SIMULATION OF SMALL STRUCTURES-OPTICS-CONTROLS SYSTEM WITH MSC/NASTRAN

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I. Introduction

One of the challenges in using either ground- or space-based high power lasers is keeping the beam on target in spite of various disturbances which, for the most part, would come through the supporting structure. Active control is one of the methods for maintaining laser beam direction. It requires (1) a Sensor which monitors the beam path and sends an error signal to the Controller when the beam is misaligned; (2) the Controller, after processing the error signal, sends a correction signal to (3) Actuators which control the position of (4) a Beam Steering Mirror (BSM), also in the optical path of the laser beam. The correction signal is designed to change the position of the BSM to that the laser beam is brought back on target.

Since it is not obvious how a system of this sort will respond to various disturbances, it is helpful to be able to simulate such a system, during the design stages, so that one might have confidence that the system will work if it gets to the hardware stage. Before applying MSC/NASTRAN to the real system, it seemed advisable to check out the implementation of MSC/NASTRAN on a small structures-optics-controls system that had the flavor of the real system but far less complexity. In that way it was hoped that procedural errors would be minimized when MSC/NASTRAN was used to analyze the real system.

This paper explains the implementation of MSC/NASTRAN as applied to the analysis of a Small Structures-Optics-Controls System (SSOCS), a sketch of which is shown in Figure 1. The SSOCS comprises a Beam Steering Mirror (BSM) supported by two Voice-Coil Actuators (VCA's) (on structural support springs "8" and "9") which change the position of the BSM, a Disturbed Mirror (DM) (on structural support springs "6","7", and "57"), a Sensor which monitors translational and angular misalignments in the beam path, and a Controller which receives the error signals from the Sensor and sends correction signals to the VCA's. The response of the SSOCS to a step function disturbance applied to the structure of the DM via $\bar{F}_7(t)$ through M_7 (between springs "7" and "57") was calculated by MSC/NASTRAN; and, the results were compared against those computed for the SSOCS by a general purpose dynamics analysis program called TIMRSP. The agreement between the results of MSC/NASTRAN and TIMRSP was considered excellent.

II. Implementation of SSOCS in MSC/NASTRAN

In keeping with simplicity, the SSOCS was set up as a 2-dimensional model. Locating the SSOCS in space was done using basic coordinate system X_0-Y_0 as illustrated in Figure 1. Coordinate systems X_1-Y_1 and X_2-Y_2 are reference frames for mirrors M1 and M2, respectively, and they allow MSC/NASTRAN to calculate translational displacements normal to the mirror reflective surface.

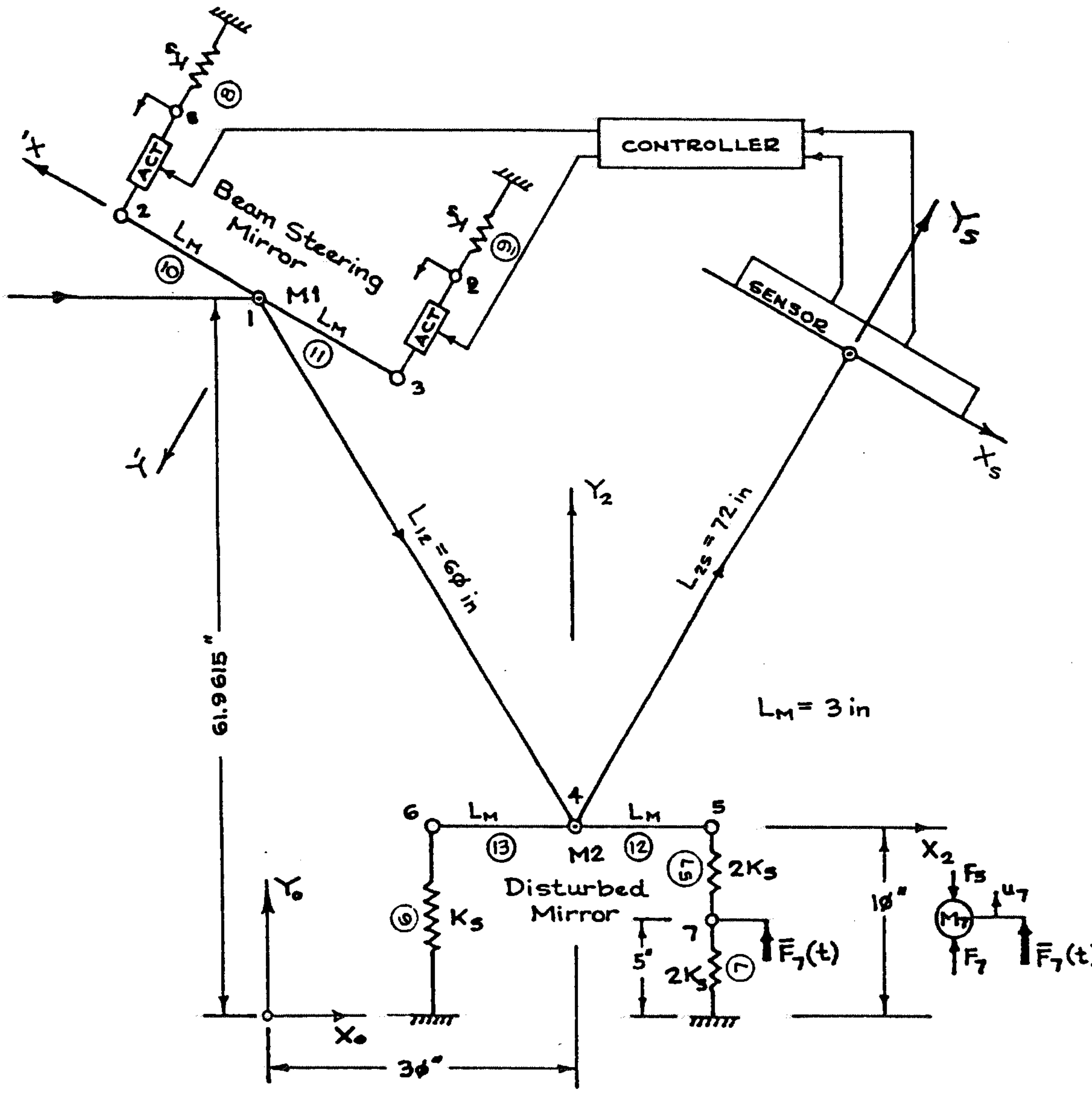

Figure 1 - Sketch of Small Structures-Optics-Controls System (SSOCS)

Selection of parameters for the SSOCS was arbitrary. Although the mirror size and mass were somewhat related to real world hardware within the author's realm of experience, the stiffness, K_S, of the structural support springs in the model were chosen purposely low to ensure that the mirrors were essentially rigid bodies in comparison to their support structure.

