VERN OVERBYE

A. O. SMITH ENGINEERING SYSTEMS

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MSC/NASTRAN

SOLUTION 99 EXPERIENCE

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ABSTRACT

Geometric and material nonlinearity is a common occurrence in dynamic analysis of structures and machinery. The MSC/NASTRAN SOL 99 procedure became available in Version 62 to analyze GNL and MNL transient loading problems. This paper illustrates SOL 99 analysis of industrial gear train applications with primary emphasis on use of the gap element to represent backlash. A small drop container analysis is also presented with comparisons made to the ANSYS gap element in transient analysis.

BACKGROUND

Geometric and material nonlinear direct transient analysis Solution 99, implemented in MSC/NASTRAN Version 62, was a logical extension of the geometric and material nonlinear static analysis (SOL 66) implemented in Version 61. The technique has been thoroughly documented (1)* including theory, solution technique, MSC/NASTRAN deck organization, and example problem solutions.

Solution 99 is quite similar to Solution 69 (Direct Transient, Superelements) in that a direct access data base is required and dynamic loads are imposed with TLOAD1 or TLOAD2 bulk data cards. The linear TSTEP card is replaced by TSTEPNL, which adds SOL 66 NLPARM solution iteration controls and convergence criteria. One-, two-, and three-dimensional elements are available for modeling convenience.

In this paper, the GAP element is used to simulate dynamic impact. All transient results are displayed using MSC/NASTRAN XY plots.

DROP CONTAINER IMPACT ANALYSIS

A heavy box containing a small spring-supported mass is allowed to free fall and undergo a perfectly inelastic impact. The analysis objective is to determine maximum displacement of the sprung mass. This example has been used previously to demonstrate the ANSYS STIF40 spring-mass-gap element (2), which is quite similar to the MSC/NASTRAN GAP element.

Figure 1a shows the problem sketch and Figure 1b shows the MSC/NASTRAN bulk data. This one DOF model shows constant acceleration applied to the mass and a one inch initial gap opening to simulate free fall. Gap closing stiffness equals the spring rate shown in Figure 1a, while the opening and transverse spring rates are set to zero. A total of 110 one millisecond time steps is used with output requested at each time step. The AUTO iteration method is used with a displacement convergence criteria.

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*See references at end of paper.

Transient displacement of the sprung mass is shown on an MSC/NASTRAN XY plot in Figure 2. Free fall time of about 0.072 seconds and maximum deflection of 1.55 inches at 0.101 seconds closely agrees with the ANSYS and theoretical result.

ROLLING MILL TORQUE ANALYSIS

Figure 3 shows a sketch of typical components in a metal rolling mill drive stand. Torsional vibration (continuous oscillatory motion) and transient shock (bar-roller impact) are of major concern to the mill designer. A rolling mill analysis program has been developed (AOS/RMAP, see Appendix A) to output transient variations of torque amplification factors* for an arbitrary torque disturbance at the rollers and display gear train natural frequencies.

The MSC/NASTRAN GAP element is suitable to replace gear-backlash representation by the deadspace function used in AOS/RMAP. Hence, an MSC/NASTRAN model was developed to represent the gear train shown in Figure 3 wherein shafts were modeled using CELAS2 elements, CMASS2 elements represented component polar moments of inertia, and gear teeth were located by rigid elements from centers of rotation. Shaft spring rates and mass polar moments of inertia used are summarized in Figure A1 (Appendix A).

Two GAP elements represent forward and reverse gear backlash by locating end B GRIDs slightly displaced from a common end A GRID. Gap closing stiffness was set equal to tooth stiffness used in the AOS/RMAP program. Transient disturbance at the roller was the exponential decay function used in the AOS/RMAP example detailed in Appendix A.

A zero backlash MSC/NASTRAN model was also solved by the direct transient method (SOL 27) replacing the gear tooth GAP elements with MPC relationships as used in AOS/RMAP to obtain gear train torsional natural frequencies (see Appendix A).

Figure 4 shows transient torque behavior at the gear and motor shafts (see Figure 3) due to the roller torque disturbance with zero gear backlash, while Figure 5 shows the effect of an excessive 0.05 inch total backlash. The oscillatory torque at the motor shaft shows nonlinear effects in gear teeth. These results compare favorably with AOS/RMAP results (for a longer analysis time period) shown in Figure A3 (Appendix A).

Although the MSC/NASTRAN GAP element has been shown to be suitable to model gear backlash effects in rolling mill analysis, there is no justification in using this approach in the well-accepted AOS/RMAP technique at this time. Material nonlinearity considerations may require more extensive program capability in the future.

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*Torque amplification = (actual torque/nominal rolling torque).

POSITIONAL CONTROL SYSTEM ANALYSIS

Figure 6 shows a sketch of a modern positional control system. An arc gear, which supports a load to be accurately positioned, is driven by a spur gear train and a bevel gear. The bevel gear is driven with a pinion coupled to a position drive transmission system. A second pinion on the bevel gear is coupled to a shutdown brake, which prevents gear train angular rotation while locked and acts as a rotational inertia load during positioning.

The GAP element was used to model 0.004 inch total backlash at each gear-pinion position. Two gap elements were used to represent forward and reverse backlash. As in the rolling mill model, two GRIDs attached by rigid elements to the arc gear center of rotation formed end B gap GRIDs with a centered end A GRID attached by a short BAR element (to represent the pinion tooth) and a rigid element to pinion center of rotation. Gap closing stiffness is 100 million lb/in and opening stiffnes 100 lb/in.

All gear shafts were modeled with CBAR elements and CMASS2 elements modeled gear polar moments of inertia. Each shaft-gear unit had a natural frequency between 200 and 2000 Hz, while gear tooth natural frequencies are on the order of 200,000 Hz.

A sawtooth angular acceleration input (about 25 Hz) was applied to the gear train at the position drive transmission shaft. A time step of 0.1 millisecond was used to excite the gear train for 60 milliseconds. The TSTEPNL calls for AUTO iteration control and displacement determines convergence criteria. A viscous damper across each gap, with a damping coefficient of about 1000 lb sec/in, was required to prevent a diverging solution.

Figure 7 shows transient behavior of shaft torque at the positional drive transmission input (see Figure 6). The figure shows a high frequency component superimposed on the fundamental frequency.

Figure 8 shows shear force versus time at the arc gear and pinion tooth BAR elements. The high frequency component on the fundamental frequency is quite obvious.

CONCLUSIONS

Solution 99 has been shown to represent a convenient method to analyze backlash effects in gear trains. Care must be taken in selecting opening and closing gap stiffness and integration time steps to insure solution convergence. A viscous damper across the gap (available in the ANSYS STIF40 element) often aids in achieving convergence. Printout or XY plotting capability for forces in material nonlinear elements would be a distinct advantage.

