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ANALYSIS OF THE XM97 TURRET DYNAMICS
WITH ACTIVE SERVO CONTROL

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A method of analysis has been developed for investigating the dynamic motion of a gun-turret configuration. The analysis allows for elastic coupling between the three main components of the turret and for active servo control system which is also coupled with the turret dynamics. The three main components of the turret are the stationary ring, the rotating ring, and the saddle-gun assembly. The gear systems in the azimuth and the elevation drives are characterized by their gear ratio, elastic stiffness and frictional coefficient. The dynamic equations which govern the motion of the		

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system are reduced to five first order equations which are solved numerically. The forces which cause the system to vibrate are generated by the helicopter structural vibration and by the torques produced by the recoil forces. The helicopter vibration effects are obtained by coupling this analysis with the finite-element analysis of the helicopter structural model. A computer program has been prepared to solve the governing equations. The program has the capability of analyzing both azimuth and elevation motions. The results generated by this program can be used directly in the prediction of hit probability. This analysis has been applied to a number of numerical examples and the results are presented and discussed. (U) Zak, Adam R.

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Introduction

The purpose of the present analysis is to investigate the effect of turret dynamics on the accuracy of gun orientation. In this analysis the turret is represented by three rigid components which can move relative to each other and are connected by elastic transmissions. The first component of the turret is the stationary ring, which is rigidly attached to the helicopter hull. The second component is the rotating ring; its rotation about the turret axis, is controlled by a drive mechanism which is characterized by effective elastic stiffness and a frictional coefficient. The third part of the turret consists of the saddle and the gun combination. This part moves about the saddle pivot axis relative to the rotating ring. This motion is also governed by an elastic transmission drive.

The vibrating motion of the turret is excited by the vibration of the hull and by the torques due to the recoil force of the gun. The effects of the hull vibration will be specified by the six acceleration components at the turret attachment point. These accelerations will be calculated numerically by an existing finite-element model of the total helicopter structure. The recoil forces will be represented by measured values.

When the turret is excited dynamically the relative motion of the various parts will cause the resolver signals to be generated which will activate the servo controls. Consequently, the dynamic motion will be governed by an interaction of the elastic properties of the transmission, the inertial properties of the turret, and the response characteristics of the servo systems. The turret vibration will be specified by two components consisting of the azimuth and the elevation angular displacements. In the present analysis these two motions will be assumed to be uncoupled since they will respond to different frequencies.

The general analysis which is developed will be valid for either the azimuth or the elevation motion. However, the hull inertia effects will be governed by different relations for the azimuth and the elevation modes and therefore these relations will be developed separately. The servo controls for both motions are similar except for the different gear ratios in the drive systems.

Equations of the Turret Dynamics

The three main components of the turret, shown in Figure 1, are the stationary ring, the rotating ring, and the saddle and gun combination. The steady state azimuth and elevation angles are denoted by ϕ and α respectively. The dynamic components corresponding to these two directions are denoted by $\Delta\phi$ and $\Delta\alpha$. The center of gravity positions for moving parts are shown in Figure 1. The center of gravity CG_1 is denoted by the length parameters a_1 and b_1 defined with reference to zero azimuth and elevation angles. The center of gravity CG_1 applies to the total mass involved in the azimuth vibration and it includes the rotating ring and the saddle-gun combination. The center of gravity CG_2 applies to the saddle-gun combination only and it is defined by the lengths a_2 , a_3 , and b_2 . The parameter a_2 defines the pivot position, and a_3 and b_2 define the position of CG_2 .

Since the dynamic equations for the azimuth and the elevation motions will be similar it is possible, up to a point, to derive equations which are valid for either of these motions. Consider a schematic representation shown in Figure 2 which shows the three components involved in the vibration. This schematic applies both to azimuth and elevation modes. The three components in Figure 2 are the drive motor, the gear transmission system, and the turret mass. For convenience the moments of inertia of the motor and the turret are referred to the turret coordinates. The moment of inertia of the gear box and the drive can be included in the motor and the turret inertias. The torques transmitted through the total system are shown in Figure 2. The torque T_m is the torque applied electrically to the motor and T_t is the torque transmitted to the turret. The effect of friction in the system is represented by the torque T_f acting on the turret. The torque T_r represents the contribution of the recoil force. The rates of change of the angular momentum for the motor and the turret are denoted by $\dot{H}_m$ and $\dot{H}_t$ respectively. Using the torques shown in Figure 2 the dynamic equations of equilibrium can be written as follows:

$$\dot{H}_m = T_m - T_t \quad (1)$$

$$\dot{H}_t = T_r + T_t + T_f \quad (2)$$

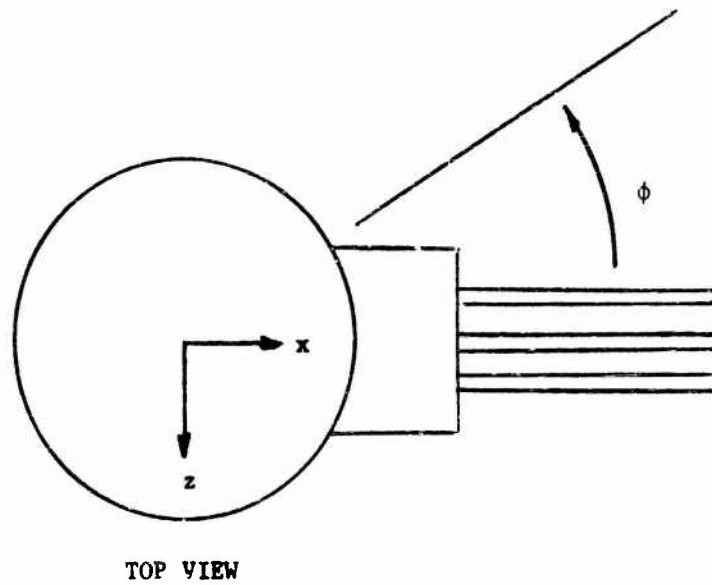
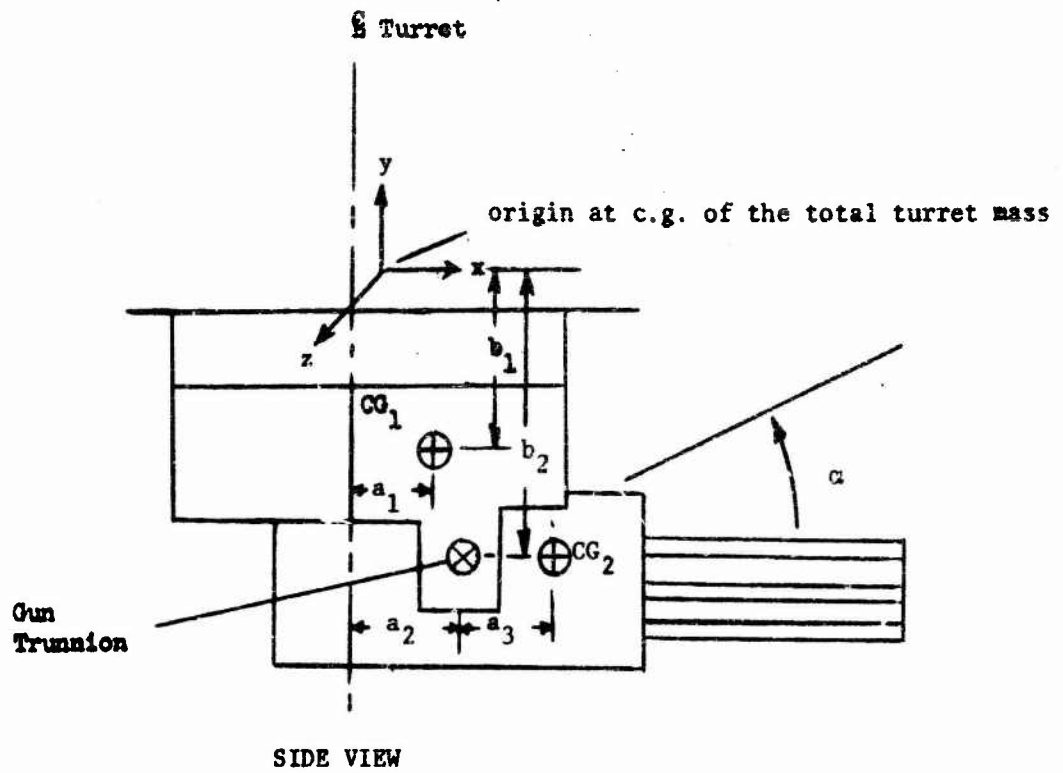