A. Beam Steering Mirror (BSM) - M1

GRID's 1, 2, and 3 locate the BSM in space relative to coordinate system CID=1. (See MSC/NASTRAN Input Data Deck for SSOCS in Appendix.) The BSM is represented by CBAR's 10 and 11. The mirror length ($2L_M$= 6 in) was representative of actual known hardware. The cross-section properties for PBAR 100 were set at A = 3.0 in^2, I_{zz}= 0.25 in^4, I_{yy}= 2.25 in^4, J = 1.0 in^4. MAT1 110 represents the properties for aluminum alloy with <u>no mass</u> specified. Mass properties for the BSM were specified on CONM2 cards <u>10, 20,</u> and 30 as 7.8889-3, 2.0555-3, and 2.0553-3 $lb\text{-}sec^2/in$, respectively. The reason for these particular mass values was that the SSOCS model was <u>first</u> analyzed in TIMRSP in which the mass of both M1 and M2 were treated as <u>true</u> rigid bodies. Their mass was given as M_M= 0.012 $lb\text{-}sec^2/in$ and the rotational mass moment of inertia as J_M= 0.037 $lb\text{-}sec^2\text{-}in^2/in$ for the TIMRSP analysis. In order for the MSC/NASTRAN SSOCS model to have the same mirror mass properties as the TIMRSP model, it was necessary that the concentrated masses at GRID's 1, 2, and 3 have the values as specified on CONM2 cards 10, 20, and 30, respectively.

B. Disturbed Mirror (DM) - M2

GRID's 4, 5, and 6 locate the DM in space relative to coordinate system CID = 2. The DM was represented by CBAR's 12 and 13 and CONM2 mass elements 40, 50, and 60. Mirror parameter values for the DM are the same as those for the BSM.

C. Voice Coil Actuators (VCA's) for BSM

Figure 2 presents a detailed sketch of a VCA representative of Actuators 2 and 3 on the SSOCS. Also written on Figure 2 are the dynamic equilibrium equations and the force-displacement relations for the pertinent mass, spring, and damper components of the VCA. The internal voice coil force on the actuator rod (and case) as a function of applied voltage is given by the expression, $F_{vc}= C_v e$, where C_v is a constant arbitrarily set at 10 lb/volt during this simulation.

Actuator 2 is connected between GRID's 2 and 8. (See Figure 1.) GRID 2 was assumed to be the effector or rod end of the actuator, whereas GRID 8 was the foot or case end of the actuator. Actuator spring, K_A= 12 lb/in, is modelled by CELAS2 28 and its damper, B_A= 0.5 lb-sec/in, is represented by CDAMP2 82. The mass of Actuator 2 rod, M_R= 0.004 $lb\text{-}sec^2/in$, is given by CONM2 202 and the mass of Actuator 2 case, M_C= 0.012 $lb\text{-}sec^2/in$, by CONM2 802.

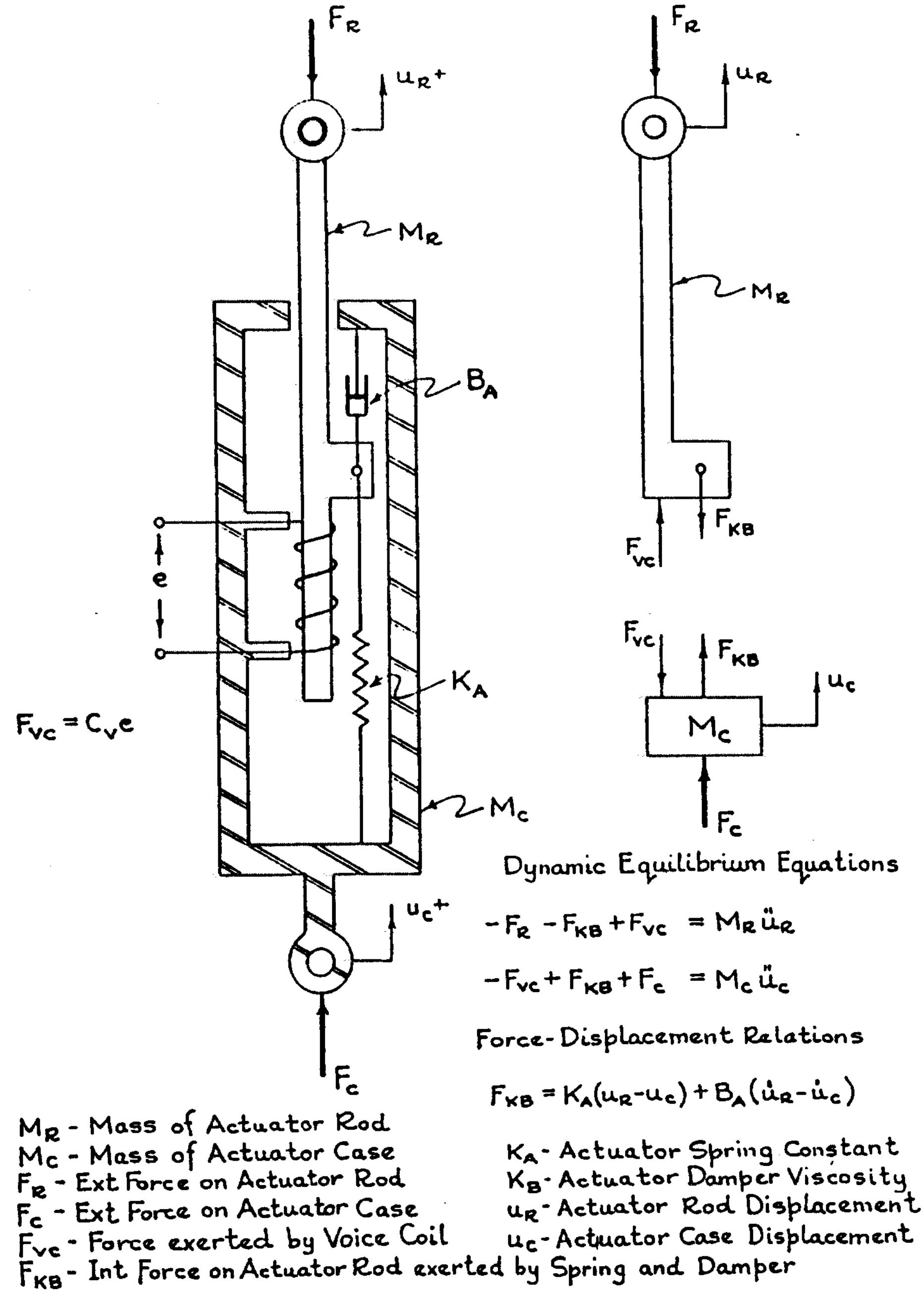

Figure 2 - Detailed Sketch of Voice-Coil Actuator (VCA)

Actuator 3 is connected between GRID's 3 and 9. (See Figure 1.) GRID 3 is the effector or rod end of Actuator 3, and GRID 9 is the foot or case end. The numerical values for the parameters of Actuator 3 are identical to the corresponding parameters of Actuator 2. CELAS2 39 and CDAMP2 93 represent the spring and damper, respectively. CONM2's 303 and 903 are the Actuator 3 rod and case masses, respectively.

