 5030,(INPUT(J),J=193,197),HIZN
PRINT 5025
PRINT 5030,(INPUT(J),J=198,202),HTX
PRINT 5030,(INPUT(J),J=203,207),HTY
PRINT 5030,(INPUT(J),J=208,212),HTZ
PRINT 5025
PRINT 5030,(INPUT(J),J=213,217),HTRAX
PRINT 5030,(INPUT(J),J=218,222),HTRAY
PRINT 5030,(INPUT(J),J=223,227),HTRAZ
PRINT 5025
PRINT 5030,(INPUT(J),J=228,232),HX
PRINT 5030,(INPUT(J),J=233,237),HY
PRINT 5030,(INPUT(J),J=238,242),HZ
PRINT 5025

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PRINT 5030, (INPUT(J), J=243, 247), IIMAX
PRINT 5030, (INPUT(J), J=248, 252), TMAX
PRINT 5030, (INPUT(J), J=253, 257), HCMG
PRINT 5025
PRINT 5030, (INPUT(J), J=258, 262), DELDOT
PRINT 5030, (INPUT(J), J=263, 267), TCMG
PRINT 5030, (INPUT(J), J=268, 272), HTDMD
PRINT 5040
REWIND 3
220 PRINT *, "DO YOU WANT WHEEL SPEED, SIZE AND WEIGHT PLOT?"
PRINT *, "ENTER 1 FOR NON-GIMBLED PLOT"
PRINT *, "ENTER 2 FOR CMG PLOT"
PRINT *, "ENTER 3 FOR DMCD PLOT"
PRINT *, "ENTER 4 FOR NO PLOT"
READ *, IPLOT
IF (IPLOT.LT.1. OR. IPLOT.GT.4) GOTO 220
GOTO (240, 260, 280, 20) IPLOT
240 CALL STUFF(HMAX, 1)
GOTO 220
260 CALL STUFF(HCMG, 2)
GOTO 220
280 CALL STUFF-HTDMCD, 3)
GOTO 220
999 CALL FITT(0, 700)
5000 FORMAT (5I5)
5005 FORMAT (5F10.3)
5010 FORMAT (5E10.4)
5015 FORMAT (9(4A10, A5/), 9(5A10/), 12(6A10/), 23(5A10/))
5020 FORMAT (5F5.2)
5025 FORMAT (1X)
5030 FORMAT (5A10, E14.7)
5035 FORMAT (6A10)
5040 FORMAT (///)
STOP
END

C

SUBROUTINE USED TO CHANGE PLOT AXES VALUES

SUBROUTINE CHANGE(XVALUE, YVALUE, XMIN, XMAX, YMIN, YMAX, JJ)
INTEGER XVALUE, YVALUE
5 PRINT *, "DO YOU WANT NEW GRAPH?"
PRINT *, "IF YES ENTER 1"
PRINT *, "IF NO ENTER 2"
READ *, JJ
IF (JJ.EQ.1) 20, 10
10 IF (JJ.EQ.2) 120, 5
20 PRINT *, "DO YOU WANT TO CHANGE AXIS MAX AND MIN VALUES"
PRINT *, "IF YES ENTER 1"
PRINT *, "IF NO ENTER 2"
READ *, JJ
APPENDIX

IF (II.EQ.1) 40,80
40 PRINT *,"ENTER X-AXIS MIN AND MAX VALUE"
READ *,XMIN,XMAX
IF (XMIN.EQ.0.0.OR.XMIN.GE.XMAX) GOTO 40
IF (XMIN.NE.1.0.OR.XMAX.NE.10.0) JJ=1
60 PRINT *,"ENTER Y-AXIS MIN AND MAX VALUE"
READ *,YMIN,YMAX
IF (YMIN.GE.YMAX) GOTO 60
80 PRINT *,"DO YOU WANT TO CHANGE # OF INTERVALS"
PRINT *,"IF YES ENTER 1"
PRINT *,"IF NO ENTER 2"
READ *,KK
IF (KK.EQ.1) 100,120
100 PRINT *,"ENTER # OF X-AXIS INTERVALS"
READ *,XVALUE
PRINT *,"ENTER # OF Y-AXIS INTERVALS"
READ *,YVALUE
120 RETURN