Figure 1. Turret Configuration and the Definition of Azimuth and Elevation Angles.

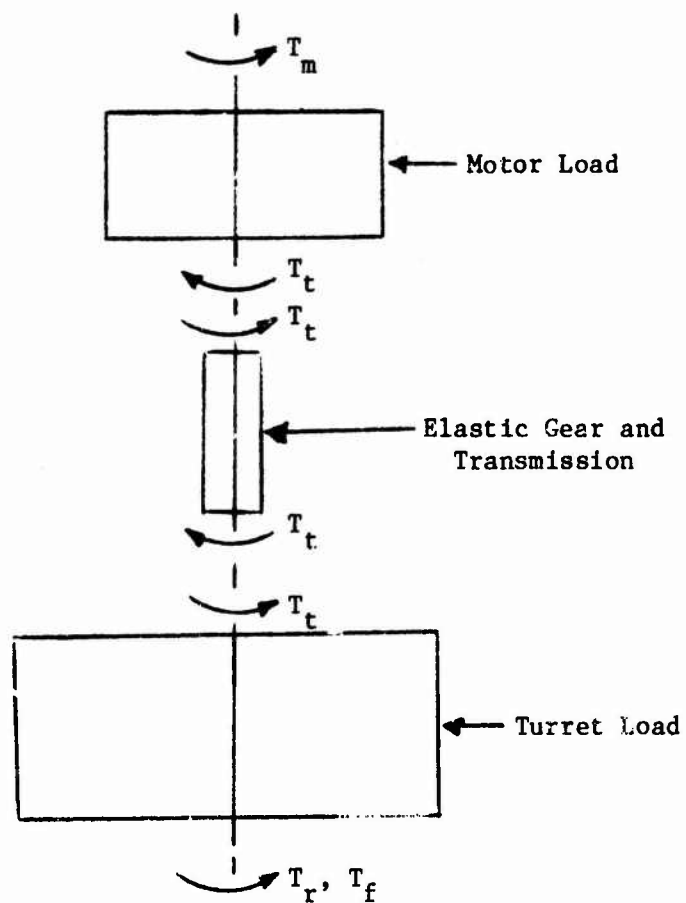


Figure 2. Schematic Drawing Illustrating a Two Degree of Freedom System to Represent Motor, Transmission and Turret Load.

The transmitted torque T_t is related to the elastic deformation of the system. In order to express equations (1) and (2) in terms of displacements the dynamic displacements $\Delta\phi$ and $\Delta\alpha$ are divided into three parts:

$$\Delta\phi = \phi_o + \phi_m + \phi_e \quad (3)$$

$$\Delta\alpha = \alpha_o + \alpha_m + \alpha_e \quad (4)$$

where ϕ_o and α_o are the dynamic components due to helicopter vibration, ϕ_m and α_m are the dynamic motion for rigid gear system drives, and ϕ_e and α_e are the contributions from the elastic effects in the system. It is also convenient at this time to define the relative displacements:

$$\phi_r = \phi_m + \phi_e \quad (5)$$

$$\alpha_r = \alpha_m + \alpha_e \quad (6)$$

The angles ϕ_r and α_r are relative angles between various parts of the turret and these are the angles which will be read by the resolver in the servo control system. It is possible now to represent the torque T_t in equations (1) and (2) in terms of displacements. For the azimuth motion:

$$T_t = -k\phi_e \quad (7)$$

and for the elevation motion:

$$T_t = -k\alpha_e \quad (8)$$

where k represents the elastic stiffness of the gear box and the transmission.

Consider now the torque T_f produced by the friction in the system. Since this term represents a combination of all frictional forces in the system, an exact analysis of this term is not possible and an empirical relation has to be used. In this analysis it will be assumed that this torque acts to oppose relative motion of the various parts of the turret, but since it is a frictional force it will be independent of the magnitude of the angular velocities. Consequently, for the azimuth motion this torque is represented by:

$$T_f = -kg(\dot{\phi}_r)/|\dot{\phi}_r| \quad (9)$$

and for the elevation motion

$$T_f = -kg(\dot{\alpha}_r)/|\dot{\alpha}_r| \quad (10)$$

where g is the damping coefficient.

Consider now the rates of change of angular momentum $\dot{H}_m$ and $\dot{H}_t$ in equations (1) and (2). These relations can be obtained from the vector relation; however, for the present case in which the azimuth and the elevation motions are uncoupled, it is easy to obtain these in scalar form. As the first step we introduce the hull accelerations at the point of the turret attachment. These accelerations are denoted by $a_x, a_y, a_z, \ddot{\theta}_x, \ddot{\theta}_y$ and $\ddot{\theta}_z$. The first three of these quantities are the linear accelerations and the remaining three are the angular accelerations. All these accelerations are relative to the coordinate system shown in Figure 1. Using fixed azimuth and elevation angles ϕ and α and the geometrical parameters shown in Figure 1, moments are taken of the mass inertia force about the axis of rotation; adding the angular rate change of momentum it can be shown that:

$$\dot{H}_t = -m_1 a_1 (a_x \sin \phi + a_z \cos \phi) + I_t \ddot{\Delta\phi} \quad (11)$$

where m is the turret mass at the CG_1 point shown in Figure 1 and I_t is the turret moment of inertia about the turret axis. Consider now the terms containing angular acceleration in equation (11). By using equations (3) and (5) we obtain:

$$\ddot{\Delta\phi} = \ddot{\phi}_o + \ddot{\phi}_r \quad (12)$$

But $\ddot{\phi}_o$ can be related to the hull vibration

$$\ddot{\phi}_o = \ddot{\theta}_y \quad (13)$$

For the motor the predominant rotations will be the relative motor speed and therefore to a good approximation

$$\dot{H}_m = I_m \ddot{\phi}_m \quad (14)$$

where I_m is the moment of inertia of the motor referred to the turret coordinates.