D. Structural Support Springs for the VCA's of the BSM

Grounded CELAS2 elements 8 and 9, connected to GRID's 8 and 9 respectively, represent the structural support springs for the VCA's. They both have a apring stiffness, K_s= 120 lb/in.

E. Structural Support Springs for the DM

Grounded CELAS2 elements 6 and 7, connected to GRID's 6 and 7 respectively, represent two of the structural support springs for the DM. Their spring stiffnesses are K_s= 120 lb/in and $2K_s$=240 lb/in, respectively. The third support spring, CELAS2 57, attached between GRID's 5 and 7, also has a spring stiffness, $2K_s$= 240 lb/in. Together spring elements 7 and 57 have a combined apring stiffness of K_s= 120 lb/in; however, a mass represented by CONM2 70 (M_7= 0.018 lb-sec^2/in) is attached to GRID 7, and the disturbance force $\bar{F}_7(t)$ is applied at that point. (See Figure 1.)

F. Disturbance Force Applied at M_7

A step function of 1.0 lb was selected for a disturbance force. It was applied for the first 0.2 sec interval of a time window of 0.5 sec. During the last 0.3 sec of the time window the disturbance force was zero (free vibration). The TLOAD1 75, DAREA 76, and TABLED1 107 card images are used to apply this disturbance to the MSC/NASTRAN model of the SSOCS.

G. Error Equations

Any movement of the BSM or DM in the optical train away from their equilibrium (or on-track) configuration will cause translational and/or angular misalignments of the laser beam as perceived by the Sensor. (See Figure 1.) If the excursions of the BSM and DM are small enough to allow small angle approximations to be applied, the resultant translational error equation would be

$$u_E = A_1 u_{1Y} + B_1 \theta_{1Z} + A_2 u_{4Y} + B_2 \theta_{4Z} \qquad (1)$$

where u_E - Translational error displacement (or misalignment) of laser beam at Sensor aperture.

A_1 - Influence coefficient for translational beam misalignment due to displacement of BSM normal to its reflective surface.

B_1 - Influence coefficient for translational beam misalignment due to rotation of BSM in the X_0-Y_0 plane.

A_2 - Influence coefficient for translational beam misalignment due to displacement of DM normal to its reflective surface.

B_2 - Influence coefficient for translational beam misalignment due to rotation of DM in the X_0-Y_0 plane.

u_{1Y} - Displacement of BSM normal to its reflective surface away from its rest position.

θ_{1Z} - Rotation of BSM in the X_0-Y_0 plane away from its rest position.

u_{4Y} - Displacement of DM normal to its reflective surface away from its rest position.

θ_{4Z} - Rotation of DM in the X_0-Y_0 plane away from its rest position.

Similarly, the resultant angular error equation at the Sensor aperture would be

$$\theta_E = D_1\theta_{1Z} + D_2\theta_{4Z} \qquad (2)$$

where θ_E - Angular error or rotational misalignment of laser beam at Sensor aperture.

D_1 - Influence coefficient for angular beam misalignment due to rotation of the BSM in the X_0-Y_0 plane.

D_2 - Influence coefficient for angular beam misalignment due to ratation of the DM in the X_0-Y_0 plane.

One might note that purely translational displacements of the BSM and the DM cause no angular beam misalignments. It was assumed that the Sensor is perfect and transmits the correct translational and angular misalignment error information to the Controller.

H. Controller Equations

In order to zero out the beam misalignment, the BSM will have to achieve new translational and angular displacements sufficient to cause an equivalent reverse effect on the beam path at the Sensor aperture. Representing this effect mathematically leads to the expressions

$$u_{corr} = -u_E \qquad (3)$$

$$\theta_{corr} = -\theta_E \qquad (4)$$

where u_{corr} - Corrective translation to zero out beam translational error.

θ_{corr} - Corrective rotation to zero out beam rotational error.

Since the BSM is the corrective optic, one has to calculate the normal and angular displacements it must execute in order to achieve u_{corr} and θ_{corr} at the Sensor aperture. This is given by the equations

$$u_{M1c} = (1/A_1)u_{corr} - (B_1/A_1D_1)\theta_{corr} \qquad (5)$$

$$\theta_{M1c} = (1/D_1)\theta_{corr} \qquad (6)$$

where u_{M1c} - Normal displacement component of BSM required to correct laser beam misalignment at Sensor aperture.

θ_{M1c} - Angular displacement component of BSM reauired to correct laser beam misalignment at Sensor aperture.

The strength of the translational and angular correction signals emanating from the Controller will, most likely, have an upper limit either due to the beam misalignment range an actual sensor could monitor or the maximum voltages which the controller circuitry will permit. In any event it was felt that this limitation should be manifested somewhere in the Controller equations. A hyperbolic tangent (Tanh) was chosen to represent the corrective translational and angular Controller signals as a function of u_{M1c} and θ_{M1c}, respectively. Under these conditions one would arrive at

$$S_u = N(u_{M1c}/u_{MAX}) \qquad (7)$$

$$S_\theta = N(\theta_{M1c}/\theta_{MAX}) \qquad (8)$$

where S_u - Translational correction signal from Controller.

S_θ - Angular correction signal from Controller.

N() - Tanh().

u_{MAX} - Normalization parameter for u_{M1c}. (u_{MAX}= 10.0)

θ_{MAX} - Normalization parameter for θ_{M1c}. (θ_{MAX}= 0.10)

SPOINT's 27 and 28 in the SSOCS MSC/NASTRAN input deck were selected to represent S_u and S_θ , respectively; and, NOLIN1 set 78 relate the correction signals to the pertinent displacements. TABLED1 278 describes the Tanh function for the range of interest. In order to ensure that the applied non-linear "force" results in the desired numerically equal scalar "displacement", one must connect a scalar spring of K = 1 to the SPOINT. CELAS2 elements 207 and 208 accomplish that operation.