REFERENCES

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2. DeSalvo, G. J., "Transient Response of a Drop Container", ANSYS Engineering Analysis System Verification Manual, Swanson Analysis Systems, Inc., Houston, PA, April 1, 1979, pp. 81.1-82.3.

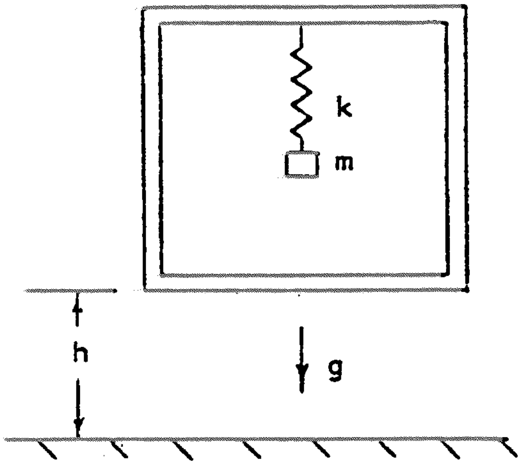
3. Ruehl, J. J., Editor, "RMAP Users Manual", A. O. SMITH Engineering Systems, Brown Deer, WI, February 16, 1981.

4. Lambert, J. L., "AOS/GRAFAX - Interactive Pre- and Post-Processor for MSC/NASTRAN", MSC/NASTRAN User's Conference Proceedings, Pasadena, CA, March 15-16, 1979.

5. Riley, E. L., et al, "AOS/GRAFAX Interactive Processing of MSC/NASTRAN Superelements", Proceedings of the Conference on Finite Element Methods and Technology, Pasadena, CA, March 19-20, 1981.

6. Webster, J. W., et al, "AOS/GRAFAX Interactive Processing of MSC/NASTRAN Dynamic Results", MSC/NASTRAN User's Conference Proceedings, Pasadena, CA, March 18-19, 1982.

7. Larkin, L. A., Editor, "CSMPPLOT", Engineering Systems User's Manual, A. O. SMITH Engineering Systems, Brown Deer, WI, April, 1982, Section 5.7.



CONDITIONS:

$m = 0.5$ LB SEC^2/IN

$k = 1973.92$ LB/IN

$h = 1.0$ IN

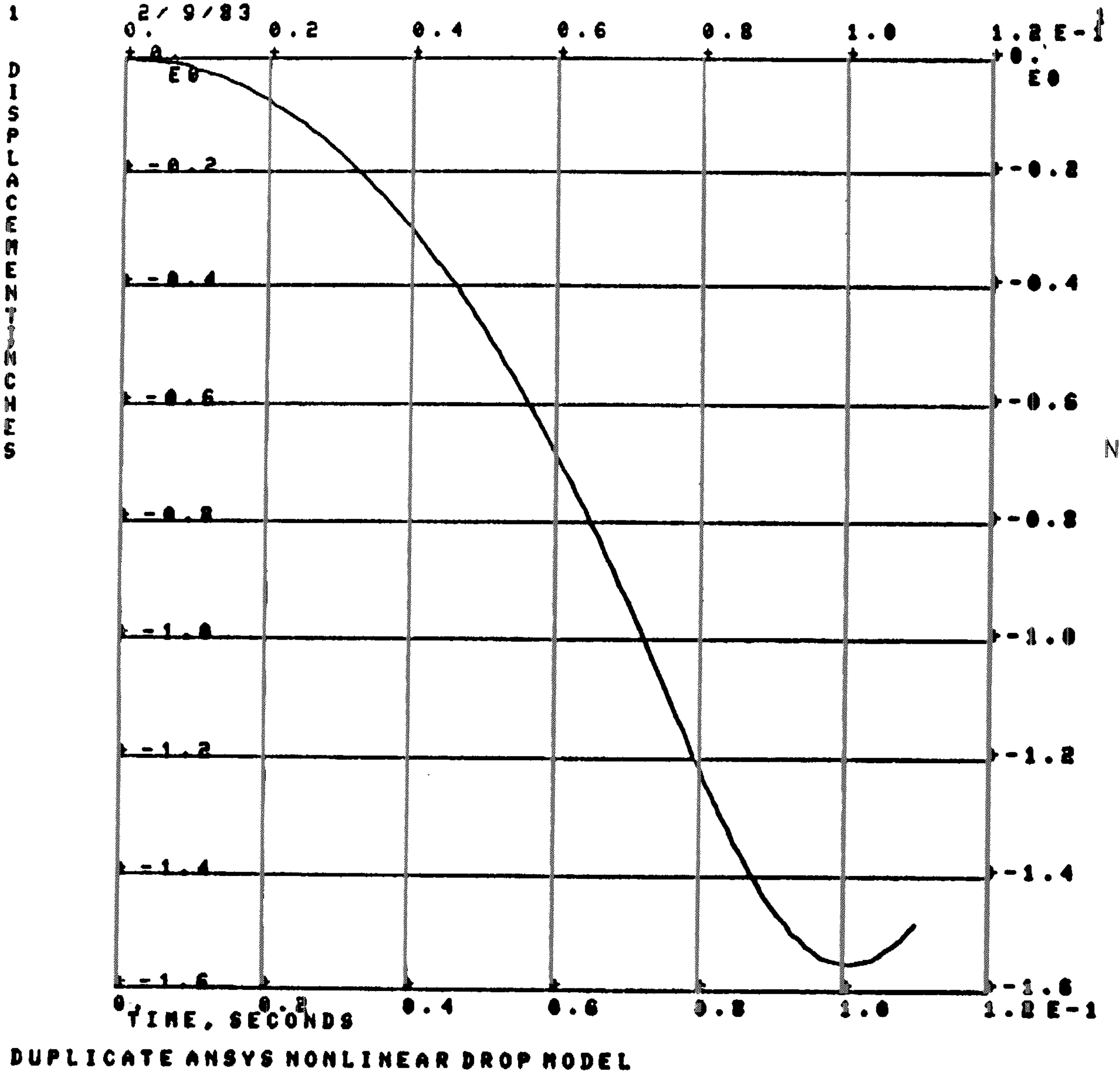
$g = 386$ IN/SEC^2

a. PROBLEM SKETCH

```
                                S O R T E D   B U L K   D A T A   E C H O
.   1   ..  2   ..  3   ..  4   ..  5   ..  6   ..  7   ..  8   ..  9   ..  10  .
CGAP    13      13      1       2       1.      0.      0.
CMASS2  2       .5      1       2
DAREA   12      1       2       -.5
GRID    1               0.      1.      0.              13456
GRID    2               0.      0.      0.              123456
PGAP    13      1.0000          1973.92 0.000   0.0
TABLED1 15                                                      +TB
+TB     0.      386.    10.     386.    ENDT
TLOAD1  10      12              3       15
TSTEPNL 1       110     .001    1       AUTO            20      U
ENDDATA
```

