N73-25210

NASA TECHNICAL REPORT

NASA TR R-414

NASA TR R-414

DIGITAL SIMULATION OF THE SERPENTUATOR USING MARSYAS

by Sudarshan P. Singh

George C. Marshall Space Flight Center
Marshall Space Flight Center, Ala. 35812

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1973

1. REPORT NO. NASA TR R-414	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Digital Simulation of the Serpentuator using MARSYAS		5. REPORT DATE June 1973 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Sudarshan P. Singh		8. PERFORMING ORGANIZATION REPORT # M543
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20540		13. TYPE OF REPORT & PERIOD COVERED Technical Report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES Prepared by Computation Laboratory, Science and Engineering.
This research was accomplished at the Computation Laboratory of Marshall Space Flight Center while the author held a National Research Council Post-doctoral Resident Research Associateship supported by the National Aeronautics and Space Administration.

16. ABSTRACT

Serpentuator is a serpentine teleoperator device for intravehicular and extravehicular activities in space. The serpentuator is simulated using the digital simulation software system MARSYAS and using the Component-Connection Simulation model and the Direct Simulation model. A comparison of the results for the two cases shows that under identical conditions, simulation execution time in the Component-Connection model case is reduced by a factor of the order of 100. A visual display of the serpentuator positions is obtained using the AMTRAN system on the Datacraft DC 6024 computer.

17. KEY WORDS Teleoperator Device Digital Simulation MARSYAS Algebraic Loops Component-Connection Model AMTRAN	18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	56	$3.00

For sale by National Technical Information Service, Springfield, Virginia 22151

ACKNOWLEDGMENTS

The author gratefully acknowledges the help and cooperation of the members of the MARSYAS group of Computer Sciences Corporation, Digital Simulation Systems, Inc., and the AMTRAN systems group in the preparation of this report. Special thanks go to my scientific advisor Dr. Heinz Trauboth of the Computation Laboratory for several helpful suggestions.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

DEFINITION OF SYMBOLS

Symbol	Definition
Θ_i	Angular position of (i + 1)th link with respect to the reference axis
$\dot{\Theta}$	First derivative of Θ
$\ddot{\Theta}$	Second derivative of Θ
δ	Input to the serpentuator
L	Length of each link
m	Mass of each link
M_m	Mass of the Astronaut
I_j	Moment of inertia of the jth link
K_i	Spring constant of ith link

DIGITAL SIMULATION OF THE SERPENTUATOR USING MARSYAS

SUMMARY

The serpentuator is a serpentine teleoperator device for intravehicular and extravehicular activities in Space. The serpentuator is simulated using the digital simulation software of Marshall System for Aerospace Systems Simulation (MARSYAS) to provide the Component-Connection Simulation model and the Direct Simulation model. A comparison of results for the two models shows that under identical conditions, computer simulation execution time for the Component-Connection model is reduced by a factor of the order of 100, in respect to the Direct Simulation model. A visual display of the serpentuator positions was obtained using the Automatic Mathematical Translation (AMTRAN) system on the Datacraft DC 6024 computer.

INTRODUCTION

In the presently used system of operations involving extravehicular activity, the astronaut is either free-flying or tethered to the ship. Such a system may be referred to as a "mechanically open space mobility system," because the astronaut functions as any free satellite of the parent ship or orbital workshop. This open mobility system has some disadvantages, such as (1) mass drainage caused by mobility achieved via rocket principles, (2) complications in space operations resulting from the orbital mechanics involved, and (3) the astronaut, on his own, is very limited in any craftsman type performance.

To obviate some of the difficulties, a "mechanically closed space mobility system" is proposed through which the astronaut and all objects necessary for extravehicular operations are mechanically connected to the parent ship. This mechanical connection is provided by a serpentine actuator called the serpentuator.

The serpentuator is a product of the development of a tooling concept for manufacturing operations in space [1]. It is a teleoperator device consisting of a number of powered links which may be actuated relative to each other. This controllable linkage provides the means to propel, guide, and stabilize astronauts or objects at the free end of the device. The serpentuator can be extended in straight, serpentine, or other configurations as required to transport, dock, and rendezvous.

In this report, the mathematical model of the serpentuator is simulated using MARSYAS. Developed by NASA's Computation Laboratory at Marshall Space Flight Center, MARSYAS is a software system for the digital simulation and analysis of large scale physical systems. A distinguishing feature of MARSYAS is its capability to accept block diagram description of systems as input. Further details may be found in References 2, 3, 4, and 5.

THE SERPENTUATOR MODEL

The mathematical model of the serpentuator is given in the form of a matrix differential equation, shown in Appendix A. The model is a five-link serpentuator, with the angular positions of the five links in respect to the y-axis being expressed by Θ_i (i = 0, 1, 2, 3, 4). The matrix equation is solved for Θ_i (i = 1, 2, 3, 4), using suitable initial values for Θ_i and suitable input functions Θ_0 and δ. Θ_0 is the angular position of the first link with respect to a reference axis and is treated as an input; δ is the angular position input applied to the serpentuator to bring about a desired configuration; M_m and m are the masses of the astronaut and each link, respectively; and I_j refers to the inertia and K to the spring constant.

Numerical values for M_m and m are given as constants while those of L, K, and I_j (j = 1,2,3,4) are given as parameters (a range of values).

For better visual interpretation of the results, plots of positions of the serpentuator links were desired. From the equations, it can be determined that the serpentuator movements are constrained to lie in the X-Y plane and thus the desired plots were easily obtained using AMTRAN.

AMTRAN is a software system developed at Marshall Space Flight Center and Teledyne/Brown Engineering Company. The AMTRAN system incorporates a conversational mode, mathematically oriented language used primarily with teletypes (locally) and graphic terminals (remotely). Further details may be found in References 6 and 7.

THE MARSYAS SIMULATION MODELS

To simulate the serpentuator using MARSYAS [2, 3, 4] the first step is to convert the given mathematical model into a simulation model (a block diagram). This is an important step since the simulation time may differ significantly depending upon how the mathematical model is converted into the simulation model. The Component-Connection model and the Direct model are two of the simulation models of the serpentuator and are described in the following paragraphs.

The Component-Connection Simulation Model

The serpentuator equations are given in Appendix A. In matrix notation, the equations may be written as

$$A(\Theta)\ddot{\Theta} = B(\Theta)(\dot{\Theta})^2 + C\Theta + Du \quad (1)$$

where A, B, C, and D are appropriate matrices and u is the input vector composite of Θ_0 and δ. Assuming that $A(\Theta)$ has an inverse denoted by $A^{-1}(\Theta)$, equation (1) may be rewritten as[1]

$$\ddot{\Theta} = A^{-1}(\Theta)\,[B(\Theta)(\dot{\Theta})^2 + C\,\Theta + D\,u] \quad . \tag{2}$$

The block diagram resulting from equation (2), using the component-connection approach [8, 9][2] is shown in Figure 1. The linear and nonlinear components are shown, as well as the connections. For simulation purposes using MARSYAS, nonlinear components and connection matrices C and D were treated as devices [2].

A listing of the MARSYAS program deck is given in Table 1. Several runs using different integration schemes, integration intervals, and inputs were obtained. It was found that the parameters used in the simulation caused the serpentuator to become unstable after a prolonged application of the input.

The Direct Simulation Model

The direct model was obtained by first expanding the matrix differential equation into four scalar differential equations and then setting up a block diagram[3], using techniques similar to those used in analog simulation. The block diagram is given in Figure 2 and reflects the complexity of the problem. A closer scrutiny reveals several interconnected linear and nonlinear loops, with linear loops nested into nonlinear loops. Since the present MARSYAS capability does not include solving systems with linear loops embedded within nonlinear loops, the model was modified by replacing linear loops with equivalent feedforward gains as indicated in Figure 3.

A listing of the MARSYAS program deck is given in Table 2. Several successful runs using different inputs, integration schemes and simulation times were obtained.

A COMPARISON OF COMPONENT-CONNECTION AND DIRECT MODEL SIMULATION RESULTS

The computer execution time is considerably less in the case of the Component-Connection model, as compared to that of the Direct model. This time was a function of the input, step size, simulation time, and integration method employed.