I. Correction Signal Voltage

Since the Controller output correction signals (S_u and S_θ) are destined for two linear actuators (rather than one linear and one angular actuator), these signals have to be combined so that the correct input voltages go to the pertinent voice coils of Actuators 2 and 3. Equations (9) and (10) describe how the Controller output correction signals must be combined so that the two linear actuators will act in concert to impart the necessary translation and/or rotation to the BSM.

$$E_2 = G_u S_u + G_\theta S_\theta \qquad (9)$$

$$E_3 = G_u S_u - G_\theta S_\theta \qquad (10)$$

where E_2 - Input voltage to VCA 2.

E_3 - Input voltage to VCA 3.

G_u - Gain factor applied to translational correction signal.

G_θ - Gain factor applied to rotational correction signal.

J. Internal Voice-Coil Force in Actuators

The internal voice-coil force vs. input voltage equations re reproduced here from Figure 2 for completeness in the system of equations to be input via Transfer Function (TF) card images.

$$F_{VC2} = C_V E_2 \qquad (11)$$

$$F_{VC3} = C_V E_3 \qquad (12)$$

K. VCA Dynamic Equilibrium Equations

In order to better understand how the internal voice-coil forces will get input to their respective VCA's in the MSC/NASTRAN transient response analysis, one has to write the VCA dynamic equilibrium equations in the format which MSC/NASTRAN will use.

$$M_C D^2 u_{8Y} - B_A D(u_{2Y} - u_{8Y}) - K_A(u_{2Y} - u_{8Y}) = -F_{VC2} + F_{8C} \qquad (13)$$

$$M_R D^2 u_{2Y} + B_A D(u_{2Y} - u_{8Y}) + K_A(u_{2Y} - u_{8Y}) = F_{VC2} - F_{R2} \qquad (14)$$

$$M_C D^2 u_{9Y} - B_A D(u_{3Y} - u_{9Y}) - K_A(u_{3Y} - u_{9Y}) = -F_{VC3} + F_{9C} \qquad (15)$$

$$M_R D^2 u_{3Y} + B_A D(u_{3Y} - u_{9Y}) + K_A(u_{3Y} - u_{9Y}) = F_{VC3} - F_{R3} \qquad (16)$$

where u_{2Y} - Displacement of GRID 2 in the Y_1-direction.

u_{3Y} - Displacement of GRID 3 in the Y_1-direction.

u_{8Y} - Displacement of GRID 8 in the Y_1-direction.

u_{9Y} - Displacement of GRID 9 in the Y_1-direction.

F_{8C} - Force between Actuator 2 case and spring element at GRID 8.

F_{9C} - Force between Actuator 3 case and spring element at GRID 9.
F_{R2} - Force between Actuator 2 rod and BSM at GRID 2.
F_{R3} - Force between Actuator 3 rod and BSM at GRID 3.
D^2 - 2nd order time differential operator.
D - 1st order time differential operator.

By virtue of the pertinent CDAMP2, CELAS2, CONM2 bulk data card images previously explained, the LHS of Eqations (13) through (16) and the F_{8C}, F_{9C}, F_{2R}, and F_{3R} terms are already included in the matrix equations MSC/NASTRAN will integrate for the transient response analysis of the SSOCS. However, the internal voice-coil forces (F_{VC2} and F_{VC3}) coming from the impressed voltages (E_2 and E_3), respectively thereon, need to be added to the forementioned matrix equations. In this case it was done by TF cards.

III. Transfer Function Table

For ease in setting up the TF card for the SSOCS analysis the Transfer Function Table (TABLE I), in which Equations (1) through (16) are represented, was formulated. Also shown in TABLE I are the EPOINT (or SPOINT) identification numbers for ease in associating the TABLE I entries with the TF bulk data card images appearing in the MSC/NASTRAN input deck reproduced in the Appendix. The values used for the constants representing a_0 in TABLE I were as follows:

$A_1 = -1.732$	$A_2 = -0.5$	$B_1/A_1D_1 = 76.2125$	$C_V = 10.0$
$B_1 = 264.0$	$B_2 = -144.0$	$1/A_1 = -0.57735$	$G_u = 1.0$
$D_1 = -2.0$	$D_2 = 2.0$	$1/D_1 = -0.5$	$G_\theta = 1.0$

IV. Results

In the original project the computer program TIMRSP was being used as the Executive Code for accomplishing the system simulation of a large structures-optics-controls (LSOC) model. To increase confidence in the ability of TIMRSP to calculate correctly the transient response of the LSOC model, a few components interfacing with the LSOC main structural assembly (MSA) were to be modelled in MSC/NASTRAN along with the MSA for an independent check of the results computed by TIMRSP. As preliminary step, the SSOCS model was devised as a test bed to compare the calculated response between TIMRSP and MSC/NASTRAN before going to the LSOC model. In this way errors due to complexity of the system model could be minimized. Once good agreement had been obtained between TIMRSP and MSC/NASTRAN on the SSOCS model, work could begin on implementing a simulation of combined selected components from the LSOC model in MSC/NASTRAN.

The Beam Translational Error curve shown in Figure 3 was calculated and plotted by TIMRSP for the Controls ON mode, whereas Figure 4 presents the same

TABLE I

TRANSFER FUNCTION TABLE

TFEQN#	E/SPOINT	u_e	b_0	b_1	b_2	u_i	a_0	a_1	a_2
(1)	e_{21}	u_E	-1.0			u_{1Y}	A_1		
						θ_{1Z}	B_1		
						u_{4Y}	A_2		
						θ_{4Z}	B_2		
(2)	e_{22}	θ_E	-1.0			θ_{1Z}	D_1		
						θ_{4Z}	D_2		
(3)	e_{23}	u_{corr}	-1.0			u_E	-1.0		
(4)	e_{24}	θ_{corr}	-1.0			θ_E	-1.0		
(5)	e_{25}	u_{M1c}	-1.0			u_{corr}	$1/A_1$		
						θ_{corr}	$-B_1/A_1D_1$		
(6)	e_{26}	θ_{M1c}	-1.0			θ_{corr}	$1/D_1$		
(7)	s_{27}	S_u	*			$N(u_{M1c}/u_{MAX})$	$u_{MAX}= 10.0$		
(8)	s_{28}	S_θ	*			$N(\theta_{M1c}/\theta_{MAX})$	$\theta_{MAX}= 0.10$		
(9)	e_{29}	E_2	-1.0			S_u	G_u		
						S_θ	G_θ		
(10)	e_{30}	E_3	-1.0			S_u	G_u		
						S_θ	$-G_\theta$		
(11)	e_{31}	F_{VC2}	-1.0			E_2	C_V		
(12)	e_{32}	F_{VC3}	-1.0			E_3	C_V		
(13)		u_{8Y}				E_2	$+C_V$		
(14)		u_{2Y}				E_2	$-C_V$		
(15)		u_{9Y}				E_3	$+C_V$		
(16)		u_{3Y}				E_3	$-C_V$		

* NOTE: Eqns (7) and (8) were represented by NOLIN1 set 78 card images.