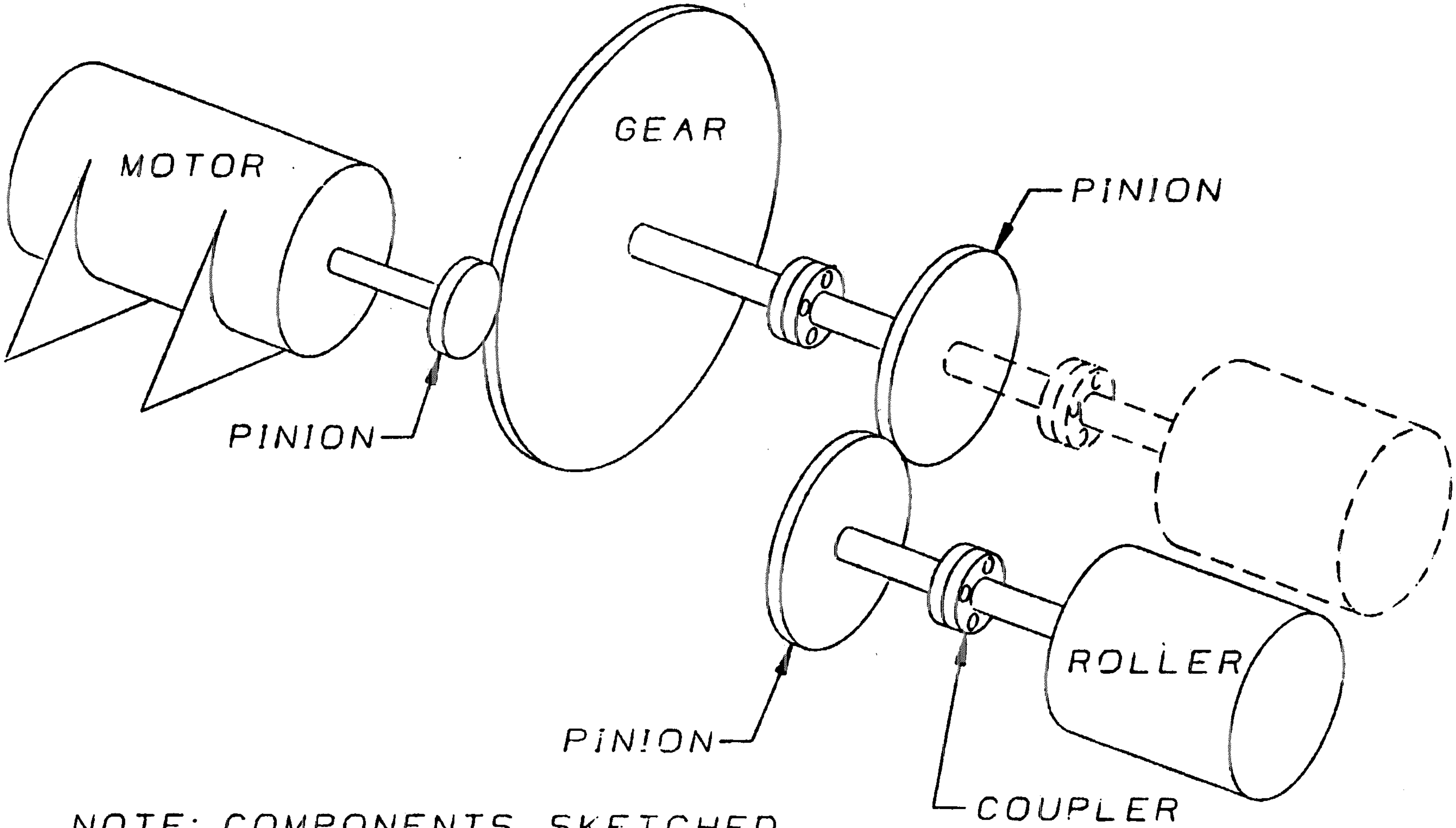
b. MSC/NASTRAN BULK DATA

FIGURE 1. MODEL FOR TRANSIENT RESPONSE OF DROP CONTAINER



NOTE: See Figure 1
for model.

FIGURE 2. TRANSIENT DISPLACEMENT OF SPRUNG MASS



NOTE: COMPONENTS SKETCHED
IN DASHED LINES
NOT MODELED.

FIGURE 3. ROLLING MILL COMPONENTS

NOTE: Compare with Figure A3a (Appendix A) AOS/RMAP results. Motor and gear shafts rotate in opposite directions.