SUBROUTINE USED TO PLOT CURVES

SUBROUTINE STUFF (ANGHOM,JJJ)
INTEGER RPH,XVALUE,YVALUE
DIMENSION WEIGHT1(122),WEIGHT2(122),WEIGHT3(122),WEIGHT4(122)
DIMENSION WEIGHT5(122),WEIGHT6(122),WEIGHT7(122),WEIGHT8(122)
DIMENSION WEIGHT9(122),R(122),WEIGHT2(122),WEIGHT3(122),WEIGHT4(122)
DIMENSION ARRAY(10)
COMMON /WEIGHT1, WEIGHT2, WEIGHT3, WEIGHT4, WEIGHT5, WEIGHT6,
* WEIGHT7, WEIGHT8, WEIGHT9, R
COMMON /URPI/ U,RP,PI
XMIN= 1.0
XMAX= 10.0
YMIN= 0.0
YMAX= 5.0
XVALUE= 9
YVALUE= 5
20 PRINT *,"DO YOU WANT WHEEL PLOT FOR:"
PRINT *,"1- HOOP"
PRINT *,"2- SOLID CYLINDER"
PRINT *,"3- ANNULAR CYLINDER"
READ *,M
IF (M.LT.1.OR.M.GT.3) 20,40
40 IF (M.EQ.3) 60,80
60 PRINT *,"ENTER THICKNESS OF ANNULAR CYLINDER IN INCHES"
READ *,THICK
30 I=1
ZNUM= (XMAX-XMIN)/100.
RADIUS= XMIN
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IF (M.EQ.3) 100,140
100   DO 120 J=2,102
      R(J)= RADIUS
      R1(J)= RADIUS+THICK
      RADIUS= RADIUS+ZNUM
   120 CONTINUE
      GOTO 180
140   DO 160 J=2,102
      R(J)= RADIUS
      R1(J)= 0.0
      RADIUS= RADIUS+ZNUM
   160 CONTINUE
180   ACC= U/RP**2
   IF (M.EQ.1) 200,220
200   HUMACC= ANGMOM*ACC
      GOTO 240
220   HUMACC= 2.*ANGMOM*ACC
240   DO 480 RPM= 500,5000,500
      OMEGA= RPM/60.*2.*PI
   DO 460 J=2,102
      GOTO (260,280,300,320,340,360,380,400,420,440) I
260   WEIGH1(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
280   WEIGH2(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
300   WEIGH3(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
320   WEIGH4(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
340   WEIGH5(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
360   WEIGH6(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
380   WEIGH7(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
400   WEIGH8(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
420   WEIGH9(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
      GOTO 460
440   WEIGH0(J)= HUMACC/(OMEGA*(R(J)**2+R1(J)**2))
   460 CONTINUE
      I= I+1
480 CONTINUE
490 CALL BINIT
      CALL SLIMY(155,730)
      CALL SLIMX(170,920)
      CALL XTICS(XVALUE)
      CALL YTICS(YVALUE)
      CALL XNEAT(0)
      CALL YNEAT(0)
APPENDIX

CALL NEWPAG
CALL NOTX(5,500,5,5H WHEEL)
CALL NOTX(0,485,6,6HEIGHT)
CALL NOTX(0,470,4,4H(LEX))
CALL NOTX(440,60,17,17H WHEEL RADIUS (IN))
CALL NOTX(370,0,36,36HRPH'S VARY FROM 500 TO 5000 STEP 500)
GOTO (500,520,540) JJ

500 CALL NOTX(445,30,16,16H NON-GIMBLED PLOT)
   GOTO 560

520 CALL NOTX(480,30,8,8HCMG PLOT)
   GOTO 560

540 CALL NOTX(470,30,9,9HDMCD PLOT)
560 GOTO (580,600,620) JJ
580 CALL NOTX(490,15,4,4HINDP)
   GOTO 640

600 CALL NOTX(450,15,14,14H SOLID CYLINDER)
   GOTO 640

620 CALL NOTX(350,15,28,28HANNULAR CYLINDER: THICKNESS-)
   CALL NOTX(650,15,6,6H INCHES)
   CALL FFORN(TTHICK,5,2,1ARRAY,32)
   CALL NOTAT(600,15,5,1ARRAY)