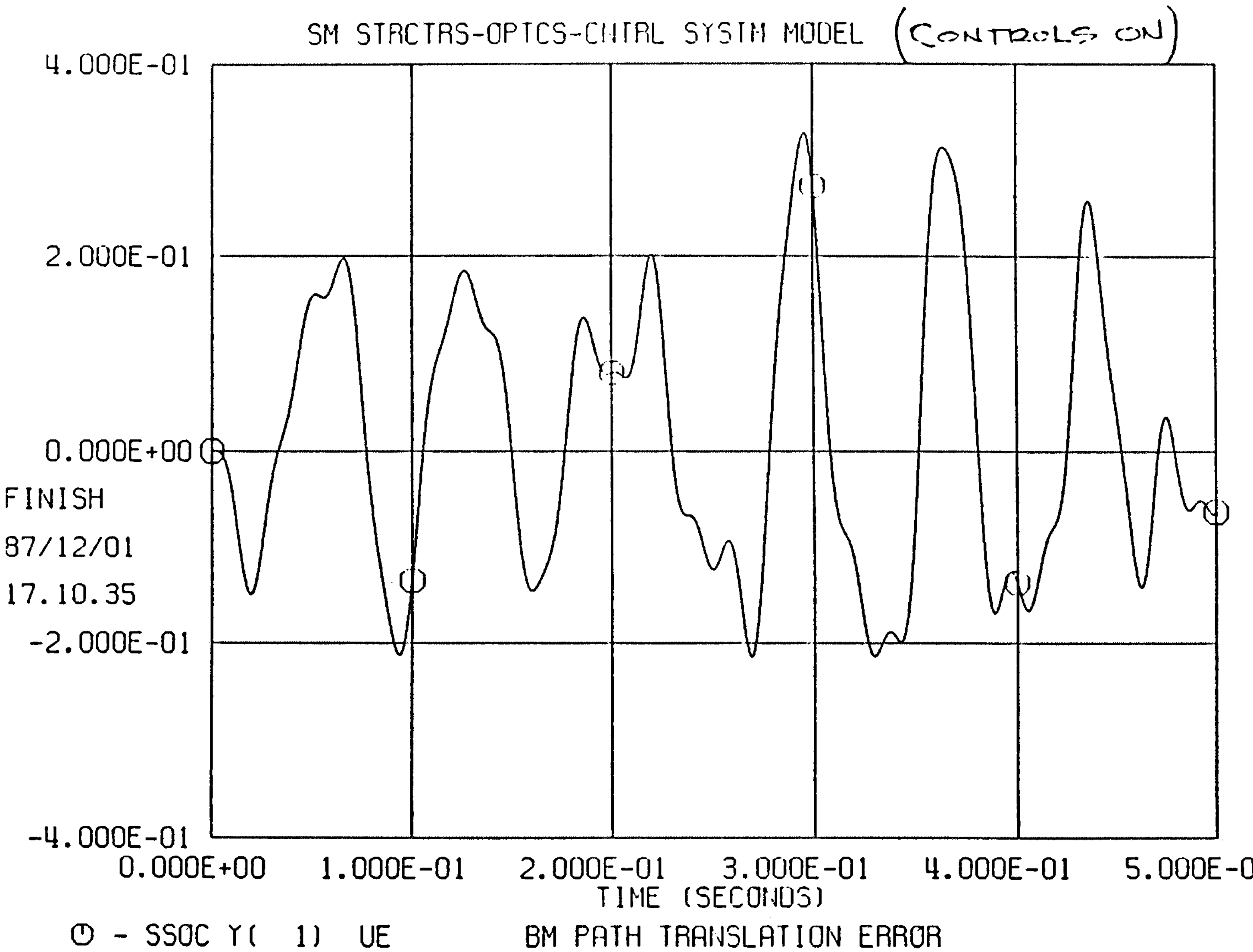

Figure 3 - Laser Beam Path Translational Error vs Time (Controls ON) as Calculated by TIMRSP