---

1. H. Blum, Notes on the Serpentuator Simulation (Unpublished Notes). Digital Simulation Systems, Inc., New York, N.Y., October, 1972.
2. Reference 9 will also be published by IEEE in "Transactions on Circuit Theory," Special Issue on Large Scale Networks, 1973.
3. A somewhat different though mathematically equivalent block diagram is obtained by Mr. A. Ventre of Computer Sciences Corporation.

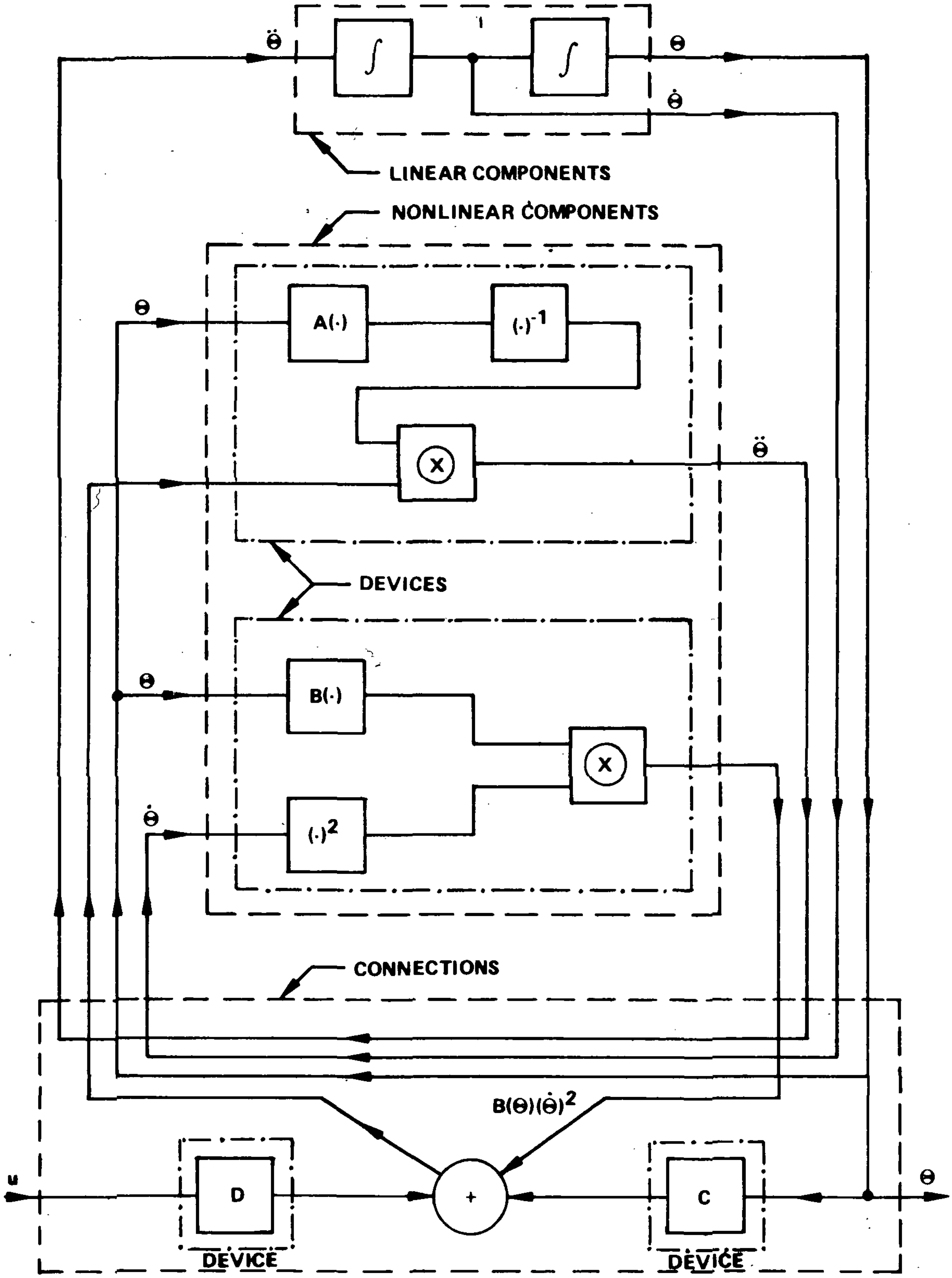


Figure 1. Component-connection simulation model of serpentuator.

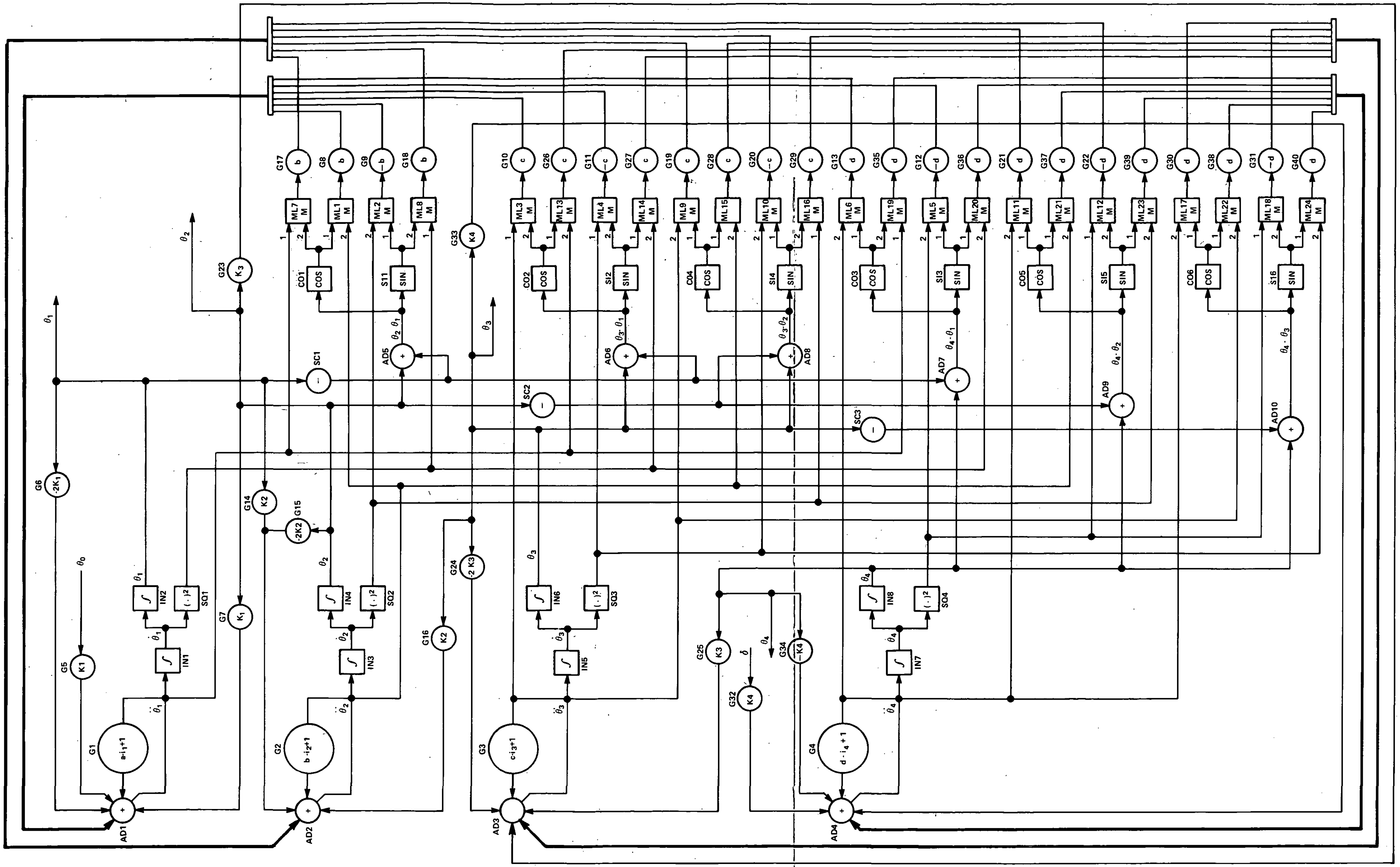


Figure 2. Direct simulation model of serpentuator.