For the case of the elevation vibration the rotational equilibrium equations are referred to the saddle pivot axis. The rate of change of the angular momentum is:

$$\dot{H}_t = m_2 ((a_2 + a_3 \cos \alpha) a_y - (a_x \cos \phi - a_z \sin \phi)(-b_2 + a_3 \sin \alpha)) + I_t \Delta \ddot{\alpha} \quad (15)$$

where m_2 is the mass of the saddle-gun combination and I_t is the moment of inertia about the saddle pivot axis. For the elevation motor it is again possible to neglect all except the motor rotational effects and therefore:

$$\dot{H}_m = I_m \ddot{\alpha}_m \quad (16)$$

Using equations (4) and (6) we can write

$$\Delta \ddot{\alpha} = \ddot{\alpha}_o + \ddot{\alpha}_r \quad (17)$$

and from coordinate transformation we can relate $\ddot{\alpha}_o$ to the hull accelerations:

$$\ddot{\alpha}_o = \ddot{\theta}_x \sin \phi + \ddot{\theta}_z \cos \phi \quad (18)$$

Consider now the azimuth vibration. By using equations (1) and (2) and substituting from (7), (9), (11), (13) and (14) we can write equations of equilibrium in the form:

$$I_m \ddot{\phi}_m - k\phi_e = T_m \quad (19)$$

$$\begin{aligned} I_t \ddot{\phi}_r + k\phi_e + kg\dot{\phi}_r / |\dot{\phi}_r| \\ = m_1 a_1 (a_x \sin \phi + a_z \cos \phi) - I_t \ddot{\theta}_y + T_r \end{aligned} \quad (20)$$

By using equation (5) we can write equations (19) and (20) in terms of two unknowns:

$$I_m \ddot{\phi}_m - k(\phi_r - \phi_m) = T_m \quad (21)$$

$$I_t \ddot{\phi}_r + k(\phi_r - \phi_m) + kg\dot{\phi}_r / |\dot{\phi}_r| = T_I + T_r \quad (22)$$

where for convenience we have defined an effective hull inertia torque:

$$T_I = m_1 a_1 (a_x \sin \phi + a_z \cos \phi) - I_t \ddot{\theta}_y \quad (23)$$

For the elevation motion vibration the corresponding equations will have the same form as (21) and (22) except we have to replace ϕ by α . The inertial torque T_I for this case will have the form:

$$T_I = -m_2((a_2+a_3 \cos \alpha)a_y - (a_x \cos \phi - a_z \sin \phi)(-b_2+a_3 \sin \alpha)) \\ - I_t(\ddot{\theta}_x \sin \phi + \ddot{\theta}_y \cos \phi) \quad (24)$$

Before discussing the solution to equations (21) and (22) it is necessary to obtain an appropriate expression for the motor torque T_m . This expression will be developed in the following section.

Servo Control System

Both the azimuth and the elevation motions are governed by the same type of servo system and the only difference is the gear ratio used in each of these motions. A simplified block diagram for the servo control is shown in Figure 3. In simplifying the actual servo diagram certain very high frequency effects were neglected. There are basically two feedback systems.

The first feedback senses the relative motion ϕ_r or α_r using a resolver signal and feeds this signal, without modification, to the front of the system. This relative motion is then subtracted from the desired control signal ϕ_c or α_c . The second feedback loop senses the speed of the motor using a tachometer and modifies this signal by a transfer function. The transfer function is defined in terms of the motor angular displacements ϕ_m or α_m and the resulting signal is subtracted from the difference of control and the resolver signals. Actually before the subtraction takes place a multiplication by a constant 535. is first performed as shown in Figure 3. The transfer function A, defined in terms of the transformed variables, has the form:

$$A = \left(\frac{1}{1.3} \times \frac{0.1s}{1+1s} \times .067s + \frac{.0192s}{7.5} \right) n \quad (25)$$

where n is the gear ratio. For the azimuth motion $n = 620$ and for the elevation $n = 810$. Consequently in terms of the transformed variable the motor torque for the azimuth motion is given by:

$$T_m = 535 \times 0.75n (\phi_c - \phi_r - \phi_s) \quad (26)$$

where we have defined ϕ_s as

$$\phi_s = A/535 \phi_m \quad (27)$$

Writing the transfer function A over a common denominator and using $n = 620$:

$$\phi_s = \frac{.0029667 s + .0062692 s^2}{1 + 0.1 s} \phi_m \quad (28)$$

Equation (23) is in terms of the transformed variable s and for our purpose we need to obtain general time relation. This is done by replacing the s parameter by a time operator:

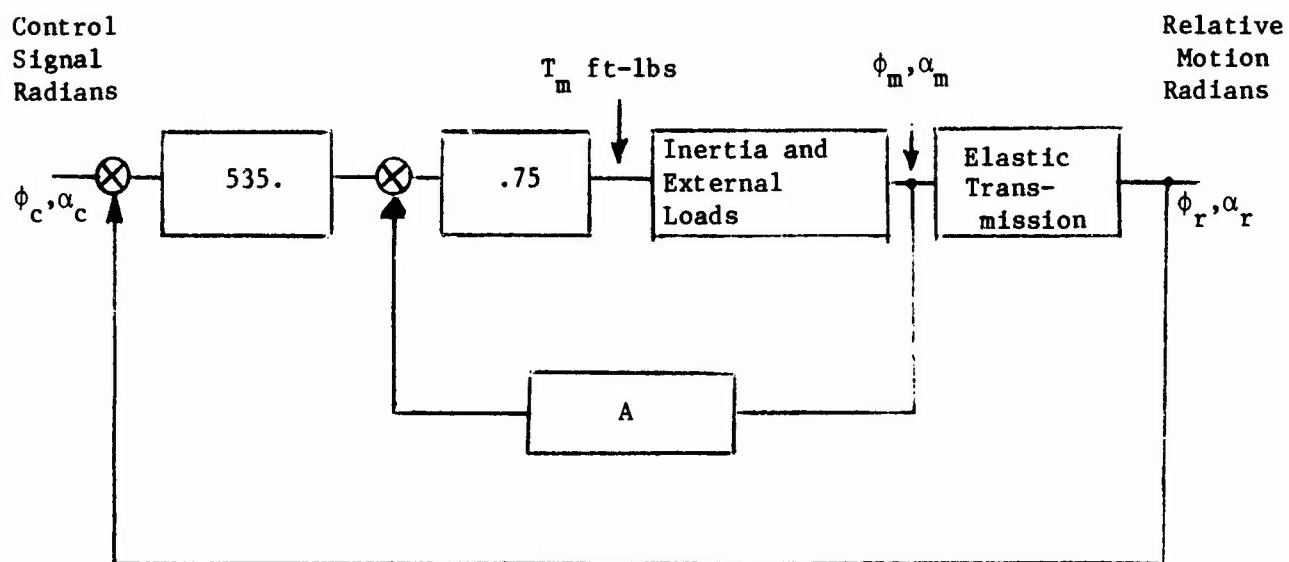


Figure 3. Servo Control System Governing Azimuth and Elevation Vibration Modes.