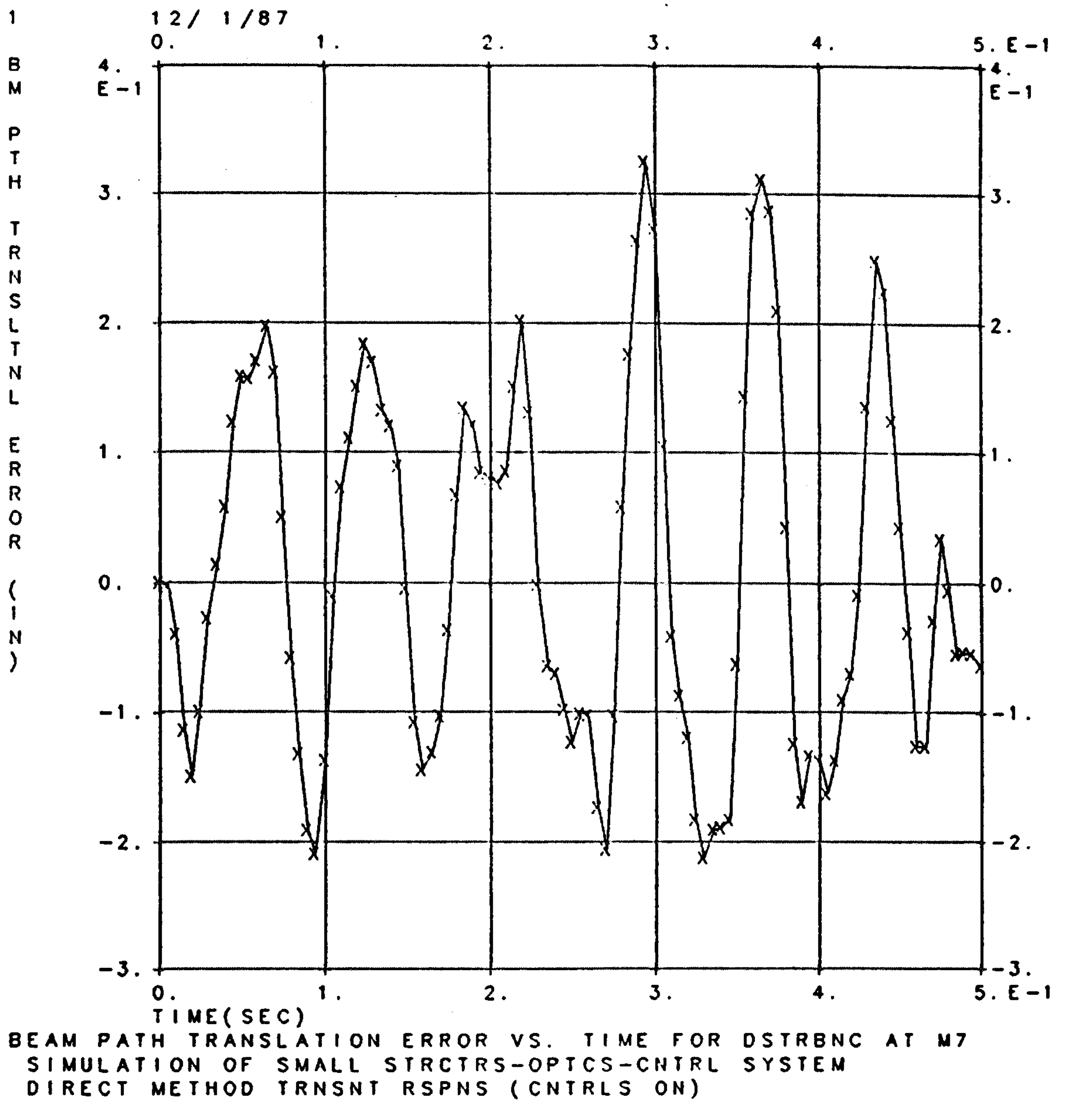

Figure 4 - Laser Beam Path Translational Error vs Time (Controls ON) as Calculated by MSC/NASTRAN

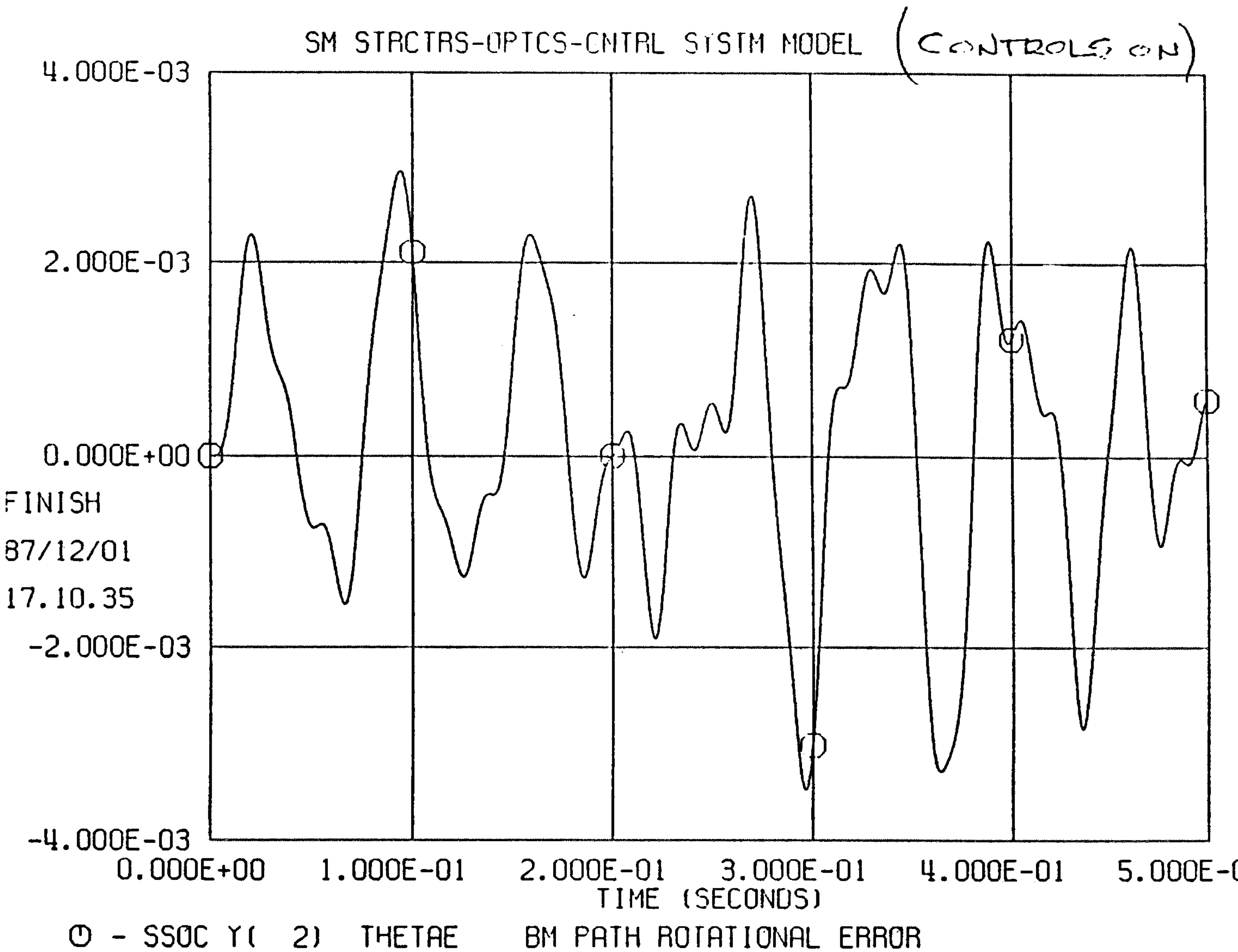

Figure 5 - Laser Beam Angular Error vs Time (Controls ON) as Calculated by TIMRSP