640 CALL DLIMX(XMIN,XMAX)
   CALL DLINY(YMIN,YMAX)
   CALL CHECK(R,WEIGHT1)
   CALL DISPLAY(R,WEIGHT1)
   CALL CPLLOT(R,WEIGHT2)
   CALL CPLLOT(R,WEIGHT3)
   CALL CPLLOT(R,WEIGHT4)
   CALL CPLLOT(R,WEIGHT5)
   CALL CPLLOT(R,WEIGHT6)
   CALL CPLLOT(R,WEIGHT7)
   CALL CPLLOT(R,WEIGHT8)
   CALL CPLLOT(R,WEIGHT9)
   CALL CPLLOT(R,WEIGHT10)
   CALL HOME
   CALL EPAUSE
   CALL CHANGE(XVALUE,YVALUE,XMIN,XMAX,YMIN,YMAX,JJ)
   IF (JJ.EQ.2) RETURN
   IF (JJ.EQ.3) GOTO 490
   GOTO 80
END

C
SUBROUTINE USED TO CHANGE NAUTICAL MILES TO FEET
C
SUBROUTINE FEET (CHANGE)
CHANGE= CHANGE*6076.103
RETURN
END
C

20
SUBROUTINE USED TO DISPLAY INPUTS

SUBROUTINE REPLACE
COMMON INPUT,LOC,REAL,EXP
DIMENSION LOC(5),REAL(9),EXP(12),INPUT(277)

20 PRINT 5000,INPUT(1),INPUT(2),INPUT(3),
*INPUT(4),INPUT(5),LOC(1)
DO 40 J=6,20,5
PRINT 5015,INPUT(J),INPUT(J+1),INPUT(J+2),
*INPUT(J+3),INPUT(J+4)
40 CONTINUE
PRINT 5005,INPUT(21),INPUT(22),INPUT(23),
*INPUT(24),INPUT(25),LOC(2)
DO 60 J=26,40,5
PRINT 5015,INPUT(J),INPUT(J+1),INPUT(J+2),
*INPUT(J+3),INPUT(J+4)
60 CONTINUE
PRINT 5010,INPUT(41),INPUT(42),INPUT(43),
*INPUT(44),INPUT(45),LOC(3)
80 PRINT 5020
READ *,CHECK
PRINT 5035
IF (CHECK.EQ.1) GOTO 120
IF (CHECK.EQ.2) 100,30
100 CALL ONE
PRINT 5035
GOTO 20
120 II= 46
DO 140 J=1,9
PRINT 5025,J,INPUT(II),INPUT(II+1),INPUT(II+2),
*INPUT(II+3),INPUT(II+4),REAL(J)
II= II+5
140 CONTINUE
160 PRINT 5020
READ *,CHECK
PRINT 5035
IF (CHECK.EQ.1) GOTO 200
IF (CHECK.EQ.2) 180,160
180 CALL TWO
PRINT 5035
GOTO 120
200 II= 91
DO 220 J=1,12
PRINT 5030,J,INPUT(II),INPUT(II+1),INPUT(II+2),
*INPUT(II+3),INPUT(II+4),INPUT(II+5),EXP(J)
II= II+6
220 CONTINUE
240 PRINT 5020
READ *,CHECK
PRINT 5035
APPENDIX

IF (CHECK.EQ.1) GOTO 280
IF (CHECK.EQ.2) 260,240

260 CALL THREE
PRINT 5035
GOTO 200

280 RETURN

5000 FORMAT (1X,"1",1X,4A10,A5,I3)
5005 FORMAT (1X,"2",1X,4A10,A5,I3)
5010 FORMAT (1X,"3",1X,4A10,A5,I3)
5015 FORMAT (3X,4A10,A5)
5020 FORMAT (1X,1X,"IF INPUTS OK ENTER 1",/1X,"IF WANT TO CHANGE",
     **" ENTER 2")
5025 FORMAT (I2,1X,5A10,F10.3)
5030 FORMAT (I2,1X,6A10,E10.4)
5035 FORMAT (1X

END

C
SUBROUTINE USED TO CHANGE INTEGER INPUTS

SUBROUTINE ONE
COMMON INPUT,LOC,REAL,EXP
DIMENSION LOC(5),REAL(9),EXP(12),INPUT(277)
20 PRINT *,"ENTER NUMBER, NEW VALUE (INTEGER)"
40 READ *,NUM,IVALUE
IF (NUM.EQ.0) RETURN
IF ((NUM.EQ.1.OR.NUM.EQ.2).AND.(IVALUE.LT.1.OR.IVALUE.GT.3))
   GOTO 20
IF (NUM.LT.1.OR.NUM.GT.3) GOTO 20
LOC(NUM)= IVALUE
GOTO 40
RETURN