$$\phi_s + .1 \frac{d\phi_s}{dt} = .0029667 \frac{d\phi_m}{dt} + .0062692 \frac{d^2\phi_m}{dt^2} \quad (29)$$

For the case of the elevation motion equation (29) is modified by replacing ϕ_s and ϕ_m by α_s and α_m and multiplying the right hand side by the factor of 810/620.

By having equations (26) and (29) the motor torque at any given time is defined although it is in a form of a differential equation.

Solution of the Governing Equations

The final form of the governing equations will be given here in terms of the azimuth deflection variable ϕ ; similar types of equations will be valid for the elevation parameter α . Consider the equation of motion (21) and substitute from equation (26):

$$I_m \ddot{\phi}_m - k(\phi_r - \phi_m) = 401.25n (\phi_c - \phi_r - \phi_s) \quad (30)$$

Equation (30), together with equations (22) and (29), represents a system of three governing equations in the variables ϕ_m , ϕ_r and ϕ_s . For the case of the elevation motion the variable ϕ is changed to α and the right hand side of equation (29) is altered by a multiplying constant as indicated previously.

The solution to the three governing equations will be obtained numerically on a computer. To do this the three second order equations are reduced to five first order equations. This is done by defining the following five variables:

$$\begin{aligned} \phi_1 &= \phi_r \\ \phi_2 &= \frac{d\phi_r}{dt} \\ \phi_3 &= \phi_m \\ \phi_4 &= \frac{d\phi_m}{dt} \\ \phi_5 &= \phi_s \end{aligned} \quad (31)$$

By using equations (31) in the governing equations (22), (29) and (30)

the following set of five first order equations follows:

$$\frac{d\phi_1}{dt} = \phi_2$$

$$\frac{d\phi_2}{dt} = \frac{1}{I_t} (-k(\phi_1 - \phi_3) - k g \dot{\phi}_2 / |\dot{\phi}_2| + T_I + T_r)$$

$$\frac{d\phi_3}{dt} = \phi_4$$

$$\frac{d\phi_4}{dt} = \frac{1}{I_m} (k(\phi_1 - \phi_3) + 401.25n (\phi_c - \phi_1 - \phi_5))$$

$$\begin{aligned} \frac{d\phi_5}{dt} = & -10\phi_5 + 0.029667 \phi_4 \\ & + 0.062692 \left(\frac{1}{I_m} (k(\phi_1 - \phi_3) + 401.25n (\phi_c - \phi_1 - \phi_5)) \right) \quad (32) \end{aligned}$$

It may be noted that in the last of equations (32) the second derivative of ϕ_m was replaced by using equation (30). Equations (32) are solved numerically.

The solution of equations (32) has been programmed on a digital computer. The description of the input parameters is given in Appendix A. The program is set up so that either the azimuth or the elevation vibrations can be analyzed separately or both motions can be handled simultaneously. The listing of the program is given in Appendix B.

Numerical Examples

In order to check out the analysis and the computer program, four numerical examples were executed. The first example consists of a step input in the recoil torque T_r of 660 lb-ft. The results are presented in Figure 4 for the response of the turret in the azimuth motion. The result for the elevation motion is similar and only the numerical values differ. The results in Figure 4 show the variation of the angle ϕ_r with time. It can be seen from these results that steady state response is reached in about 0.15 seconds. The steady state response is