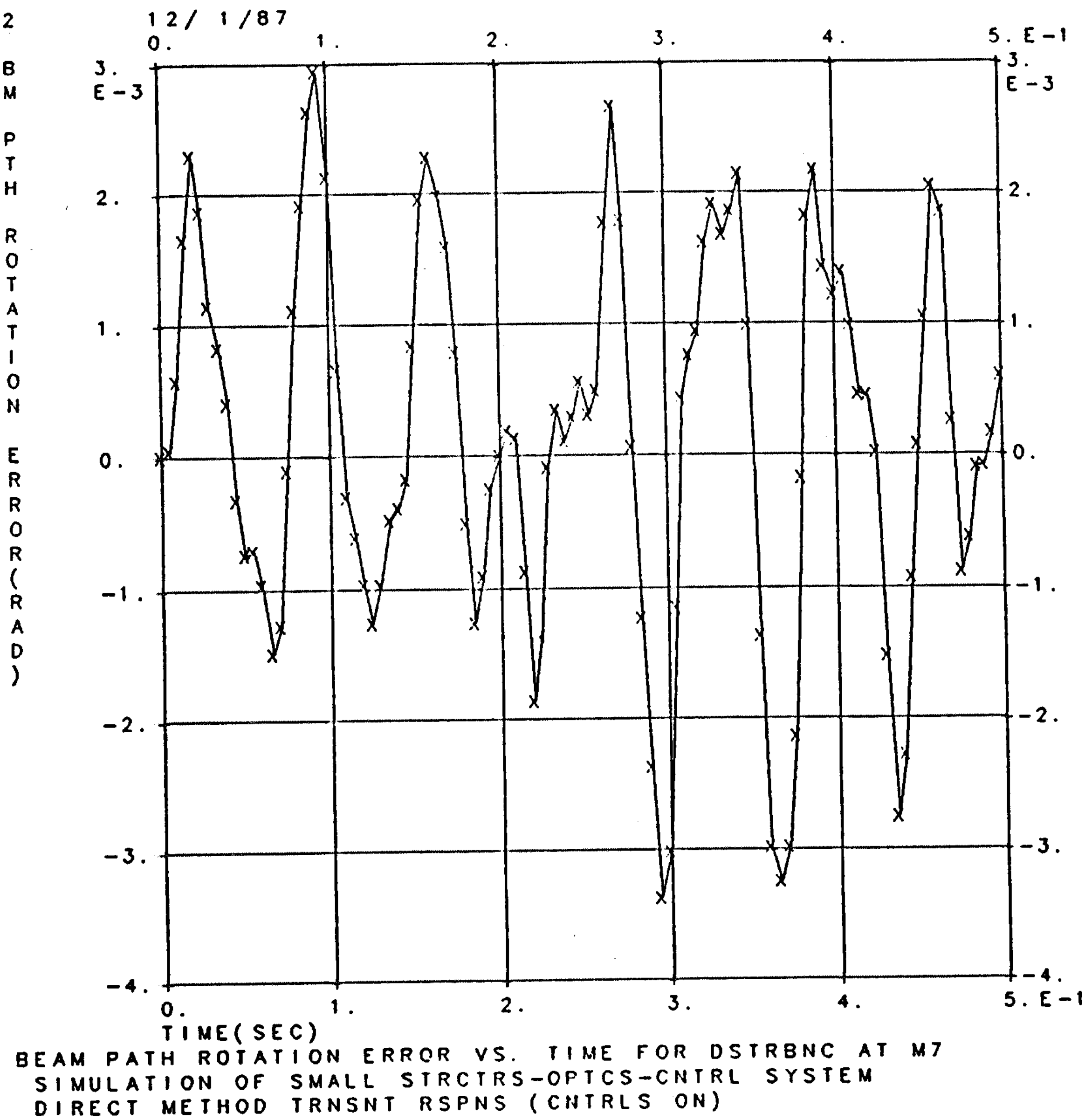

Figure 6 - Laser Beam Path Angular Error vs Time (Controls ON) as Calculated by MSC/NASTRAN

error curve as computed by MSC/NASTRAN. A comparison of Figures 3 and 4 shows excellent agreement. In fact, if one examines the tabulated output (not in this paper) from TIMRSP and MSC/NASTRAN for the Beam Translational Error vs Time values, he or she would note agreement within two and many times three significant figures for corresponding error quantities.

Similarly, the Beam Angular Error curve shown in Figure 5 for TIMRSP agrees very closely with that presented in Figure 6 as calculated by MSC/NASTRAN. If one studied the tabular outputs for Beam Angular Error vs Time as analyzed by TIMRSP and MSC/NASTRAN, one would see again agreement to two and three significant figures.

V. Conclusions

Because the agreement on the Beam Path Error curves between TIMRSP and MSC/NASTRAN was so close, one could conclude that the SSOCS model was correctly implemented in the two codes. Since the SSOCS model was an intermediate step to implementing MSC/NASTRAN on the more complex LSOC model, very little time was spent on tweaking model parameters or designing higher order (or more sophisticated) control algorithms to see if a reduction in the Beam Path Error, over that which was obtained herein, could be achieved. Engaging this challenge is left to any interested readers.