TABLE 1. LISTING OF MARSYAS PROGRAM FOR COMPONENT-CONNECTION SIMULATION MODEL OF SERPENTUATOR

```
* THIS IS A LISTING OF THE MARSYAS DECK FOR THE COMPONENT-CONNECTION MODEL. *
@RUN,//T XSNAK7,735023,SSINGH3IN212,3,100
@ASG,T 1,F
@ASG,X REVMARSYAS*MARSYAS
@DATA,I 1
BEGIN: SNAKE $
DEVICE: AINV,8,4,7 $
       SUBROUTINE AINV(U,Y,P)
       DIMENSION U(8),Y(4),P(7)
       DIMENSION A(4,4),V(3),JC(4),X(4)
       A(1,1)=P(1)
       A(1,2)=P(5)*COS(U(2)-U(1))
       A(1,3)=P(6)*COS(U(3)-U(1))
       A(1,4)=P(7)*COS(U(4)-U(1))
       A(2,1)=A(1,2)
       A(2,2)=P(2)
       A(2,3)=P(6)*COS(U(3)-U(2))
       A(2,4)=P(7)*COS(U(4)-U(2))
       A(3,1)=A(1,3)
       A(3,2)=A(2,3)
       A(3,3)=P(3)
       A(3,4)=P(7)*COS(U(4)-U(3))
       A(4,1)=A(1,4)
       A(4,2)=A(2,4)
       A(4,3)=A(3,4)
       A(4,4)=P(4)
       N=4
       V(1)=3.0
       CALL GJR(A,N,N,N,N,$150,JC,V)
       DO 200 I=1,4
200    X(I)=U(4+I)
       M=4
       N=1
       CALL MXMLT(A,X,Y,M,M,N,M,M)
       GO TO 400
150    IF (V(1)) 152,151,152
151    WRITE (6,153)
153    FORMAT (' MATRIX A IS SINGULAR')
       STOP
152    WRITE (6,154)
154    FORMAT (' OVERFLOW')
       STOP
400    RETURN
       END
DEVICE: BB,8,4,3 $
       SUBROUTINE BB(U,Y,P)
       DIMENSION U(8),Y(4),P(3)
       DIMENSION B(4,4),X(4)
       B(I,1)=0.
       B(1,2)= P(1)*SIN(U(2)-U(1))
       B(1,3)= P(2)*SIN(U(3)-U(1))
       B(1,4)= P(3)*SIN(U(4)-U(1))
       B(2,1)=-B(1,2)
       B(2,2)=0.
       B(2,3)= P(2)*SIN(U(3)-U(2))
       B(2,4)= P(3)*SIN(U(4)-U(2))
```

TABLE 1. (Continued)

```
      B(3,1)=-B(1,3)
      B(3,2)=-B(2,3)
      B(3,3)=0.
      B(3,4)= P(3)*SIN(U(4)-U(3))
      B(4,1)=-B(1,4)
      B(4,2)=-B(2,4)
      B(4,3)=-B(3,4)
      B(4,4)=0.
      DO 100 I=1,4
100   X(I)=U(I+4)**2
      M=4
      N=1
      CALL MXMLT(B,X,Y,M,M,N,M,M)
      RETURN
      END
DEVICE: MC,4,4,4 $
      SUBROUTINE MC(U,Y,P)
      DIMENSION U(4),Y(4),P(4)
      REAL K
      DIMENSION K(4,4)
      K(1,1)=2*P(1)
      K(1,2)=-P(1)
      K(1,3)=0.
      K(1,4)=0.
      K(2,1)=-P(2)
      K(2,2)=2*P(2)
      K(2,3)=-P(2)
      K(2,4)=0.
      K(3,1)=0.
      K(3,2)=-P(3)
      K(3,3)=2*P(3)
      K(3,4)=-P(3)
      K(4,1)=0.
      K(4,2)=0.
      K(4,3)=-P(4)
      K(4,4)=P(4)
      M=4
      N=1
      CALL MXMLT(K,U,Y,M,M,N,M,M)
      RETURN
      END
DEVICE: DM,2,4,2 $
      SUBROUTINE DM(U,Y,P)
      DIMENSION U(2),Y(4),P(2)
      DIMENSION D(4,2)
      D(1,1)=-P(1)
      D(1,2)=0.
      D(2,1)=0.
      D(2,2)=0.
      D(3,1)=0.
      D(3,2)=0.
      D(4,1)=0.
      D(4,2)=-P(2)
      M=4
      N=1
```

TABLE 1. (Concluded)

```
      L=2
      CALL MXMLT(D,U,Y,M,L,N,M,L)
      RETURN
      END
MODEL: SERPENTUATOR $
INPUTS: THETA0, DELTA $
OUTPUTS: THETA1,THETA2,THETA3,THETA4 $
ELEMENTS: AINV,AX(6.423385,6.361275,6.299165,3.242055,
6.366275,6.304165,6.242055) $
: BB,BX(6.356275,6.304165,6.242055) $
: MC,CX(10.,10.,10.,10.) $
: DM,DX(10.,10.) $
:AD,AD1,AD2,AD3,AD4 $
:IN,IN1,IN2,IN3,IN4,IN5,IN6,IN7,IN8 $
CONNECT: THETA0,1#DX#1,AD1,5#AX#1,IN1,IN2,THETA1 $
:DELTA,2#DX#2,AD2,6#AX#2,IN3,IN4,THETA2 $
: DX#3,AD3,7#AX#3,IN5,IN6,THETA3 $
:DX#4,AD4,8#AX#4,IN7,IN8,THETA4 $
: IN2,1#CX#1,AD1 $
: IN4,2#CX#2,AD2 $
: IN6,3#CX#3,AD3 $
: IN8,4#CX#4,AD4 $
: IN2,1#AX $
: IN4,2#AX $
: IN6,3#AX $
: IN8,4#AX $
: IN2,1#BX#1,AD1 $
: IN4,2#BX#2,AD2 $
: IN6,3#BX#3,AD3 $
: IN8,4#BX#4,AD4 $
: IN1,5#BX $
: IN3,6#BX $
: IN5,7#BX $
: IN7,8#BX $
END $
SIMULATE: SERPENTUATOR $
EXCITE: DELTA,FSIN(1.,.1,0.),THETA0,ZERO $
INTEGRATE: RK,TIMESTEP,.01 $
STOP IF: TIME.GT.1.36 $
END $
PRINT: DELTA,THETA1,THETA2,THETA3,THETA4 $
SAMPLE: STEP, 1 $
END $
END: SNAKE $
@END
@ADD REVMARSYAS*MARSYAS.
@FIN
@FIN
```

TABLE 2. LISTING OF MARSYAS PROGRAM FOR DIRECT SIMULATION MODEL OF SERPENTUATOR

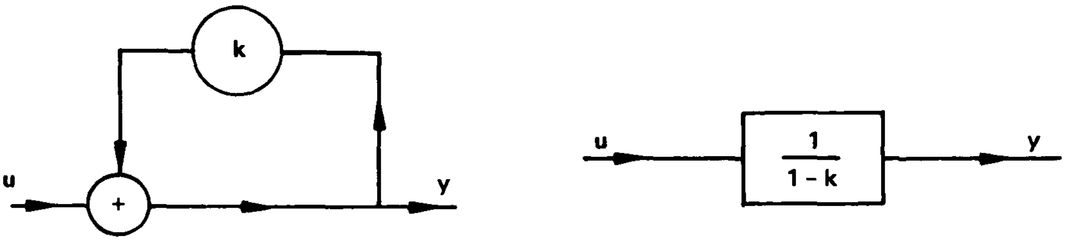
```
* THIS IS A LISTING OF THE MARSYAS DECK FOR THE DIRECT SIMULATION MODEL. **
BEGIN , SNAKE $
MODEL, SERPENTUATOR$
INPUTS, THETA0, DELTA$
OUTPUTS, THETA1, THETA2,THETA3, THETA4,X1,X2,X3,X4,Y1,Y2,Y3,Y4 $
ELEMENTS, AD, AD1, AD2, AD3, AD4, AD5, AD6, AD7, AD8, AD9, AD10$
=, AD, AD11,AD12,AD13,AD14,AD15,AD16 $
=, SC, SC1, SC2, SC3 $
=, ML, M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11, M12, M13, M14, M15, M16, M1
7, M18, M19, M20, M21, M22, M23, M24 $
=, IN,IN1,IN2,IN3,IN4,IN5,IN6,IN7,IN8 $
=, CM, G 1(-0.15568115 ), G 2(-0.15720119 ), G 3(-0.15875119 ), G 4(-0.30844634)
, G 5( 10.0)
, G 6(-20.0)
, G 7( 10.0)
, G 8( 6.366275)
, G 9(-6.366275)
, G10( 6.304165)
, G11(-6.304165)
, G12(-6.242055)
, G13( 6.242055)
, G14( 10.0)
, G15(-20.0)
, G16( 10.0)
, G17( 6.366275)
, G18( 6.366275)
, G19( 6.304165)
, G20(-6.304165)
, G21( 6.242055)
, G22(-6.242055)
, G23( 10.0)
, G24(-20.0)
, G25( 10.0)
, G26( 6.304165)
, G27( 6.304165)
, G28( 6.304165)
, G29( 6.304165)
, G30( 6.242055)
, G31(-6.242055)
, G32( 10.0)
, G33( 10.0)
, G34(-10.0)
, G35( 6.242055)
, G36( 6.242055)
, G37( 6.242055)
, G38( 6.242055)
, G39( 6.242055)
, G40( 6.242055)  $
=, CM, G41(2.),G42(2.),G43(2.),G44(2.),G45(2.),G46(2.),G47(2.),G48(2.) $
=, CO, CO1(1.,0.),CO2(1.,0.),CO3(1.,0.),CO4(1.,0.),CO5(1.,0.),CO6(1.,0.) $
=, CO, CO7(1.,0.),CO8(1.,0.),CO9(1.,0.),CO10(1.,0.) $
=, SI, SI1(1.,0.),SI2(1.,0.),SI3(1.,0.),SI4(1.,0.),SI5(1.,0.),SI6(1.,0.) $
=, SI, SI8(1.,0.),SI7(1.,0.),SI9(1.,0.),SI10(1.,0.) $
=, PF, SQ1(2.), SQ2(2.), SQ 3(2.), SQ4(2.) $
CONNECT, THETA 0, G5, AD1,G1,
```