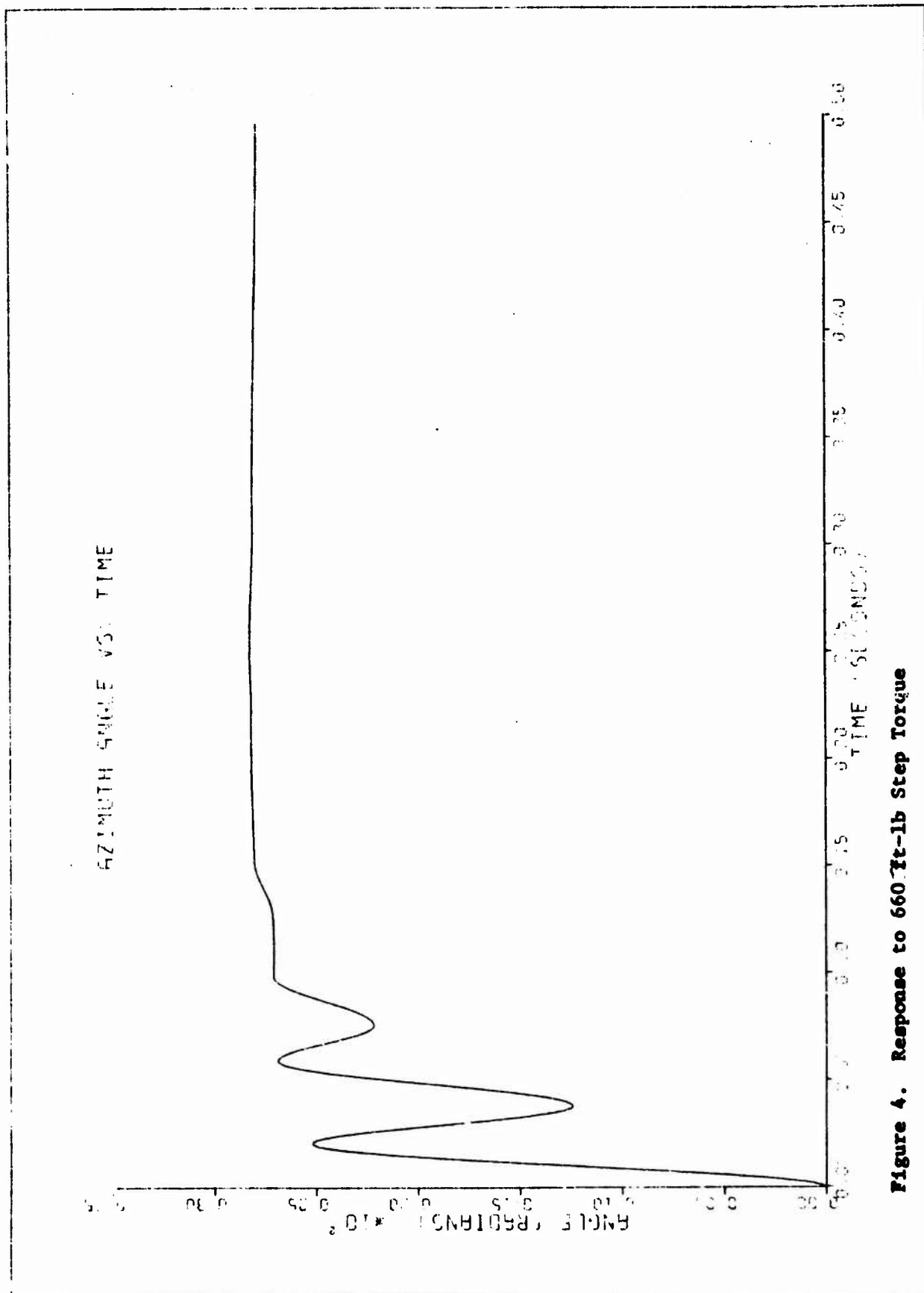


Figure 4. Response to 660 Ft-lb Step Torque

about 2.7 milliradians. This response compares closely with the equipment specification of 2.5 milliradians static deflections for 660 ft-lbs torque. During the transient period the oscillations can be seen to have a frequency of about 30 cps which agrees with the natural frequency of the system.

In the next three examples the turret was subject to oscillating torque given by:

$$T_r = 300 (1 + \sin \omega t) \quad (33)$$

In the three examples the frequency ω was taken to be 62.8, 188.5 and 282.7 radians per second. These values correspond to 10, 30 and 45 cycles per second. The results for these three examples are shown in Figures 5 to 7. Again, the results are given only for the azimuth motion. In the calculations the control signal ϕ_c in the servo controls was set at zero. Therefore the turret attempts to follow this value; however, due to the dynamics of the system the turret deflection ϕ_r does oscillate. The results in Figure 5 to 7 for the sinusoidal input show a sinusoidal response superimposed on a step input. The mean value of the response agrees with a step input of 300 ft-lbs torque. As expected the amplitude of the sinusoidal response reaches a maximum value at the natural frequency of 30 cps.

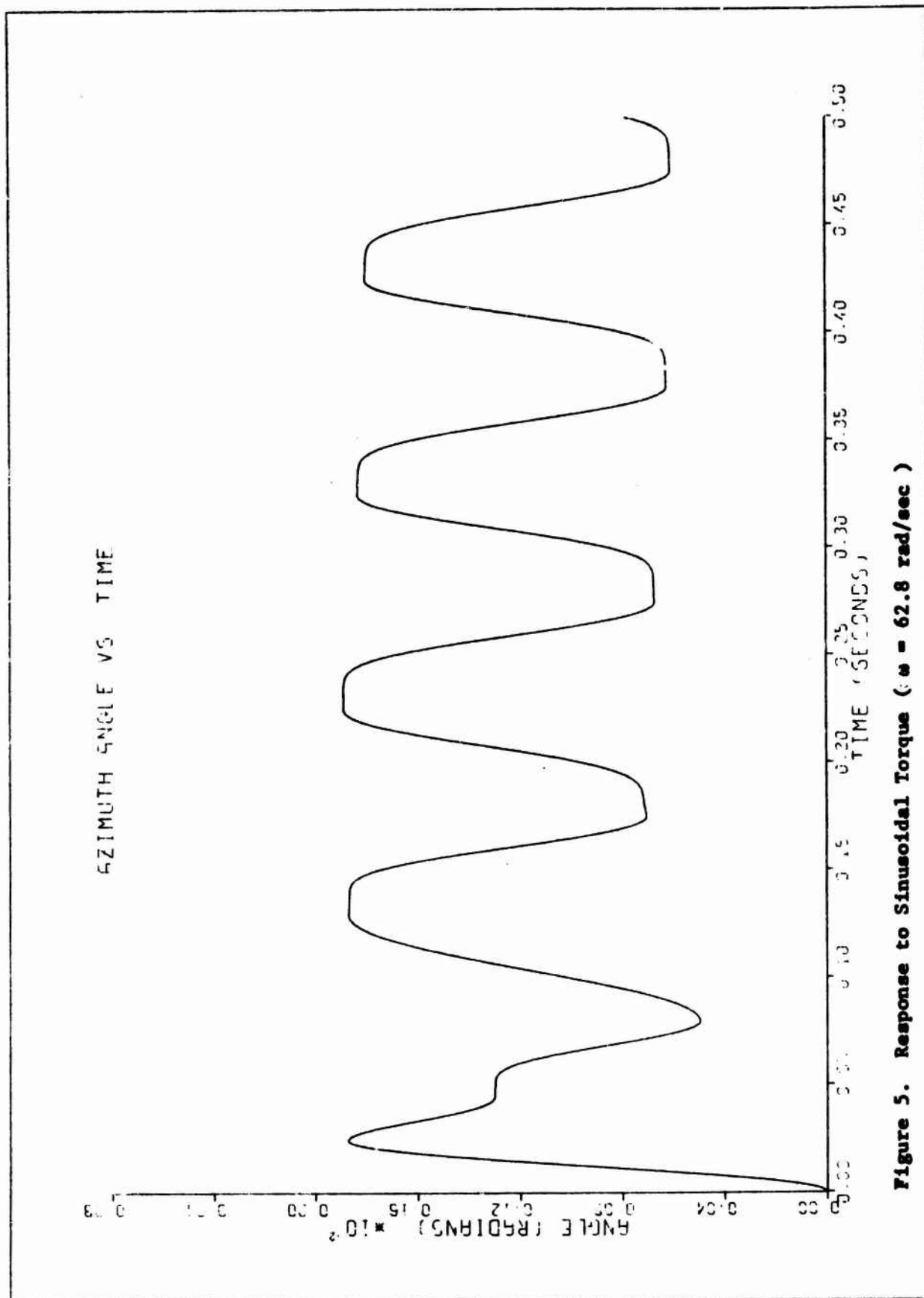


Figure 5. Response to Sinusoidal Torque ($\omega = 62.8$ rad/sec)