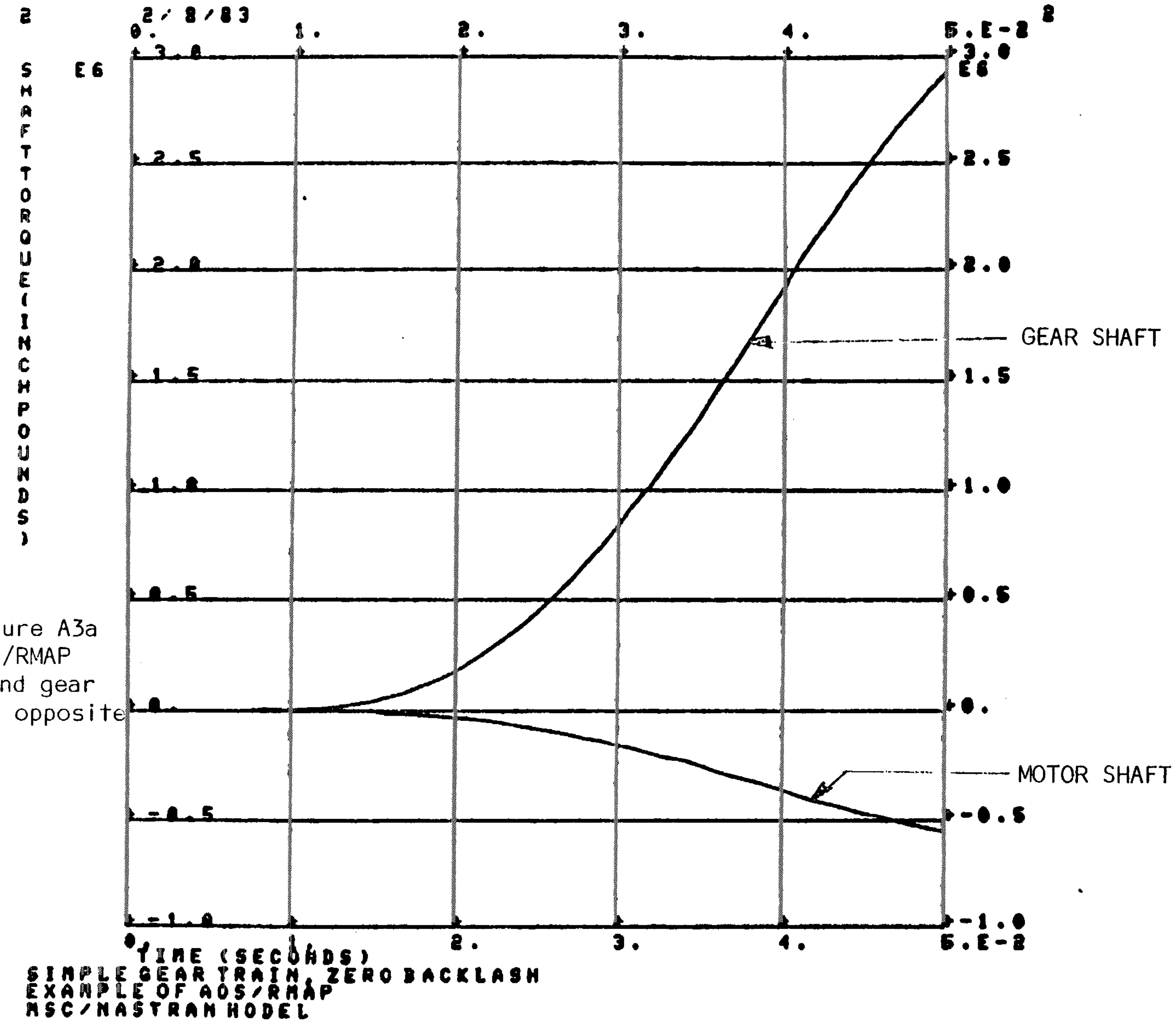
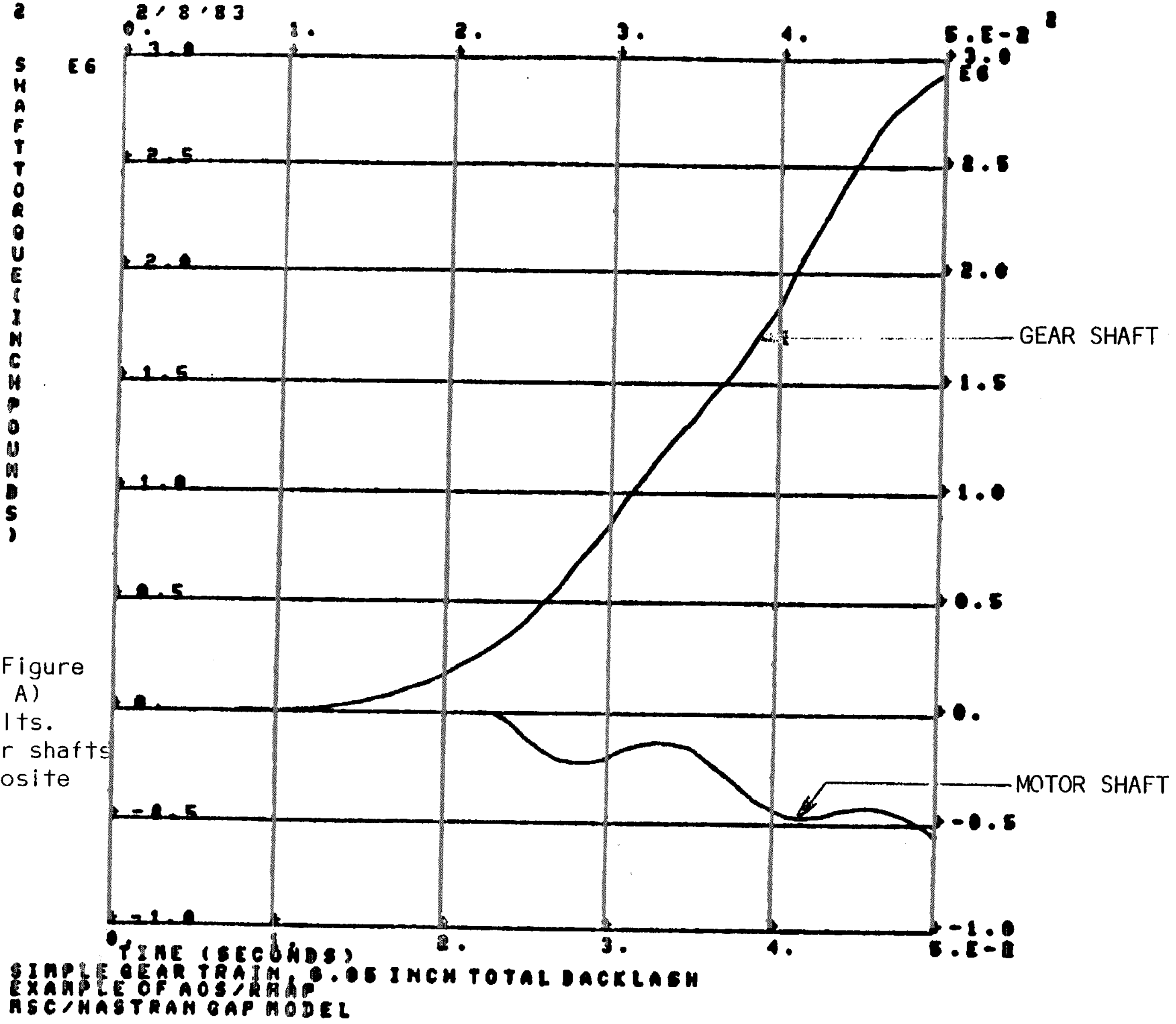


FIGURE 4. MSC/NASTRAN XY PLOT OF ROLLING MILL



NOTE: Compare with Figure A3b (Appendix A) AOS/RMAP results. Motor and gear shafts rotate in opposite directions.

FIGURE 5. MSC/NASTRAN XY PLOT OF ROLLING MILL TRANSIENT SHAFT TORQUE (0.05 INCH TOTAL GEAR-PINION BACKLASH).