TABLE 2. (Continued)

```
                              IN1, IN2, THETA 1 $
=, IN2, G6, AD1 $
=, IN1,SQ1,M8(U1),G18,AD2,G2,
                              IN3,IN4,THETA2 $
=,G1,  M7(U1),G17,AD2 $
=, IN4,G7,AD1 $
=, IN2,G14,AD2 $
=, IN4,G15,AD2 $
=, IN2,SC1,AD5,CO1,M1(U1),G8,AD1 $
=, CO1,M7(U2) $
=, AD5,SI1,M2(U1),G9,AD1 $
=, SI1,M8(U2) $
=, G2,    M1(U2) $
=, IN3,SQ2,M2(U2) $
=, IN4,AD5 $
=, IN4,SC2,AD8,CO4,M9(U1),G19,AD2 $
=, AD8,SI4,M10(U1),G20,AD2 $
=, SC2,AD9,CO5,M11(U1),G21,AD2 $
=, IN4,G23,AD3,G3,
                   IN5,IN6,THETA3 $
=, IN6,G16,AD2 $
=,G3,  M3(U1),G10,AD1 $
=, IN6,AD6 $
=, SC1,AD6,CO2,M13(U1),G26,AD3 $
=, CO2,M3(U2) $
=,  G1,M13(U2) $
=,  G1,M19(U1),G35,AD4,G4,
                              IN7,IN8,THETA4 $
=, IN5,SQ3,M4(U1),G11,AD1 $
=, SC1,AD7,CO3,M6(U1),G13,AD1 $
=, IN8,AD7 $
=, IN8,AD9 $
=, IN6,AD8 $
=, IN6,SC3,AD10,CO6,M17(U1),G30,AD3 $
=, IN8,AD10 $
=, AD6,SI2,M4(U2) $
=, SI2,M14(U1),G27,AD3 $
=, SQ1,M14(U2) $
=, SQ1,M20(U2),G36,AD4 $
=,  G3,M9(U2) $
=,  G3,M22(U2),G38,AD4 $
=,CO6,M22(U1) $
=, SQ3,M10(U2) $
=, SQ3,M24(U2),G40,AD4 $
=, IN4,M16(U1),G29,AD3 $
=, IN4,M23(U2),G39,AD4 $
=, SI4,M16(U2) $
=,  G2,M15(U2),G28,AD3 $
=,  G2,M21(U2),G37,AD4 $
```

TABLE 2. (Concluded)

```
*, CO4,M15(U1) $
*, G4,    M6(U2) $
*, CO3,M19(U2) $
*, G4,M11(U2) $
*, CO5,M21(U1) $
*, AD7,SI3,M5(U1),G12,AD1 $
*,IN7,SQ4,M5(U2) $
*, SQ4,M18(U1),G31,AD3 $
*, SQ4,M12(U1),G22,AD2 $
*, AD9,SI5,M12(U2) $
*, SI5,M23(U1) $
*, AD10,SI6,M18(U2) $
*, SI6,M24(U1) $
*, IN6,G24,AD3 $
*, IN8,G25,AD3 $
*, IN8,G34,AD4 $
*, DELTA,G32,AD4 $
*, IN6,G33,AD4 $
*, SI3,M20(U1) $
*,  G4,M17(U2) $
*, IN2,SI7,G41,X1 $
*, IN2,CO7,G42,Y1 $
*, IN4,SI8,G43,AD11,X2 $
*, G41,AD11 $
*,
IN4,CO8,G44,AD12,Y2 $
*, G42,AD12 $
*, IN6,SI9,G45,AD13,X3 $
*, AD11,AD13 $
*, IN6,CO9,G46,AD14,Y3 $
*, AD12,AD14 $
*, IN8,SI10,G47,AD15,X4 $
*,AD13,AD15 $
*, IN8,CO10, G48,AD16,Y4 $
*,AD14,AD16 $
END $
SIMULATE, SERPENTUATOR $
EXCITE, FRAMP(4000.),          DELTA, ZERO, THETA0 $
STOP IF,TIME.GT.,  5 $
END $
PRINT AT STEPS, 1,
DELTA,               THETA1, THETA2,THETA3, THETA4 ,
X1,X2,X3,X4,Y1,Y2,Y3,Y4 $
END $
END, SNAKE $
```



(a) Linear loop with gain k (b) Equivalent feedforward path

Figure 3. Equivalence of feed-forward and linear loop gains.

The reason that a longer execution time was required for the Direct model is that the bulk of computer time was used in solving nonlinear loops by Newton's method. Earlier simulations of the Direct model did not yield any results because of excessive time required for the Newton subroutine in MARSYAS [5]. This routine was then modified by deleting the MXHOI routine. The MXHOI routine is a part of the matrix inversion routine used to determine the inverse of the Jacobian matrix at each computation point. At a given point, the inverse is determined in MXHOI by iteratively improving the value of the inverse at the previous computation point. If, however, after 20 iterations the inverse was not improved to the desired accuracy, the inverse was computed directly. It was found that in this particular problem, the inverse improvement was not accomplished in MXHOI and, after 20 iterations, the inverse was being computed directly. By deleting the MXHOI routine, each inverse was computed directly, saving the time taken by MXHOI for 20 iterations at each computation point.

Also in the Direct model, the four nonlinear loops were interconnected and were treated as a single large nonlinear loop. This may be another reason for the longer time needed for the Newton subroutine.

In the Component-Connection model, the nonlinear loops were eliminated by the process of inverting $A(\Theta)$ at each time-step. This was accomplished by creating the device AINV in the program. Creating devices that carried out matrix multiplication and matrix inversion required the use of FORTRAN programming. However, once these devices are made a part of the standard library of MARSYAS, there will be no further need to use FORTRAN programming. The formulation of the Direct model does not require FORTRAN programming.

VISUAL REPRESENTATION OF RESULTS

The results were obtained as values of Θ_i (i = 1, 2, 3, 4) as a function of the time, the X,Y coordinates of the hinge positions, and the plots of these X,Y coordinates versus time. These are given in Appendix B for a few representative cases. Although the present MARSYAS capability does include plotting one set of values against another, it was desirable to see what the serpentuator actually looked like in the X-Y plane at any given instant. This was possible by plotting the serpentuator positions at various times using the AMTRAN system on the Datacraft DC6024 computer [6,7].