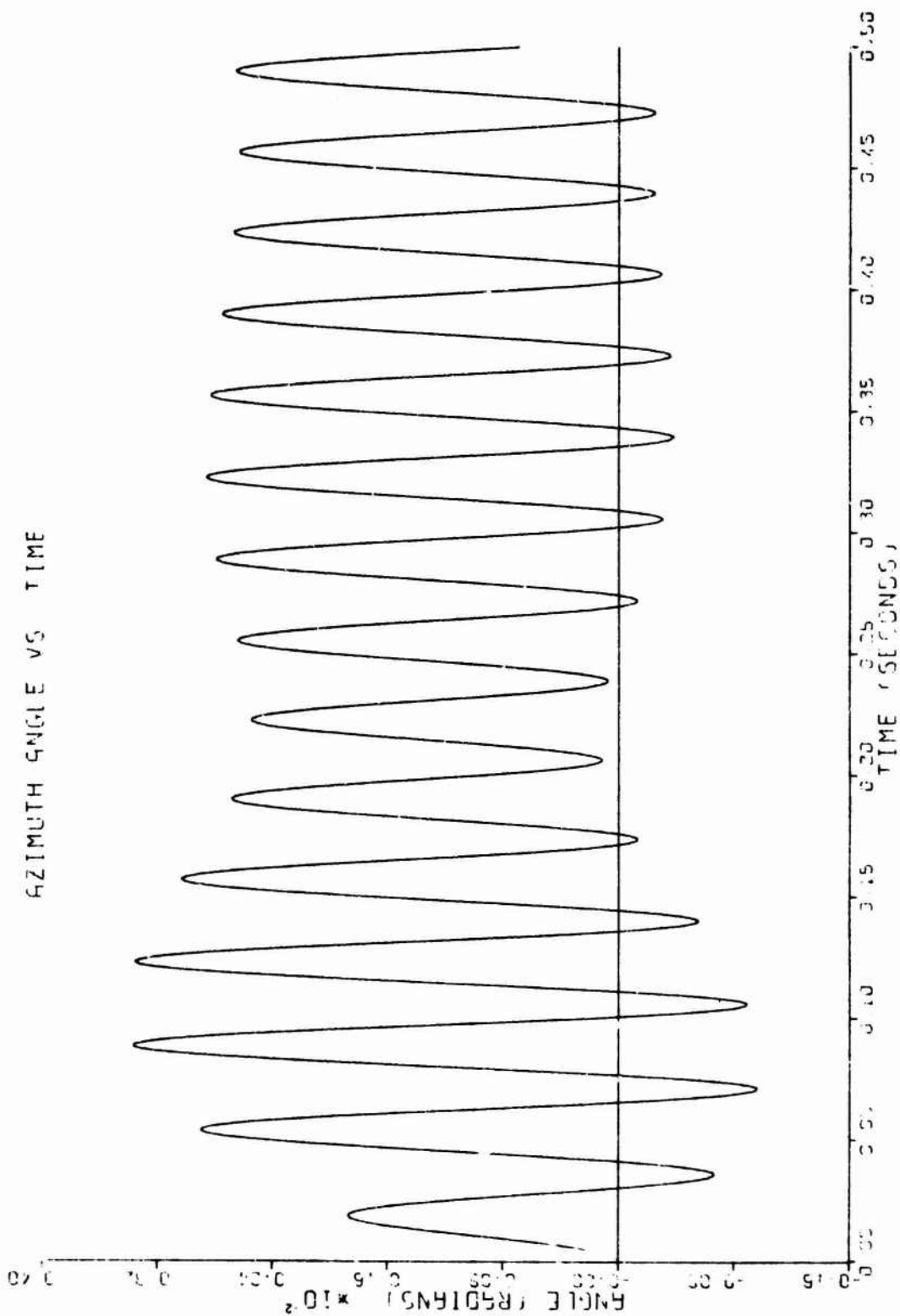


Figure 6. Response to Sinusoidal Torque ($\omega = 188.5$ rad/sec)

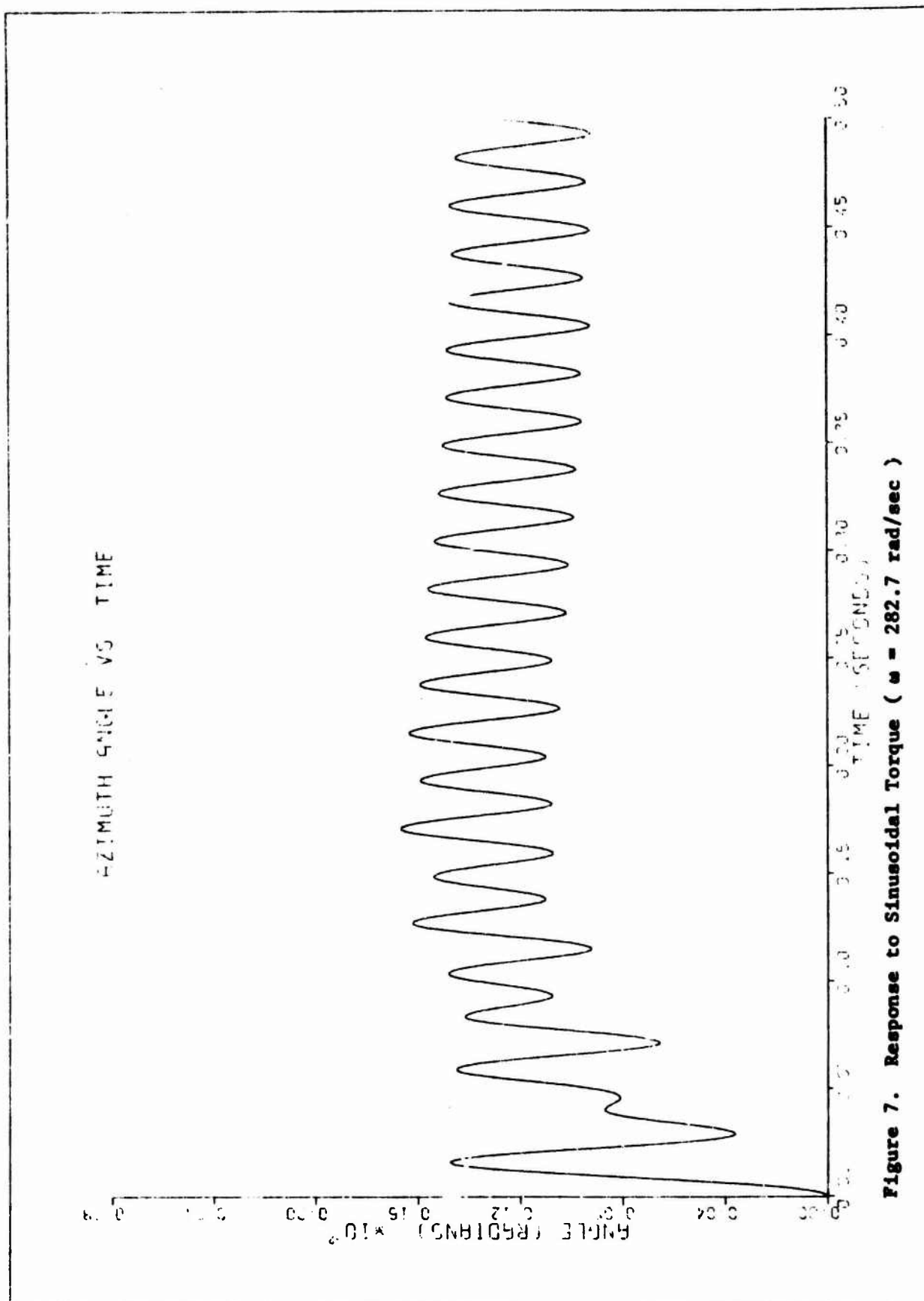


Figure 7. Response to Sinusoidal Torque ($\omega = 282.7$ rad/sec)