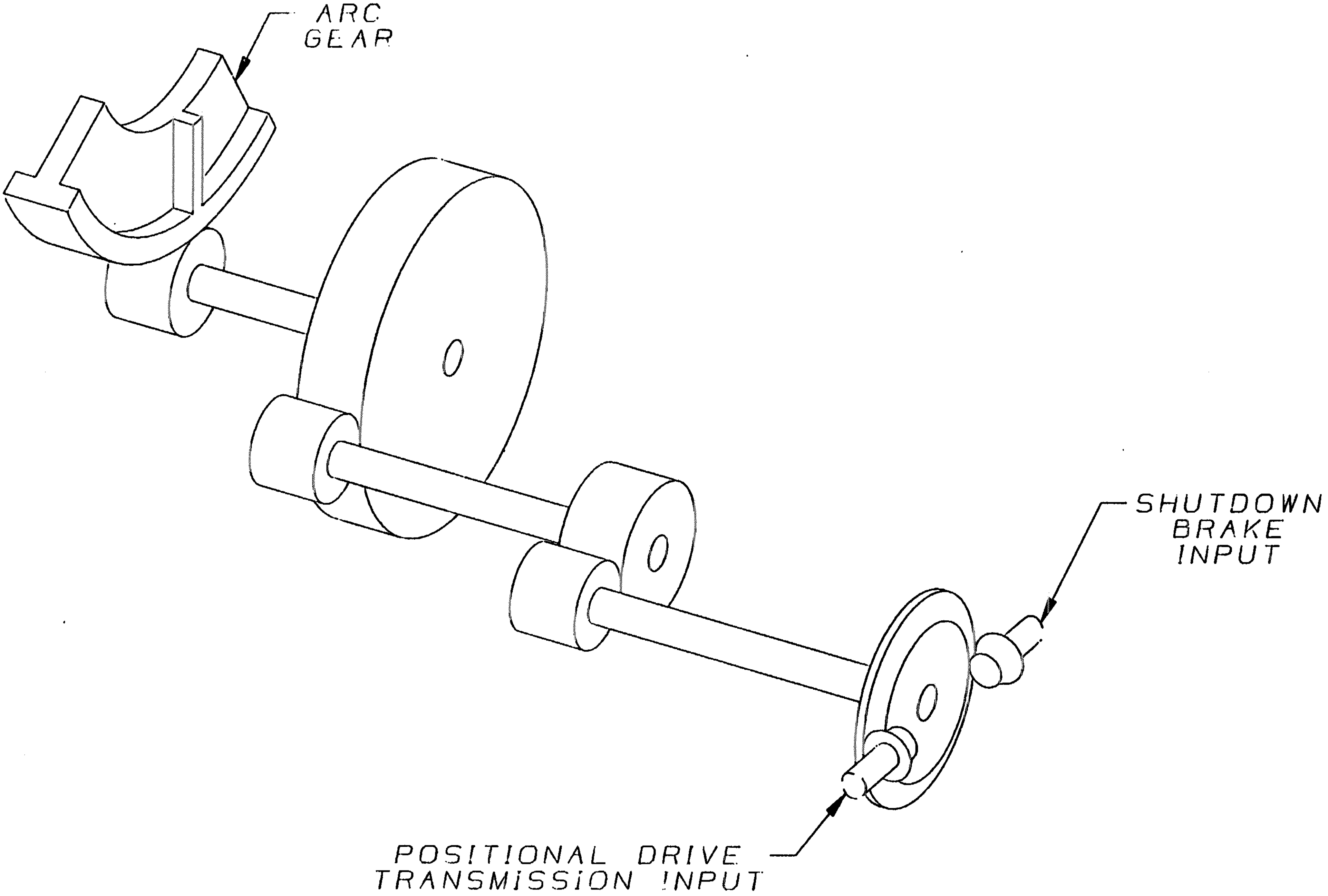
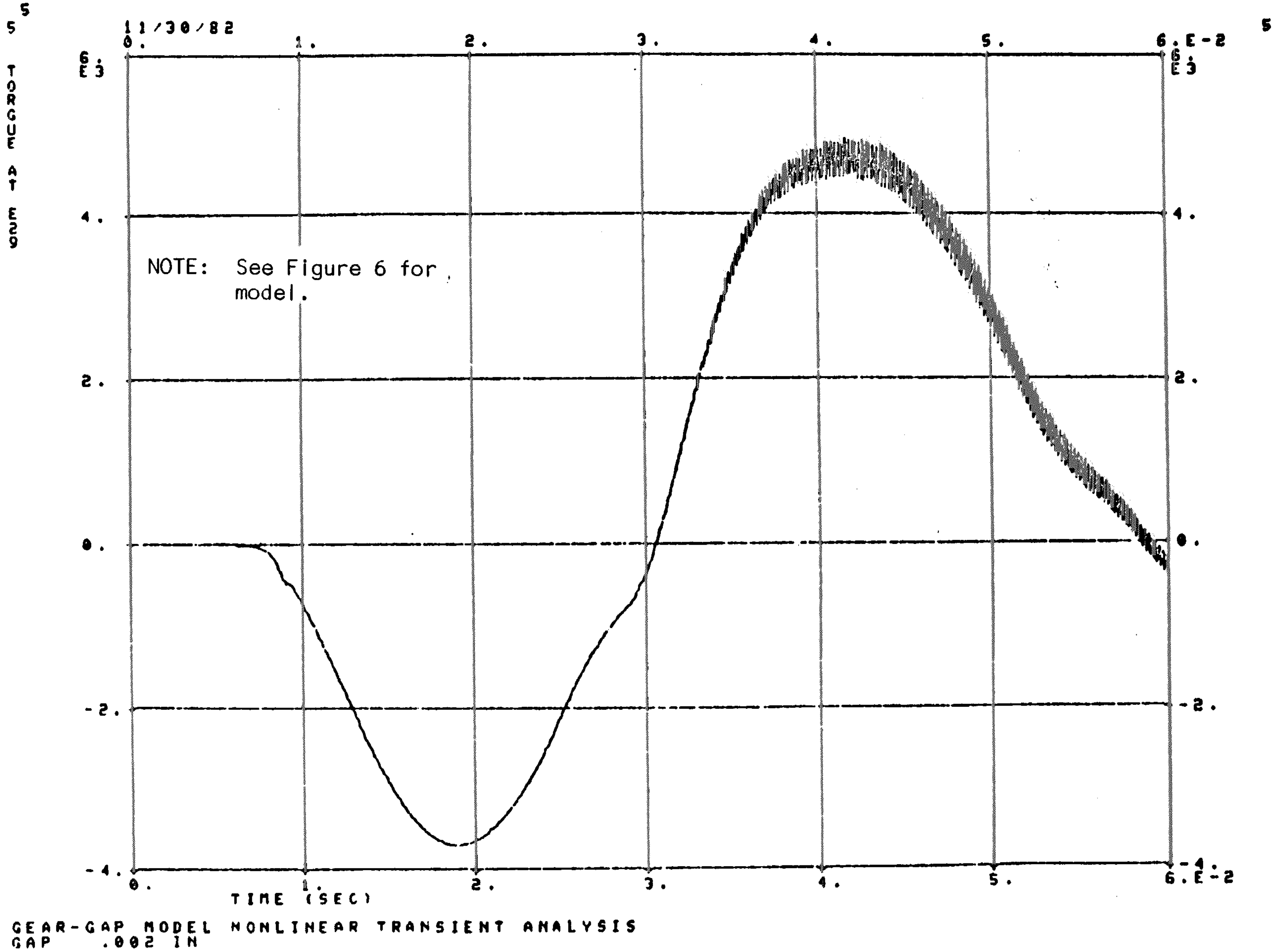
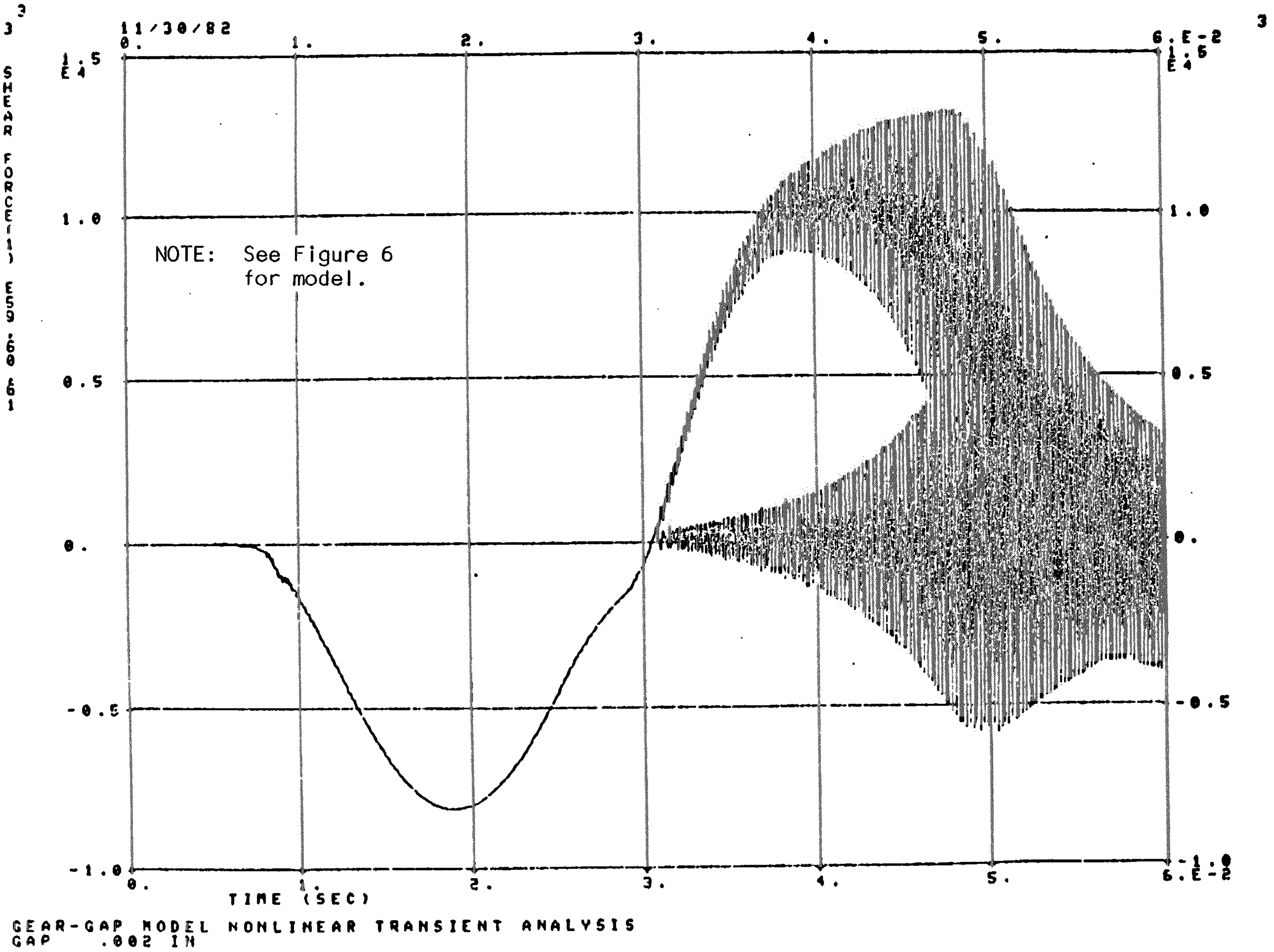