It was found convenient to write a program to calculate the X,Y coordinates of the hinge-positions from the angular position of the links, rather than to input this data from MARSYAS results. This reduces the amount of data input to the AMTRAN system, since for every run only five arrays of angular positions Θ_i need to be input, rather than six pairs of arrays of X,Y coordinate values for the hinge-positions. The AMTRAN program listings are given in Table 3, and plots of serpentuator-link positions at discrete instants of time are given in Figure 4. The length of all the links is two units. The apparent inequality in lengths was due to unequal X and Y scales. In a typical case, the X-axis represents 10 units while the Y-axis represents 0.5 units.

CONCLUSIONS AND RECOMMENDATIONS

The serpentuator simulation through MARSYAS has served several purposes. For one, the problem which had hitherto defied solution by analog simulation and other techniques, has been solved using MARSYAS, giving valuable insight into the working of the serpentuator model. Also, the capability of MARSYAS to handle large scale systems has been demonstrated. It can be seen that a Component-Connection technique [8] may lead to simplification of the problem, as was shown in the present case. The Direct model of the serpentuator has proved to be a "tough" problem to solve on MARSYAS, exercising most of its capabilities and thereby serving as a check on the system.

This has led to some modifications, such as deletion of the MXHOI routine, and has pointed the way for future research. Some of the features that may be added to MARSYAS are:

1. Further modification of the Newton routine to make it less time consuming and exploring alternative methods for solving nonlinear loops.

2. Further implementation of the capability for solving nonlinear loops, having embedded linear loops. Mathematics for this capability has been worked out and implementation will be simply a matter of additional software design.

3. Further work on a multiple simulation capability using different inputs in the same run. Work on this capability is presently in progress.

4. Further study of the capability to implement the MARSYAS system on smaller computers with shorter turn around time for runs. This is presently under consideration as a long range goal.

In this report, the simulation of the serpentuator has used a given set of values for the parameters and initial conditions. As a result, valuable insight into the nature of the serpentuator behavior has been obtained. This should prove quite useful for subsequent design improvements and modifications of the serpentuator.

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812, December 20, 1972

TABLE 3. AMTRAN PROGRAM LISTINGS FOR VISUAL DISPLAY OF THE SERPENTUATOR

2. LIST SS.

```
1.    'SERPENTUATOR'.
2.    I=Ø,T=1
3.    L=2,M=I.
4.    IF N EQ 1 THEN SD1(T1,T2,T3,T4),GO TO 8.
5.    IF N EQ 2 THEN SD2(T1,T2,T3,T4),GO TO 8.
6.    IF N EQ 3 THEN SD3(X1,X2,X3,X4,Y1,Y2,Y3,Y4),GO TO 19.5.
7.    IF N EQ 4 THEN SD4(T1,T2,T3,T4),GO TO 8.
8.    J=INTERVALS T1.
9.    TØ=ARRAY Ø,Ø,J.
10.   XØ=L*SIN TØ.
11.   X1=XØ+L*SIN T1.
12.   X2=X1+L*SIN T2.
13.   X3=X2+L*SIN T3.
14.   X4=X3+L*SIN T4.
15.   YØ=L*COS TØ.
16.   Y1=YØ+L*COS T1.
17.   Y2=Y1+L*COS T2.
18.   Y3=Y2+L*COS T3.
19.   Y4=Y3+L*COS T4.
19.5  IF N EQ 3 THEN J=INTERVALS X1,T=2.
19.8  IF N EQ 3 THEN TØ=ARRAY Ø,Ø,J.
19.9  IF N EQ 3 THEN G=ARRAY 2,2,J,XØ=TØ,YØ=TØ+G,Y1=Y1+G,Y2=Y2+G,
      Y3=Y3+G,Y4=Y4+G.
20.   SET X=TØ, SUB I,XØ SUB I,X1 SUB I,X2 SUB I,X3 SUB I,X4 SUB I.
21.   I=I+T, IF I GT J THEN GO TO 25.
22.   SET Y=TØ SUB I,XØ SUB I,X1 SUB I,X2 SUB I,X3 SUB I,X4 SUB I.
23.   X=X&Y.
24.   IF I LT J THEN GO TO 21.
25.   I=M.
26.   SET Y=TØ SUB I,YØ SUB I,Y1 SUB I,Y2 SUB I,Y3 SUB I,Y4 SUB I.
27.   I=I+T, IF I GT J THEN GO TO 31.
* PRESS CARRIAGE RETURN TO ERASE AND CONTINUE*

28.   SET Z=TØ SUB I,YØ SUB I,Y1 SUB I,Y2 SUB I,Y3 SUB I,Y4 SUB I.
29.   Y=Y&Z.
30.   IF I LT J THEN GO TO 27.
31.   K=-(INTERVALS Y+1)/6.
32.   SCOPE (X,Y,K&Ø).
33.   IF N EQ 1 THEN TYPEOUT'
             SERPENTUATOR',TYPEOUT'
             INPUT RAMP (-4ØØØØ)
             T=.Ø15 SECS, SNAKE 3'.
```

TABLE 3. (Continued)

```
    33.5  IF N EQ 1 THEN TYPEOUT'
                 X-AXIS=10, Y-AXIS=.17'.
    34.   IF N EQ 2 THEN TYPEOUT'
                                              SERPENTUATOR'.
    35.   IF N EQ 2 THEN TYPEOUT'
                                              INPUT RAMP (25.136)'.
    36.   IF N EQ 2 THEN TYPEOUT'
                                              T=.25 SECS, COBRA1'.
    37.   IF N EQ 2 THEN TYPEOUT'
                                              X-AXIS=10, Y-AXIS=.5
    38.   IF N EQ 3 THEN TYPEOUT'
                 SERPENTUATOR'.
    39.   IF N EQ 3 THEN TYPEOUT'
                 INPUT DPLUSE (1,.05,.01)
                 T=.25 SECS, RPTLD7'.
    40.   IF N EQ 3 THEN TYPEOUT'
                 X-AXIS=1Ø, Y-AXIS=.6'.
    41.   IF N EQ 4 THEN TYPEOUT'
                 SERPENTUATOR'.
    42.   IF N EQ 4 THEN TYPEOUT'
                 INPUT SIN .1T
                T=.5 SECS, RPTLD9'.
    43.   IF N EQ 4 THEN TYPEOUT'
* PRESS CARRIAGE RETURN TO ERASE AND CONTINUE*

                 X-AXIS=10, Y-AXIS =1.05'.
    44.   NAME SS(N).

2     LIST XS.

     1.   N=5.
     2.   N=N-1.
     3.   SS(N).
     4.   PAUSE.
     5.   IF N GT 1 THEN GO TO 2.
     6.   NAME XS.

2.
```

TABLE 3. (Continued)

```
1.    'INPUT=RAMP, SLOPE -40000.'.
2.    SET A=0,.000047,.000073,.000118,.000056,-.000099,
      -.000996,-.000842.
3.    SET S=0,-.000518,-.000807,-.001684,-.001508,
      -.000605,.011298,.0199.
4.    SET D=0,.00533,.00844,.024036,.03137,.03957,.0659,.0736.
5.    SET F=0,.0049,.007779,.02268,.0302,.03925,.07708,.09384.
6.    F=-F.
7.    NAME SD1(A,S,D,F).


0.5   'INPUT RAMP, SLOPE 25.136'.
1.    SET A=0,.000006,.000127,.00107,.00533,.01524,.02508,
      .03013,.03374,.042,.0582.
2.    A=-A.
3.    SET S=0,.000037,.000555,.003695,.01598,.04357,.07677,
      .1041,.1216,.1284,.1225.
4.    SET D=0,.00028,.002296,.008792,.02507,.05629,.09993,
      .1508,.2031,.2514,.2914.
5.    D=-D.
6.    SET F=0,.00025,.001883,.006208,.01449,.02805,.04829,
      .07668,.1148,.1642,.2267.
7.    NAME SD2(A,S,D,F).


1.    'INPUT=DELAYED PULSE'.
2.    'XX1 THRU 4 AND YY1 THRU 4 CONTAIN DATA.'.
3.    X1=XX1,X2=XX2,X3=XX3,X4=XX4.
4.    Y1=YY1,Y2=YY2,Y3=YY3,Y4=YY4.
5.    NAME SD3(X1,X2,X3,X4,Y1,Y2,Y3,Y4).


1.    'INPUT SIN 0.1T'.
2.    SET A=0,-.0000007,-.00002,-.00044,-.00547,-.0328,
      -.03266,.0232,.0582,.07275,.08637.
3.    SET S=0,.000005,.00007,.00105,.01175,.0757,.1615,
      .2301,.3022,.3884,.4769.
4.    SET D=0,.00001,.0001,.000803,.0067,.0436,.1295,.2551,
      .3639,.4663,.5708.
5.    D=-D.
6.    SET F=0,.000009,.00006,.000192,.000404,.000437,
      -.000281,-.002411,-.006241,-.01272,-.02284.
7.    NAME SD4(A,S,D,F).
```