APPENDIX A

Description of Input Cards and Input Parameters

- Card 1: This card contains the parameter IM; if IM = 1 then azimuth motion is to be analyzed before elevation, if IM = 2 then elevation is first. FORMAT (I10)
- Card 2: This card contains the parameter NM which can either be 1 or 2; and this parameter establishes whether 1 or 2 motions are to be analyzed. FORMAT(I10)
- Card 3: Contains parameters a_1 , a_2 , a_3 , b_1 , and b_2 which define the centers of gravity for azimuth and elevation motion. The parameters a_1 , a_2 , a_3 , b_1 , and b_2 are shown in Figure 1. The units are feet. FORMAT(5F10.3)
- Card 4: All the remaining cards, starting with this one, are to be repeated for each motion. For example if NM = 1 then these cards are not repeated, if NM = 2 then these cards are repeated twice. The Card 4 contains AM, AI1, and AI2. The parameter AM is the mass in pounds of the vibrating part of the turret. AI1 and AI2 are the moments of inertia for the turret load and the motor referred to their own coordinates. The inertias are in slug-ft² units. FORMAT(F10.5, 2E15.5)
- Card 5: This card contains TK and TG where TK is the torsional stiffness of the gear system in lb-ft per radian, and TG is the non-dimensional frictional damping coefficient FORMAT(E10.3,F10.5)
- Card 6: This card contains the gear ratio. It should be 620 for azimuth and 810 for elevation. FORMAT(F10.5)
- Card 7: This inputs four parameters PRMT where PRMT(1) and PRMT(2) represent the starting and the end points in time, PRMT(3) is the initial integration interval, and PRMT(4) is the upper error bound. FORMAT(4E15.6)

APPENDIX B

Computer Program Listing

C MAIN

C
C

COMMON/STIFF/TK,TG

COMMON/PASS/AM,A11,A12,A,R,GP

COMMON/MOTION/IM,N

COMMON/ANGLE/ PHI,ALPHA

DIMENSION PEMY(5),DERY(5),AUX(8,5),Y(5)

EXTERNAL FCT,OUTP

C SET MOTION TO BE FIRST,IM=1 AZIMUTH,IM=2 ELEVATION

READ(5,1002) IM

C
C

SET NUMBER OF MOTIONS TO BE ANALYZED,1 OR 2

C
C

READ(5,1002) NM

C
C

READ ANGLES PHI AND ALPHA IN DEGREES

C
C

READ(5,1001) PHI,ALPHA

WRITE(6,2004) PHI,ALPHA

PI=3.1415926/180.

PHI=PHI*PI

ALPHA=ALPHA*PI

DO 99 N=1,NM

IF(IM.EQ.N) GO TO 12

WRITE(6,1600)

GO TO 13

12 WRITE(6,1500)

13 CONTINUE

C
C

READ MOMENT OF MASS AND MOMENT OF INERTIA OF LOAD AND MOTOR

C
C

MOMENTS OF INERTIA ARE RELATIVE TO MOTOR COORDINATES

READ(5,1000)AM,A11,A12

C
C

READ CENTER OF GRAVITY OFFSET FEET

C
C

READ(5,1001) A,P

C
C

READ GEAR BOX RATIO

C
C

READ(5,1000)CF

C
C

READ TRANSMISSION STIFFNESS,FT-LBS, AND DAMPING COEFFICIENT

C
C

READ(5,1003)TK,TG

WRITE(6,2001) AM,A11,A12

WRITE(6,2001) A,P

WRITE(6,2002) TK,TG

WRITE(6,2003) GR

AI1=AI1*(GR)**2

AI2=AI2*(GR)**2

C
C SET INITIAL DISPLACEMENTS
C

DO 10 I=1,5

10 Y(I)=0.0

C
C SET ERROR WEIGHTS
C

DO 11 I=1,5

11 DEPY(I)=.2

C
READ(5,1004)(PRMT(I),I=1,4)

C
WRITE(6,2005)

CALL RKGS(PRMT,Y,DEPY,5,IHLF,FCT,OUTP,AUX)

99 CONTINUE

C
1000 FORMAT(F10.5,2E15.5)

1001 FORMAT(2F10.3)

1002 FORMAT(I10)

1003 FORMAT(5I0.3,F10.5)

1004 FORMAT(4E15.6)

1500 FORMAT(50X,'AZIMUTH VIBRATION')

1600 FORMAT(50X,'ELEVATION VIBRATION')

2000 FORMAT(7X,'MASS TUPPET INERTIA MOTOR INERTIA'/4X,3E18.6)

2001 FORMAT(7X,'CENTER OF GRAVITY POSITION'/4X,2E18.6)

2002 FORMAT(7X,'GEAR STIFFNESS DAMPING COEFFICIENT'/4X,2E18.6)

2003 FORMAT(4X,' GEAR RATIO '/4X,F10.0)

2004 FORMAT(9X,'AZIMUTH AND ELEVATION ANGLES'/4X,2F20.6)

2005 FORMAT(9X,'TIME , ANGULAR DISPLACEMENT IN RADIANS')

STOP

END

```
SUBROUTINE OUTP(X,Y,DERY,IHLF,NDIM,PRMT)
```

```
  DIMENSION Y(5),DERY(5),PRMT(5)
```

```
  WRITE(6,1000) X,Y(1)
```

```
1000 FORMAT(3X,6E15.6)
```

```
  RETURN
```

```
  END
```

G LEVEL 21

FCT

DATE = 74261

SUBROUTINE FCT(X,Y,DERY)

COMMON/STIFF/TK,TG

COMMON/MASS/AM,AI1,AI2,A,B,GR

DIMENSION PRMT(5),DERY(5),AUX(8,5),Y(5)

P=0.0

CALL RFORCE(X,TR)

CALL IFORCE(X,TH)

AF=ABS(Y(2))

IF(AF.EQ.0.0) AF=1.0

C=4.0125E+02*GR

C
C
EVALUATE RIGHT HAND SIDE OF GOVERNING EQUATIONS

DERY(1)=Y(2)

DERY(2)=-TK/AI1*(Y(1)-Y(3)+Y(2)/AF*TG)+(TR+TH)/AI1

DERY(3)=Y(4)

DERY(4)=TK/AI2*(Y(1)-Y(3)) +C/AI2*(P-Y(1)-Y(5))

DERY(5)=(4.785047E-5*Y(4)+1.011186E-4*DERY(4))*GR-10.*Y(5)

RETURN

END

LEVEL 21

IFORCE

DATE 74261

```
SUBROUTINE IFORCE(X,TH)
COMMON /ANGLE/ PHI,ALPHA,SA,CA,SP,CP
COMMON/MASS/AM,AI1,AI2,A,B,GR
COMMON/MOTION/IM,N
COMMON /NUMB/ NITER,HDAT,X0,RPLT(5),CONFIG(3)
COMMON /ACCEL/ T1(2600),T2(2600),T3(2600),UDD(2600),
$ VDD(2600),WDD(2600)
```