C
SUBROUTINE USED TO CHANGE REAL INPUTS

SUBROUTINE TWO
COMMON INPUT,LOC,REAL,EXP
DIMENSION LOC(5),REAL(9),EXP(12),INPUT(277)
20 PRINT *,"ENTER NUMBER, NEW VALUE (REAL)"
40 READ *,NUM,VALUE
IF (NUM.EQ.0) RETURN
IF (NUM.LT.1.OR.NUM.GT.9) GOTO 20
REAL(NUM)= VALUE
GOTO 40
RETURN
APPENDIX

SUBROUTINE USED TO CHANGE EXP. INPUTS

C
C
SUBROUTINE THREE
COMMON INPUT,LOC,REAL,EXP
DIMENSION LOC(5),REAL(9),EXP(12),INPUT(277)
20 PRINT *,"ENTER NUMBER, NEW VALUE (EXP)"
PRINT *,"ENTER 0,0. TO STOP"
40 READ *,NUM,VALUE
IF (NUM.EQ.0) RETURN
IF (NUM.LT.1.OR.NUM.GT.12) GOTO 20
EXP(NUM)= VALUE
GOTO 40
RETURN
END
REFERENCES


### TABLE I. CONVERSION FACTORS FROM U.S. CUSTOMARY TO S.I. UNITS

<table>
<thead>
<tr>
<th>Customary Unit</th>
<th>Metric Unit</th>
</tr>
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<tbody>
<tr>
<td>1 inch</td>
<td>2.54 centimeters</td>
</tr>
<tr>
<td>1 foot</td>
<td>0.305 meters</td>
</tr>
<tr>
<td>1 mile</td>
<td>1.61 kilometers</td>
</tr>
<tr>
<td>1 pound (wt)</td>
<td>4.95 newtons = 0.454 kilograms</td>
</tr>
<tr>
<td>1 foot-pound</td>
<td>1.38 newton-meters</td>
</tr>
<tr>
<td>1 slug-foot²</td>
<td>1.36 kilogram-meters²</td>
</tr>
<tr>
<td>1 slug-foot²/seconds</td>
<td>1.36 kilogram-meters²/seconds</td>
</tr>
</tbody>
</table>
Inputs
1. Environmental Disturbance Torques
2. Spacecraft Rotational Inertia
3. Data Specifying Spacecraft's Orbit

Analyze Orbit to Determine Maximum Orbital Rate of Change

Calculate Momentum Due to:
1. Environmental Disturbance Torques
2. Maneuvers
3. Orientation Tracking

Calculate Reaction Wheel, GMC, and DMCD Sizing Requirements

Calculate Weight of Wheel

Plot Wheel Radius versus Wheel Weight for Various Wheel Speeds

Figure 1. Flow diagram.
Figure 2. Relationship between the orbital reference frame and the three vehicle reference frames.
Figure 3. Orbit definition.

Figure 4. DMCD configuration.
Figure 5. Weight curves for nongimbled reaction wheel.
Figure 5. Continued.

(b) Solid cylinder.
(c) Annular cylinder.

Figure 5. Concluded.
Figure 6. Weight curve for CMG.
Figure 6. Continued.

RPM's vary from 500 to 5000 step 500.

(b) Solid cylinder.
Figure 6. Concluded.
Figure 7. Weight curves for DMCD.
(b) Solid cylinder.

Figure 7. Continued.
Figure 7. Concluded.

(c) Annular cylinder.
Figure 8. Input default values.