TABLE 3. (Continued)

```
1.    I=0.
2.    REPEAT 26,XO SUB I=0.,I=I+1.
2.5   X =XO.
2.6   .
3.    NAME XXO.
```

```
1.    SET X1=0.,0.,.0000042,.00003017,.0001215,.0003668.
1.5   X1 SUB 1=.0000042745788.
1.6   X1 SUB 2=X1 SUB 1, X1 SUB 1= 0.
2.    SET X2=.0009318,.0020699,.0041682,.0078184,.0136493.
2.5   X5=.021979.
3.    SET X3=.0322966,.0432069,.0529087,.0596874,.062227.
3.5   X6=.0598137.
4.    SET X4=.052448,.0407998,.0260171,.0094485.
5.    X=X1&X2&X5&X3&X6&X4.
6.    X=-X.
7.    SET X5=.0076046,.0240618,.0405689,.0524481.
8.    X=X&X5.
8.1   XX1=X.
9.    .
10.   NAME XX1.
```

```
1.    SET X=0,0,.00003,.00017,.00052,00125,00265,.00509,.00915.
1.5   X SUB 5=.00125, X SUB 6=.00265.
2.    SET Y=.015566,.02516,.03856,.05595,.10254,.13194,.16547,.20282.
2.5   Y2=Y SUB (0 THRU 3),Y3=.077262&Y SUB (4 THRU LAST), Y= Y2 & Y3.
3.    SET Y1=.24324,.28574,.32926,.37291,.41602,.49928,.53925.
3.5   Y6=Y1 SUB (0 THRU 5),Y7=.458197&Y1 SUB (6 THRU LAST),Y1=Y6&Y7.
3.8   Y1 SUB 6=Y1 SUB 5, Y1 SUB 5=.458197.
4.    Z = X&Y&Y1.
5.    .
6.    .
7.    NAME XX2.
```

```
1.    SET X=0,0,.0002791,.0013604,.003048,.005405,.0081194,.010788,.013437.
2.    SET Y=.016063,.01866,.021225,.02377,.026285,.028792,.031293,.0337897.
3.    SET Z=.36283*.1,.038521,.041242,.043691,.046106,.048478,.050795,.0530
      5,.055238.
4.    B=X&Y&Z.
5.    .
6.    NAME XX3.
```

TABLE 3. (Continued)

```
1.    SET A=0,0,.000003,.0000121,.0000262,.000044,.000062,.000073.
2.    SET B=.000075,.00006422,.0000362.
3.    SET C=.000014,.000093,.000213,.000387.
4.    SET D =.000634,.000966,.00139,.00191,.002514,.003194,.00394,.00474.
5.    SET E=.005595,.006606,.007484.
6.    X=A&B&(-C&D&E).
7.    .
8.    NAME XX4.
```

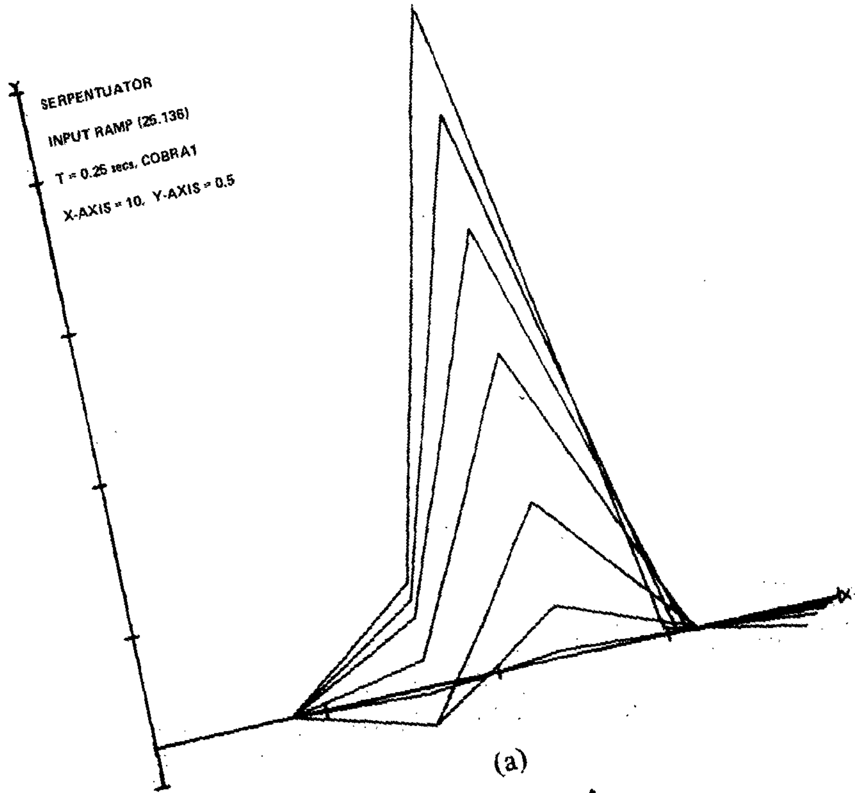
```
 1.    I=0.
 2.    X SUB I =2.0.
 3.    I=I+1.
 4.    IF I LT 14 THEN GO TO 2.
 5.    I=0.
 6.    Y SUB I=1.999, I=I+1.
 7.    IF I LT 12 THEN GO TO 6.
 8.    Y =X&Y.
 9.    .
10.    NAME YY1.
```

```
1.    I=0.
2.    REPEAT 17, Y1 SUB I=.4,I=I+1.
3.    REPEAT 2, Y1 SUB I =.398, I=I+1.
4.    REPEAT 2, Y1 SUB I=.397, I=I+1.
5.    REPEAT 2, Y1 SUB I=.396, I=I+1.
6.    REPEAT 2, Y1 SUB I=.395,I=I+1.
7.    Y1 SUB I= .394.
8.    Y2=10*Y1.
8.1   .
9.    NAME YY2.
```

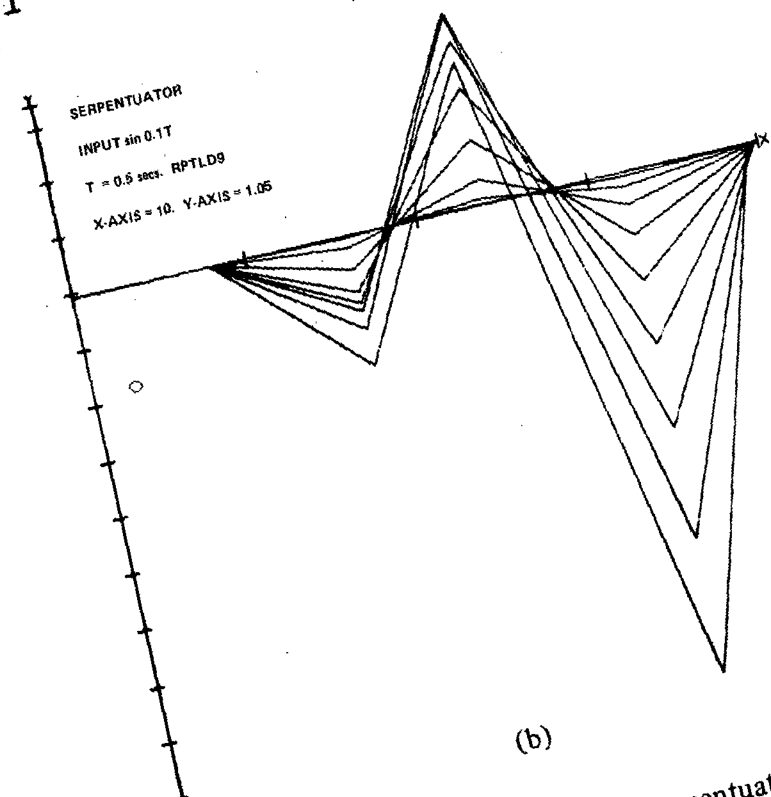
```
1.    I=0.
2.    REPEAT 10, X SUB I=6.,I=I+1.
3.    SET Y=5.999,5.998,5.996,5.993,5.989,5.983,5.976,5.967,5.957.
4.    SET Z=5.946,5.933,5.919,5.903,5.886,5.866,5.849.
5.    A=X&Y&Z.
6.    .
7.    NAME YY3.
```