FIGURE 6 POSITIONAL CONTROL GEAR TRAIN



NOTE: See Figure 6 for model.

FIGURE 7. TRANSIENT TORQUE VARIATION AT TRANSMISSION INPUT SHAFT



NOTE: See Figure 6 for model.

FIGURE 8. TRANSIENT SHEAR VARIATION IN ARC GEAR - PINION TEETH.

APPENDIX A

A. O. SMITH ROLLING MILL ANALYSIS PROGRAM

PROGRAM DESCRIPTION

The A. O. SMITH Rolling Mill Analysis Program (AOS/RMAP) was developed to aid the rolling mill designer in calculating torsional vibrational frequencies of typical rolling mill gear trains as well as transient shock response due to roller impact loads (3)*. The interactive AOS/RMAP procedure** allows the designer to enter component polar moments of inertia, shaft torsional spring constants and damping, and gear teeth stiffness and backlash data along with motor nominal torque and speed as well as a description of transient torque disturbance at the rollers. The gear train circuit is displayed and data editing allows input data correction.

A batch MSC/NASTRAN run is submitted to yield gear train torsional natural frequencies (without gear backlash) and a batch CSMP*** run is submitted to yield transient torque amplification factors(see text) throughout the gear train. Torsional frequency results are interpreted using interactive displays of the MSC/NASTRAN Real Eigenvalue table and AOS/GRAFAX (4, 5, 6) line graphs of rotational displacements versus GRID ID for mode shapes. An A. O. SMITH proprietary CSMPPLOT program (7) plots dynamic results such as torque amplification factors from the CSMP run.

AOS/RMAP EXAMPLE ANALYSIS

The rolling mill gear train sketched in Figure 3 (see text) results in AOS/RMAP displays shown in Figure A1 as stiffness and inertial data are entered and reviewed. Note that a nominal gear tooth force is calculated between the speed reduction gear and pinion. The speed reversing pinion, on the other hand, arbitrarily has unit radius making gear tooth force equal to transmitted torque.

An MSC/NASTRAN run deck is generated interactively for torsional frequency analysis (SOL 25) without gear backlash and with infinite tooth stiffness. This deck consists of GRIDs, CMASS2 polar moments of inertia, CELAS2 torsional springs, MPC gear-pinion speed ratios, along with the appropriate EIGR and SUPORT cards. Five elastic frequenies from 6.85 to 130.0 Hz were obtained. Figure A2 shows an AOS/GRAFAX line graph of R1 displacement versus GRID ID for the lowest frequency elastic mode. This graph is useful in interpreting rotational mode shapes.