<table>
<thead>
<tr>
<th>1 INOSE-</th>
<th>VEHICLE POINTING ORIENTATION</th>
</tr>
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<tbody>
<tr>
<td>1= SIDEWAYS</td>
<td></td>
</tr>
<tr>
<td>2= NOSE DOWN</td>
<td></td>
</tr>
<tr>
<td>3= NOSE FORWARD</td>
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</table>

<table>
<thead>
<tr>
<th>2 ISATOR-</th>
<th>CELESTIAL ORIENTATION</th>
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<tbody>
<tr>
<td>1= EARTH</td>
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<tr>
<td>2= SUN</td>
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<tr>
<td>3= INERTIAL</td>
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<table>
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<th>NUMBER OF GIMBALED CONFIGURATIONS</th>
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IF INPUTS OK ENTER 1
IF WANT TO CHANGE ENTER 2

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<table>
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<th>ORBIT INCLINATION (DEG)</th>
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<th>TIME BETWEEN WHEEL UNLOADING (ORBITS)</th>
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<th>X-AXIS MANEUVER RATE (DEG/SEC)</th>
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<tbody>
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<table>
<thead>
<tr>
<th>7 PDOTRY-</th>
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<tbody>
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<table>
<thead>
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IF INPUTS OK ENTER 1
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<th>10 XJ-</th>
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IF INPUTS OK ENTER 1
IF WANT TO CHANGE ENTER 2
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>APOA</td>
<td>APOAPSIS ALTITUDE (FT)</td>
<td>1063318E+07</td>
</tr>
<tr>
<td>RP</td>
<td>RADIUS AT PERIAPSIS (FT)</td>
<td>2151949E+08</td>
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<tr>
<td>THETAD</td>
<td>MAXIMUM ORBITAL ANGULAR RATE (RAD/SEC)</td>
<td>1194795E-02</td>
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<tr>
<td>T</td>
<td>ORBITAL PERIOD (SEC)</td>
<td>5370454E+04</td>
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All momentum in (SLUG-FT**2)/SEC

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<tr>
<th>Symbol</th>
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<tr>
<td>HXMAN</td>
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<tr>
<td>HYMAN</td>
<td>Y-AXIS MANEUVER MOMENTUM</td>
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<td>HZMAN</td>
<td>Z-AXIS MANEUVER MOMENTUM</td>
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<td>HTX</td>
<td>X-AXIS DISTURBANCE TORQUE MOMENTUM</td>
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<td>HTY</td>
<td>Y-AXIS DISTURBANCE TORQUE MOMENTUM</td>
<td>4557093E-02</td>
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<td>HTZ</td>
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<td>HTRAKX</td>
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<tr>
<td>HTRAKY</td>
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<tr>
<td>HX</td>
<td>TOTAL X-AXIS MOMENTUM</td>
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</tr>
<tr>
<td>HY</td>
<td>TOTAL Y-AXIS MOMENTUM</td>
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<tr>
<td>HZ</td>
<td>TOTAL Z-AXIS MOMENTUM</td>
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<td>HMAX</td>
<td>MAXIMUM MOMENTUM ANY AXIS</td>
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<td>TMAX</td>
<td>MAXIMUM TORQUE ANY AXIS (FT-LBS)</td>
<td>1391798E+01</td>
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<tr>
<td>HCMG</td>
<td>CMG WHEEL MOMENTUM</td>
<td>1435261E+02</td>
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<tr>
<td>DELDOT</td>
<td>PEAK GIMBAL RATE (RAD/SEC)</td>
<td>4112024E+02</td>
</tr>
<tr>
<td>TCMG</td>
<td>PEAK TORQUER TORQUE (FT-LBS)</td>
<td>2504819E+00</td>
</tr>
<tr>
<td>HTDMCD</td>
<td>DMCD WHEEL MOMENTUM REQUIR.</td>
<td>5078648E+02</td>
</tr>
</tbody>
</table>

Figure 9. Calculated output values.
An interactive computer program has been developed which computes the sizing requirements for nongimbled reaction wheels, control moment gyros (CMG), and dual momentum control devices (DMCD) used in Earth-orbiting spacecraft. The program accepts as inputs the spacecraft's environmental disturbance torques, rotational inertias, maneuver rates, and orbital data. From these inputs, wheel weights are calculated for a range of radii and rotational speeds. The shape of the momentum wheel may be chosen to be either a hoop, solid cylinder, or annular cylinder. The program provides graphic output illustrating the trade-off potential between the weight, radius, and wheel speed. A number of the intermediate calculations such as the X-, Y-, and Z-axis total momentum, the momentum absorption requirements for reaction wheels, CMG's, DMCD's, and basic orbit analysis information are also provided as program output.

Cooperative education student at Georgia Institute of Technology