APPENDIX - MSC/NASTRAN Input Deck for SSOCS Model

```
*DECK NSSOC
ID NSTRN,SSOC
SOL 27
TIME 10
DIAG 8
ALTER 382
MATPRN   K2PP,B2PP,M2PP//  $
ALTER 391
MATPRN   KDD,BDD,MDD//  $
ENDALTER
CEND
TITLE = SIMULATION OF SMALL STRCTRS-OPTCS-CNTRL SYSTEM
SUBTITLE = DIRECT METHOD TRNSNT RSPNS (CNTRLS ON)
NONLINEAR=78
TFL=1
TSTEP=72
DLOAD=75
SET 8=7
OLOAD=8
SET 9=27,28
NLLOAD=9
SET 7=1,2,3,4,7,21,22,27,28
SDISPL=7
OUTPUT(XYPLOT)
PLOTTER NASTPLOT(T,0)
XPAPER=11.0
YPAPER=11.0
XGRID=YES
YGRID=YES
XAXIS=YES
YAXIS=YES
CURVELINESYMBOL=1
XTITLE=TIME(SEC)
YTITLE=BM PTH TRNSLTNL ERROR (IN)
TCURVE=BEAM PATH TRANSLATION ERROR VS. TIME FOR DSTRBNC AT M7
XYPLOT SDISPL / 21(T1)
YTITLE=BM PTH ROTATION ERROR(RAD)
TCURVE=BEAM PATH ROTATION ERROR VS. TIME FOR DSTRBNC AT M7
XYPLOT SDISPL / 22(T1)
$
BEGIN BULK
$
$    COORDINATE SYSTEM FOR BM STRNG MRR, M1
$
CORD2R,1,,0.0,61.9615,0.0,0.0,61.9615,1.0,+CRD1
+CRD1,-1.0,62.5389,1.0
$
$    COORDINATE SYSTEM FOR DSTRBD MRR, M2
$
CORD2R,2,,30.0,10.0,0.0,30.0,10.0,1.0,+CRD2
+CRD2,31.0,10.0,1.0
$    GRIDS FOR BM STRNG MRR, M1
GRID,1,1,0.0,0.0,0.0,1,1345
GRID,2,1,3.0,0.0,0.0,1
GRID,3,1,-3.0,0.0,0.0,1
$    GRIDS FOR DSTRBD MRR, M2
GRID,4,2,0.0,0.0,0.0,2,1345
GRID,5,2,3.0,0.0,0.0,2
GRID,6,2,-3.0,0.0,0.0,2
$    GRIDS FOR M1 SUPPORT STRUCTURE
```

```
GRID,8,1,3.0,-5.0,0.0,1,13456
GRID,9,1,-3.0,-5.0,0.0,1,13456
$     GRIDS FOR M2 SUPPORT STRCTR AND MASS M7
GRID,7,2,3.0,-5.0,0.0,2,13456
CONM2,70,7,,0.018
$     M1 ELEMENTS
CBAR,10,100,1,2,8
CBAR,11,100,1,3,9
PBAR,100,110,3.0,0.25,2.25,1.0
MAT1,110,1.0E6,,0.3
CONM2,10,1,,7.8889-3
CONM2,20,2,,2.0555-3
CONM2,30,3,,2.0555-3
$     M2 ELEMENTS
CBAR,12,100,4,5,7
CBAR,13,100,4,6,7
CONM2,40,4,,7.8889-3
CONM2,50,5,,2.0555-3
CONM2,60,6,,2.0555-3
$     STRCTR SPRING SUPPORT FOR BM STRNG MRR ACTRS
CELAS2,8,120.0,8,2
CELAS2,9,120.0,9,2
$     STRCTR SPRING SUPPORT FOR DSTRBD MRR, M2
CELAS2,57,240.0,5,2,7,2
CELAS2,6,120.0,6,2
CELAS2,7,240.0,7,2
$     DISTURBANCE FORCE APPL'D TO M7
DAREA,76,7,2,1.0
TLOAD1,75,76,,0,107
TABLED1,107,,,,,,,,+TB107A
+TB107A,0.0,1.0,0.2,1.0,0.2,0.0,0.5,0.0,+TB107B
+TB107B,ENDT
$     ACTUATOR 2 ELEMENTS
CELAS2,28,12.0,8,2,2,2
CDAMP2,82,0.5,8,2,2,2
CONM2,202,2,,0.004      $MASS OF ACTR 2 ROD
CONM2,802,8,,0.012      $MASS OF ACTR 2 CASE
$     ACTUATOR 3 ELEMENTS
CELAS2,39,12.0,9,2,3,2
CDAMP2,93,0.5,9,2,3,2
CONM2,303,3,,0.004      $MASS OF ACTR 3 ROD
CONM2,903,9,,0.012      $MASS OF ACTR 3 CASE
$     VARIABLES FOR CONTROLLER COMPONENTS
SPOINT,27,28
EPOINT,21,THRU,26
EPOINT,29,THRU,32
$     ERROR EQNS
TF,1,21,0,-1.0,,,,,+TF21A
+TF21A,1,2,-1.732,,,,,,+TF21B
+TF21B,1,6,264.0,,,,,,+TF21C
+TF21C,4,2,-0.50,,,,,,+TF21D
+TF21D,4,6,-144.0
TF,1,22,0,-1.0,,,,,+TF22A
+TF22A,1,6,-2.0,,,,,,+TF22B
+TF22B,4,6,2.0
$     CONTROLLER EQNS
TF,1,23,0,-1.0,,,,,+TF23A
+TF23A,21,0,-1.0
TF,1,24,0,-1.0,,,,,+TF24A
+TF24A,22,0,-1.0
```

```
TF,1,25,0,-1.0,,,,,+TF25A
+TF25A,23,0,-.5774,,,,,,+TF25B
+TF25B,24,0,-76.2125
TF,1,26,0,-1.0,,,,,+TF26A
+TF26A,24,0,-0.5
$
NOLIN1,78,27,0,0.1,25,0,278     $ SF=1/UMAX=0.1
NOLIN1,78,28,0,10.0,26,0,278    $ SF=1/THETMAX=10.0
TABLED1,278,,,,,,,,+TB278A
+TB278A,-5.0,-.99991,-4.5,-.99975,-4.0,-.99933,-3.5,-.99818,+TB278B
+TB278B,-3.0,-.99505,-2.5,-.98661,-2.0,-.96403,-1.8,-.94681,+TB278C
+TB278C,-1.6,-.92167,-1.5,-.90515,-1.4,-.88535,-1.3,-.86172,+TB278D
+TB278D,-1.2,-.83365,-1.1,-.80050,-1.0,-.76159,-0.9,-.71630,+TB278E
+TB278E,-0.8,-.66404,-0.7,-.60437,-0.6,-.53705,-0.5,-.46212,+TB278F
+TB278F,-0.4,-.37995,-0.3,-.29131,-0.2,-.19738,-0.1,-.09967,+TB278G
+TB278G,-.05,-.04996,-.01,-.0100,0.0,0.0000,0.01,.0100,+TB278H
+TB278H,0.05,0.04996,0.1,0.09967,0.2,0.19738,0.3,0.29131,+TB278I
+TB278I,0.4,0.37995,0.5,0.46212,0.6,0.53705,0.7,0.60437,+TB278J
+TB278J,0.8,0.66404,0.9,0.71630,1.0,0.76159,1.1,0.80050,+TB278K
+TB278K,1.2,0.83365,1.3,0.86172,1.4,0.88535,1.5,0.90515,+TB278L
+TB278L,1.6,0.92167,1.8,0.94681,2.0,0.96403,2.5,0.98661,+TB278M
+TB278M,3.0,0.99505,3.5,0.99818,4.0,0.99933,4.5,0.99975,+TB278N
+TB278N,5.0,0.99991,ENDT
$    STFFNSS (TO MAKE APPL'D FORCE = DSPL)  FOR NOLIN CORR SIG
CELAS2,207,1.0,27,0
$CMASS2,207,1.0-6,27,0
$CDAMP2,207,2.0-3,27,0
CELAS2,208,1.0,28,0
$CMASS2,28,1.0-6,28,0
$CDAMP2,28,2.0-3,28,0
$    VOLTAGE GENERATED FOR VOICE COIL ACTRS
TF,1,29,0,-1.0,,,,,+TF29A
+TF29A,27,0,1.0,,,,,,+TF29B
+TF29B,28,0,1.0
TF,1,30,0,-1.0,,,,,+TF30A
+TF30A,27,0,1.0,,,,,,+TF30B
+TF30B,28,0,-1.0
$    VOICE COIL FORCES APPL'D TO ACTRS
TF,1,31,0,-1.0,,,,,+TF31A
+TF31A,29,0,10.0
TF,1,32,0,-1.0,,,,,+TF32A
+TF32A,30,0,10.0
$    APPLY VOICE COIL FORCE TO ACTRS
$    ACTUATOR 2
TF,1,8,2,,,,,,+TF8A
+TF8A,29,0,10.0
TF,1,2,2,,,,,,+TF2A
+TF2A,29,0,-10.0
$    ACTUATOR 3
TF,1,9,2,,,,,,+TF9A
+TF9A,30,0,10.0
TF,1,3,2,,,,,,+TF3A
+TF3A,30,0,-10.0
$
TSTEP,72,5000,0.0001,50
PARAM,NEWSEQ,-1
PARAM,USETPRT,1
ENDDATA
```