TABLE 3. (Concluded)

```
I=0.
REPEAT 10, X SUB I=8.,I=I+1.
SET Y=7.999,7.998,7.996,7.993,7.989.
SET Z=7.983,7.976,7.967,7.957,7.945.
SET Z1=7.933,7.918,7.903,7.886,7.866,7.848.
X=X&Y&Z&Z1.
.
NAME YY4.
```

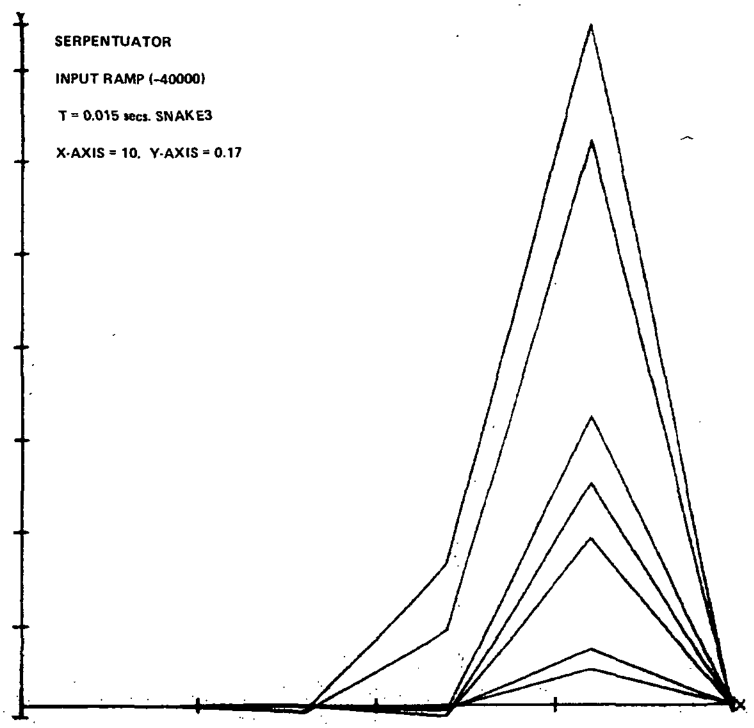


(a)

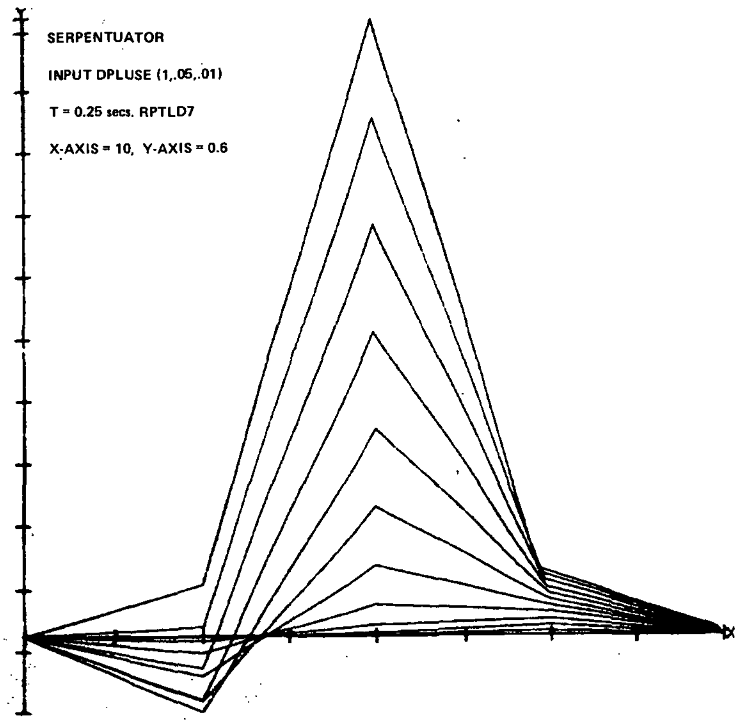


(b)

Figure 4. Visual display of serpentuator.



(c)



(d)

Figure 4. (Concluded).

APPENDIX A. SERPENTUATOR EQUATIONS

$$\begin{bmatrix} & & \\ & A(\Theta) & \\ & & \end{bmatrix} \begin{bmatrix} \ddot{\Theta}_1 \\ \ddot{\Theta}_2 \\ \ddot{\Theta}_3 \\ \ddot{\Theta}_4 \end{bmatrix} + \begin{bmatrix} & & \\ & B(\Theta) & \\ & & \end{bmatrix} \begin{bmatrix} (\dot{\Theta}_1)^2 \\ (\dot{\Theta}_2)^2 \\ (\dot{\Theta}_3)^2 \\ (\dot{\Theta}_4)^2 \end{bmatrix} - \frac{1}{L^2} \begin{bmatrix} 2K_1 & -K_1 & 0 & 0 \\ -K_2 & 2K_2 & -K_2 & 0 \\ 0 & -K_3 & 2K_3 & -K_3 \\ 0 & 0 & -K_4 & K_4 \end{bmatrix} \begin{bmatrix} \Theta_1 \\ \Theta_2 \\ \Theta_3 \\ \Theta_4 \end{bmatrix}$$

$$= \frac{1}{L^2} \begin{bmatrix} -K_1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -K_4 \end{bmatrix} \begin{bmatrix} \Theta_0 \\ \delta \end{bmatrix}$$

where

$$A = \begin{bmatrix} (a-i_1) & b\cos(\Theta_2-\Theta_1) & c\cos(\Theta_3-\Theta_1) & d\cos(\Theta_4-\Theta_1) \\ b\cos(\Theta_2-\Theta_1) & (b-i_2) & c\cos(\Theta_3-\Theta_2) & d\cos(\Theta_4-\Theta_2) \\ c\cos(\Theta_3-\Theta_1) & c\cos(\Theta_3-\Theta_2) & (c-i_3) & d\cos(\Theta_4-\Theta_3) \\ d\cos(\Theta_4-\Theta_1) & d\cos(\Theta_4-\Theta_2) & d\cos(\Theta_4-\Theta_3) & (d-i_4) \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & -b\sin(\Theta_2-\Theta_1) & -c\sin(\Theta_3-\Theta_1) & -d\sin(\Theta_4-\Theta_1) \\ b\sin(\Theta_2-\Theta_1) & 0 & -c\sin(\Theta_3-\Theta_2) & -d\sin(\Theta_4-\Theta_2) \\ c\sin(\Theta_3-\Theta_1) & c\sin(\Theta_3-\Theta_2) & 0 & -d\sin(\Theta_4-\Theta_3) \\ d\sin(\Theta_4-\Theta_1) & d\sin(\Theta_4-\Theta_2) & d\sin(\Theta_4-\Theta_3) & 0 \end{bmatrix}$$

where $i_k = I_k/L^2$, $k = 1,2,3,4$, and

$a = 3.5m + M_m$

$b = 2.5m + M_m$

$$c = 1.5m + M_m$$

$$d = 0.5m + M_m \ .$$

Letting

$$k_i = K_i/L^2 \quad , \quad i = 1,2,3,4$$

the serpentuator equations for the direct model block diagram may be written as:

$$\begin{aligned}\ddot{\Theta}_1 = {} & (a + 1 - i_1)\,\ddot{\Theta}_1 + b\cos(\Theta_2 - \Theta_1)\,\ddot{\Theta}_2 + c\cos(\Theta_3 - \Theta_1)\,\ddot{\Theta}_3 + d\cos(\Theta_4 - \Theta_1)\,\ddot{\Theta}_4 \\ & - b\sin(\Theta_2 - \Theta_1)\,(\dot{\Theta}_2)^2 - c\sin(\Theta_3 - \Theta_1)\,(\dot{\Theta}_3)^2 - d\sin(\Theta_4 - \Theta_1)\,(\dot{\Theta}_4)^2 - 2k_1\Theta_1 \\ & + k_1\Theta_2 + k_1\Theta_0 \ .\end{aligned}$$