C

```
CALL POINT(X,NUM,XN)
THX=-T1(NUM)+(T1(NUM)-T1(NUM+1))*(X-XN)/HDAT
THY=T3(NUM)+(T3(NUM+1)-T3(NUM))*(X-XN)/HDAT
THZ=T2(NUM)+(T2(NUM+1)-T2(NUM))*(X-XN)/HDAT
AX=-UDD(NUM)+(UDD(NUM)-UDD(NUM+1))*(X-XN)/HDAT
AY=WDD(NUM)+(WDD(NUM+1)-WDD(NUM))*(X-XN)/HDAT
AZ=VDD(NUM)+(VDD(NUM+1)-VDD(NUM))*(X-XN)/HDAT
IF(IM.EQ.N) GO TO 9
```

C

FORCE FOR ELEVATION DIRECTION

```
TH=-AM*A*(-AY*CA+(AX*CP-AZ*SP)*SA)-AI1*(THX*SP+THZ*CP)
```

```
GO TO 10
```

9

```
CONTINUE
```

C

FORCE FOR AZIMUTH DIRECTION

```
TH=AM*A*(AX*SP+AZ*CP)-AI1*THY
```

10

```
CONTINUE
```

```
RETURN
```

```
END
```

SUBROUTINE RFORCE(X,TR)

COMMON/ANGLE/ PFI,ALPHA

COMMON/MOTION/IN,N

IF(IM.EQ.N) GO TO 9

C FORCE FOR ELEVATION DIRECTION

W=282.7

TR=150.*(1.+SIN(W*X))

GO TO 10

9 CONTINUE

C FORCE FOR AZIMUTH DIRECTION

W=282.7

TR=300.*(1.+SIN(W*X))

10 CONTINUE

RETURN

END

SUBROUTINE RKGS(PRMT,Y,DERY,NDIM,IHLF,FCT,OUTP,AUX)

C
C

R
R
R

DIMENSION Y(5),DERY(5),AUX(8,5),A(4),B(4),C(4),PRMT(5)

DO 1 I=1,NDIM

1 AUX(8,I)=.0666667*DERY(I)

X=PRMT(1)

XEND=PRMT(2)

H=PRMT(3)

PRMT(5)=0.

CALL FCT(X,Y,DERY)

C
C

FPP7R TEST

IF(H*(XEND-X))38,37,2

C
C

PREPARATIONS FOR RUNGE-KUTTA METHOD

2 A(1)=.5

A(2)=.2928932

A(3)=1.707107

A(4)=.1666667

B(1)=2.

B(2)=1.

B(3)=1.

B(4)=2.

C(1)=.5

C(2)=.2928932

C(3)=1.707107

C(4)=.5

C
C

PREPARATIONS OF FIRST RUNGE-KUTTA STEP

DO 3 I=1,NDIM

AUX(1,I)=Y(I)

AUX(2,I)=DERY(I)

AUX(3,I)=0.

3 AUX(6,I)=0.

IREC=0

H=H+H

IHLF=-1

ISTEP=0

IEND=0

C
C

START OF A RUNGE-KUTTA STEP

4 IF((X+H-XEND)*H)7,6,5

5 H=XEND-X

6 IEND=1

C
C

RECORDING OF INITIAL VALUES OF THIS STEP

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7 CALL OUTP(X,Y,DERY,IPEC,NDIM,PRMT)

IF(PEPY(5))4C,8,40

8 ITEST=0

9 ISTEP=ISTEP+1

C

C

C

START OF INNERMOST RUNGE-KUTTA LOOP

J=1

10 AJ=A(J)

RJ=B(J)

CJ=C(J)

DO 11 I=1,NDIM

R1=H*DERY(I)

R2=AJ*(R1-RJ+AUX(6,I))

Y(I)=Y(I)+R2

R2=R2+R2+R2

11 AUX(6,I)=AUX(6,I)+R2-CJ*R1

IF(J-4)12,15,15

12 J=J+1

IF(J-3)13,14,13

13 X=X+.5*H

14 CALL FCT(X,Y,DERY)

GOTO 10

C

C

C

C

TEST OF ACCURACY

15 IF(ITEST)16,16,20

C

C

IN CASE ITEST=0 THERE IS NO POSSIBILITY FOR TESTING OF ACCURACY

16 DO 17 I=1,NDIM

17 AUX(4,I)=Y(I)

ITEST=1

ISTEP=ISTEP+ISTEP-2

18 INLE=INLE+1

X=X-H

H=.5*H

DO 19 I=1,NDIM

Y(I)=AUX(1,I)

DERY(I)=AUX(2,I)

19 AUX(6,I)=AUX(3,I)

GOTO 9

C

C

IN CASE ITEST=1 TESTING OF ACCURACY IS POSSIBLE

20 IMOD=ISTEP/2

IF(ISTEP-IMOD-IMOD)21,23,21

21 CALL FCT(X,Y,DERY)

DO 22 I=1,NDIM


```

      AUX(5,I)=Y(I)
22  AUX(7,I)=DERV(I)
      GOTD 9
C
C  COMPUTATION OF TEST VALUE DELT
23  DELT=0.
      DO 24 I=1,NDIM
24  DELT=DELT+AUX(8,I)*ABS(AUX(4,I)-Y(I))
      IF(DELT-PRMT(4))28,28,25

```

```

C
C  ERROR IS TOO GREAT
25  IF(IHLF-10)26,36,36
26  DO 27 I=1,NDIM
27  AUX(4,I)=AUX(5,I)
      ISTEP=ISTEP+ISTEP-4
      X=X-H
      IEND=0
      GOTD 18
C
C  RESULT VALUES ARE GOOD
28  CALL FCT(X,Y,DERV)
      DO 29 I=1,NDIM
      AUX(1,I)=Y(I)
      AUX(2,I)=DERV(I)
      AUX(3,I)=AUX(6,I)
      Y(I)=AUX(5,I)
29  DERY(I)=AUX(7,I)
      CALL OUTP(X-H,Y,DERV,IHLF,NDIM,PRMT)
      IF(PRMT(5))40,30,40
30  DO 31 I=1,NDIM
      Y(I)=AUX(1,I)
31  DERY(I)=AUX(2,I)
      IPRC=IHLF
      IF(IEND)32,32,39
C
C  INCREMENT GETS DOUBLED
32  IHLF=IHLF-1
      ISTEP=ISTEP/2
      H=H+H
      IF(IHLF)4,33,33
33  IMOD=ISTEP/2
      IF(ISTEP-IMOD-IMOD)4,34,4
34  IF(DELT-.02*PRMT(4))35,35,4
35  IHLF=IHLF-1
      ISTEP=ISTEP/2
      H=H+H
      GOTD 4
C

```