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*See references at end of paper.

**AOS/RMAP is available on the A. O. SMITH Time Sharing Computer System.

***IBM's Continuous Systems Modeling Program.

A CSMP deck is generated to impose a transient torque input to the gear train at the rollers (in this example). Zero backlash and an excessive 0.05 inch gear-pinion total backlash analyses were performed. Results are shown in Figure A3.

The figure shows that the gear shaft responds to the roller torque disturbance before the motor shaft and that excessive backlash in the gear-pinion set causes torque oscillations at the motor shaft.

SUMMARY

The AOS/RMAP interactive procedure aids the rolling mill designer to subject the mill to numerous roller torque distrubances during design and graphically interpret results.

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EXAMPLE OF AOS/RMAP                                                    12/29/82

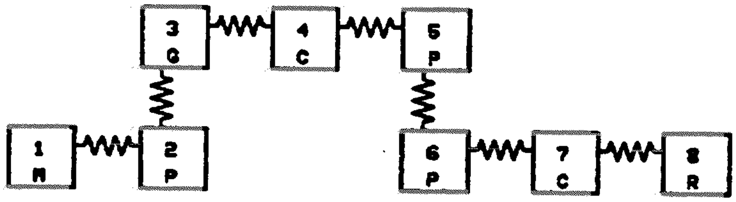

STATION KEY:

NUMBER TYPE MOMENT OF INERTIA   SPEED        RADIUS    TORQUE NOMINAL TORQUE
             (IN-LB-SEC**2)   (RAD/SEC)       (IN)      TYPE      (IN-LB)
-----------------------------------------------------------------------------
   1     M        13250.          .0            .0         0       200000.
   2     P        250.00          .0          36.00        0       200000.
   3     G        32500.          .0          172.0        0       955556.
   4     C        2250.0          .0            .0         0       955556.
   5     P        300.00          .0          1.000        0       955556.
   6     P        300.00          .0          1.000        0       955556.
   7     C        13500.          .0            .0         0       955556.
   8     R        12000.          .0            .0         1       955556.


CONNECTION KEY:

NUMBER FROM TO PLOT STIFFNESS*        DAMPING        BACKLASH  NOMINAL TORQUE
               LOC. (IN-LB/RAD) (IN-LB-SEC/RAD)       (IN)        (IN-LB)
-----------------------------------------------------------------------------
   1     1    2   1   3.5000E+08      .0             .0           200000.
  2G     2    3   2   8.0000E+07      .0             5.000E-02    5555.55
   3     3    4   1   3.5000E+08      .0             .0           955558.
   4     4    5   1   2.5000E+08      .0             .0           955556.
  5G     5    6   3   1.0000E+10      .0             .0           955556.
   6     6    7   1   8.0000E+07      .0             .0           955556.
   7     7    8   1   8.0000E+07      .0             .0           955556.

 * IF CONNECTION IS BETWEEN GEAR TEETH, STIFFNESS UNITS ARE LB/IN,
   AND NOMINAL TORQUE IS NOMINAL FORCE(LB)
```

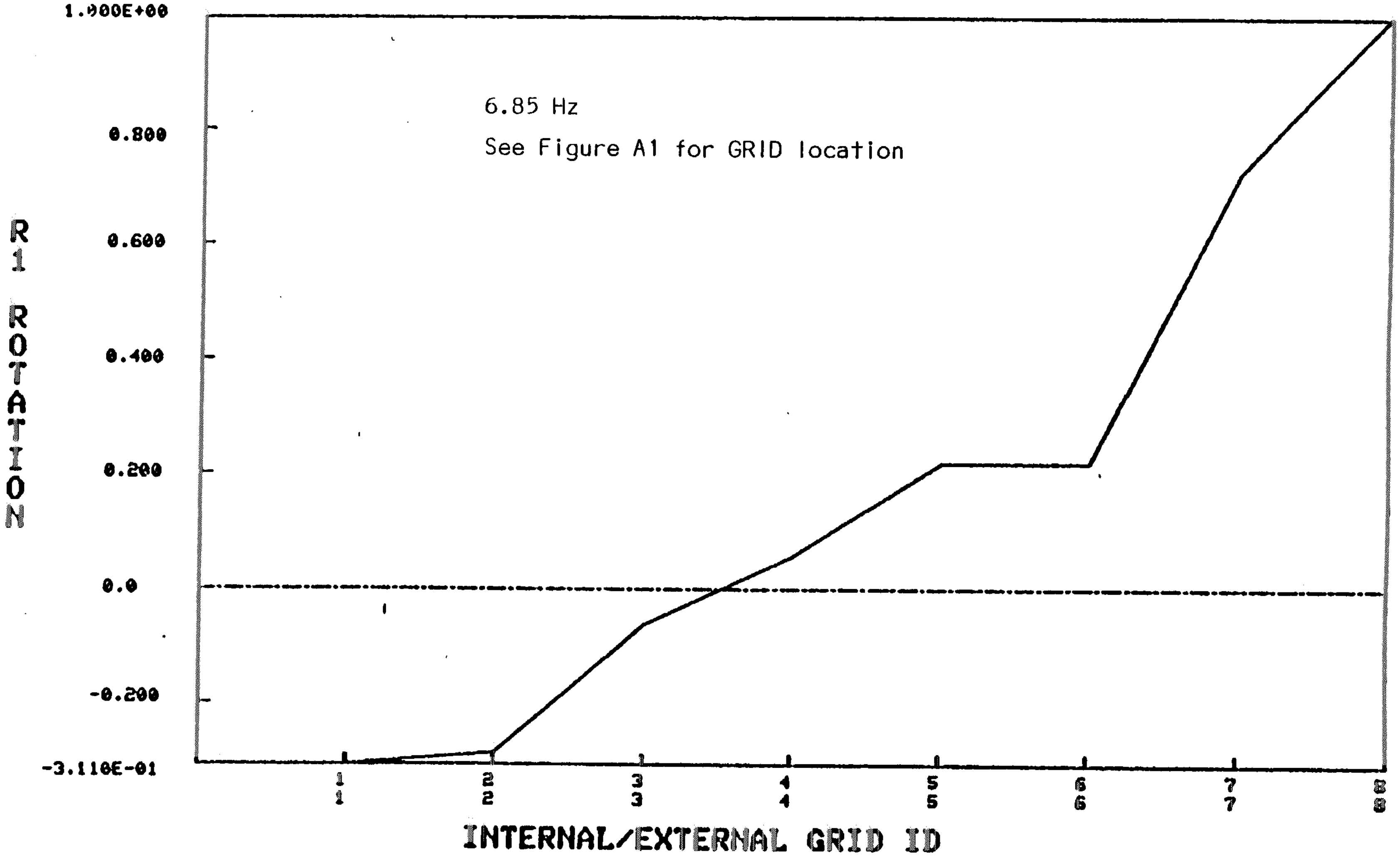


NOMENCLATURE:
M - motor
P - pinion
G - gear
C - coupling
R - roller

See Figure 3 above for gear train sketch.

FIGURE A1. AOS/RMAP DISPLAY

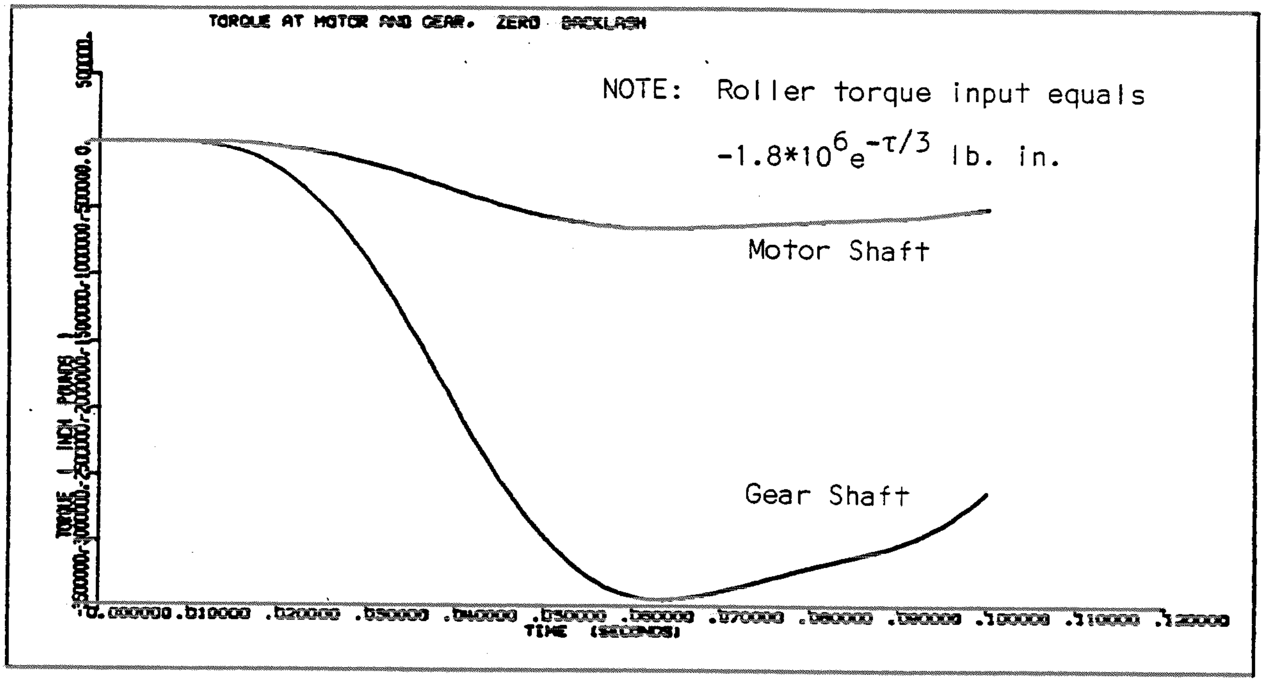
AOS GRAFAX MODEL: EDGER SUBCASE 2 29-DEC-82
EXAMPLE OF AOS/RMAP
VDOEDGER



6.85 Hz

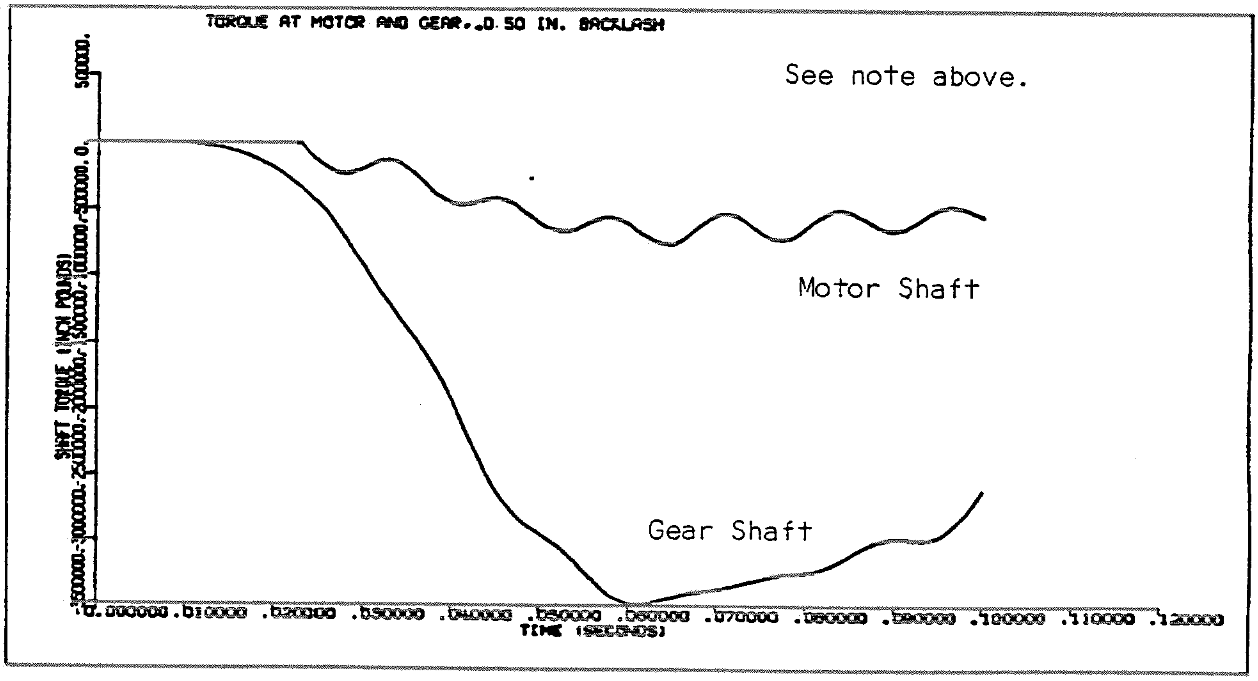
See Figure A1 for GRID location

ENTER RANGE TO BE GRAPHED:



NOTE: Roller torque input equals $-1.8*10^{6}e^{-\tau/3}$ lb. in.

a. Gear-Pinion Backlash: 0.0 inches



See note above.

b. Gear-Pinion Backlash: 0.05 inches

FIGURE A3. AOS/RMAP EXAMPLE ANALYSIS TORQUE RESULTS