$$\begin{aligned}\ddot{\Theta}_2 = {} & b\cos(\Theta_2 - \Theta_1)\,\ddot{\Theta}_1 + (b + 1 - i_2)\,\ddot{\Theta}_2 + c\cos(\Theta_3 - \Theta_2)\,\ddot{\Theta}_3 + d\cos(\Theta_4 - \Theta_2)\,\ddot{\Theta}_4 \\ & + b\sin(\Theta_2 - \Theta_1)\,(\dot{\Theta}_1)^2 - c\sin(\Theta_3 - \Theta_2)\,(\dot{\Theta}_3)^2 - d\sin(\Theta_4 - \Theta_2)\,(\dot{\Theta}_4)^2 + k_2\Theta_1 \\ & - 2k_2\Theta_2 + k_2\Theta_3 \ .\end{aligned}$$

$$\begin{aligned}\ddot{\Theta}_3 = {} & c\cos(\Theta_3 - \Theta_1)\,\ddot{\Theta}_1 + c\cos(\Theta_3 - \Theta_2)\,\ddot{\Theta}_2 + (c + 1 - i_3)\,\ddot{\Theta}_3 + d\cos(\Theta_4 - \Theta_3)\,\ddot{\Theta}_4 \\ & + c\sin(\Theta_3 - \Theta_1)\,(\dot{\Theta}_1)^2 + c\sin(\Theta_3 - \Theta_2)\,(\dot{\Theta}_2)^2 - d\sin(\Theta_4 - \Theta_3)\,(\dot{\Theta}_4)^2 + k_3\Theta_2 \\ & - 2k_3\Theta_3 + k_3\Theta_4\end{aligned}$$

$$\begin{aligned}\ddot{\Theta}_4 = {} & d\cos(\Theta_4 - \Theta_1)\,\ddot{\Theta}_1 + d\cos(\Theta_4 - \Theta_2)\,\ddot{\Theta}_2 + d\cos(\Theta_4 - \Theta_3)\,\ddot{\Theta}_3 + (d + 1 - i_4)\,\ddot{\Theta}_4 \\ & + d\sin(\Theta_4 - \Theta_1)\,(\dot{\Theta}_1)^2 + d\sin(\Theta_4 - \Theta_2)\,(\dot{\Theta}_2)^2 + d\sin(\Theta_4 - \Theta_3)\,(\dot{\Theta}_3)^2 + k_4\Theta_3 \\ & - k_4\Theta_4 + k_4\delta \ .\end{aligned}$$

Given

$$m = 0.06211 \quad \text{and}$$

$$M_m = 6.211,$$

then

$I_1 = I_2 = I_3$ varies from 0.02 to 2.2,

I_4 varies from 1.22 to 122.2,

K varies from 10 to 10,000, and

L varies from 2 to 10.

For simulation, the following values were chosen:

$I_1 = I_2 = I_3 = .02$,

$I_4 = 12$,

$L = 2$, and

$K_1 = K_2 = K_3 = K_4 = 40$.

Therefore,

$a = 6.428385$	$a + 1 - i_1 = 7.423385$
$b = 6.366275$	$b + 1 - i_2 = 7.361275$
$c = 6.304165$	$c + 1 - i_3 = 7.299165$
$d = 6.242055$	$d + 1 - i_4 = 4.242055$

$i_1 = i_2 = i_3 = 0.005$

$i_4 = 3.0$

$k_1 = k_2 = k_3 = k_4 = 10$.

G1 = -0.15568115	G5 = 10	G9 = -6.366275
G2 = -0.15720119	G6 = -20	G10 = 6.304165
G3 = -0.15875119	G7 = 10	G11 = 6.304165
G4 = -0.30844634	G8 = 6.366275	G12 = -6.242055

G13 = 6.242055	G23 = 10.	G32 = 10
G14 = 10	G24 = –20.	G33 = 10
G15 = –20	G25 = 10.	G34 = –10
G16 = 10	G26 = 6.304165	G35 = 6.242055
G17 = 6.366275	G27 = 6.304165	G36 = 6.242055
G18 = 6.366275	G28 = 6.304165	G37 = 6.242055
G19 = 6.304165	G29 = 6.304165	G38 = 6.242055
G20 = –6.304165	G30 = 6.242055	G39 = 6.242055
G21 = 6.242055	G31 = –6.242055	G40 = 6.242055
G22 = –6.242055		

Note: Values of G1, G2, G3 and G4 are the equivalent values according to Figure 3.

APPENDIX B. REPRESENTATIVE PLOTS OF THE x,y COORDINATES OF THE SERPENTUATOR HINGE POSITIONS

NAME- BALENT

DIST. CODE- BIN212

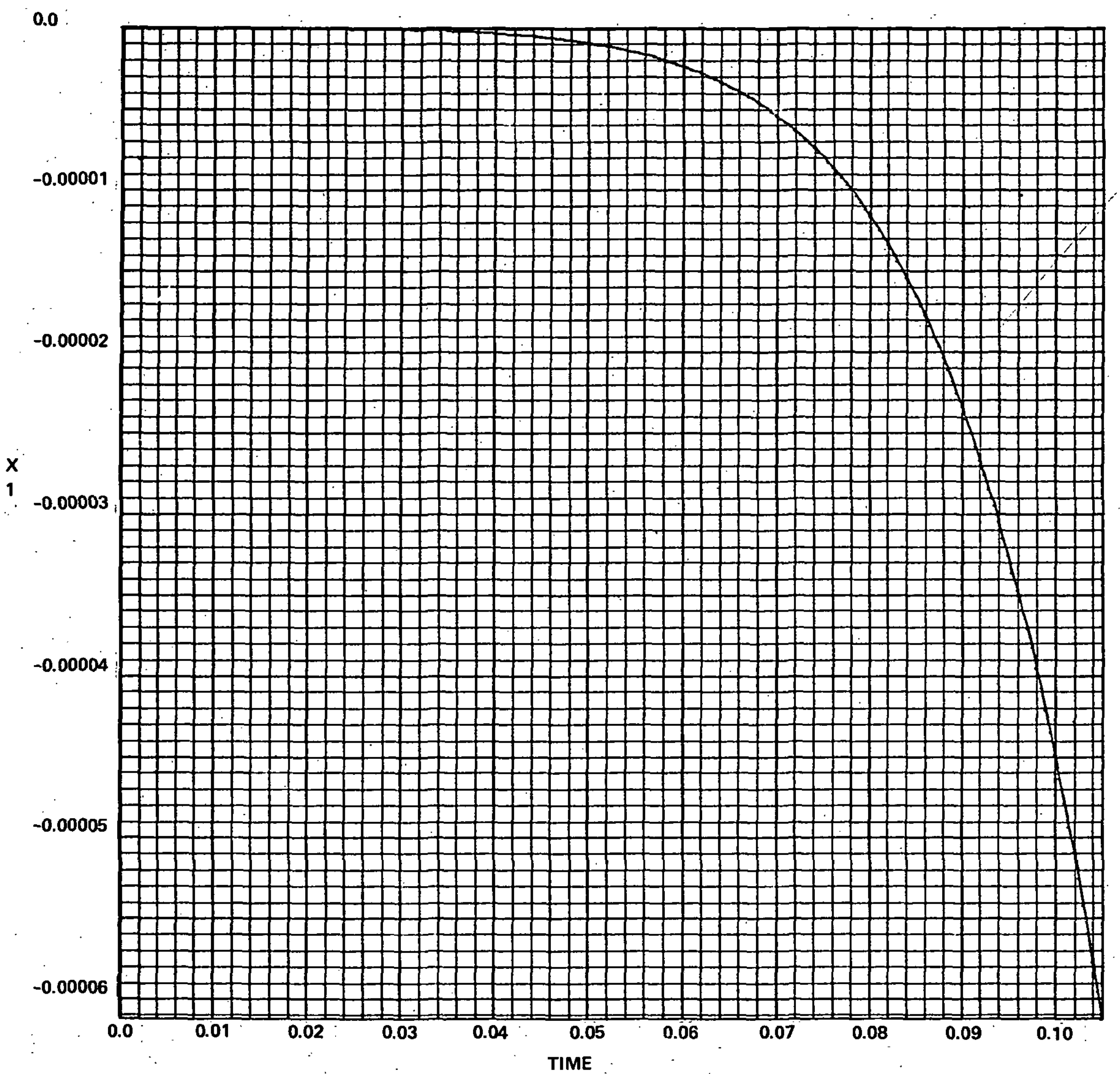
RUN ID- RPTLD4

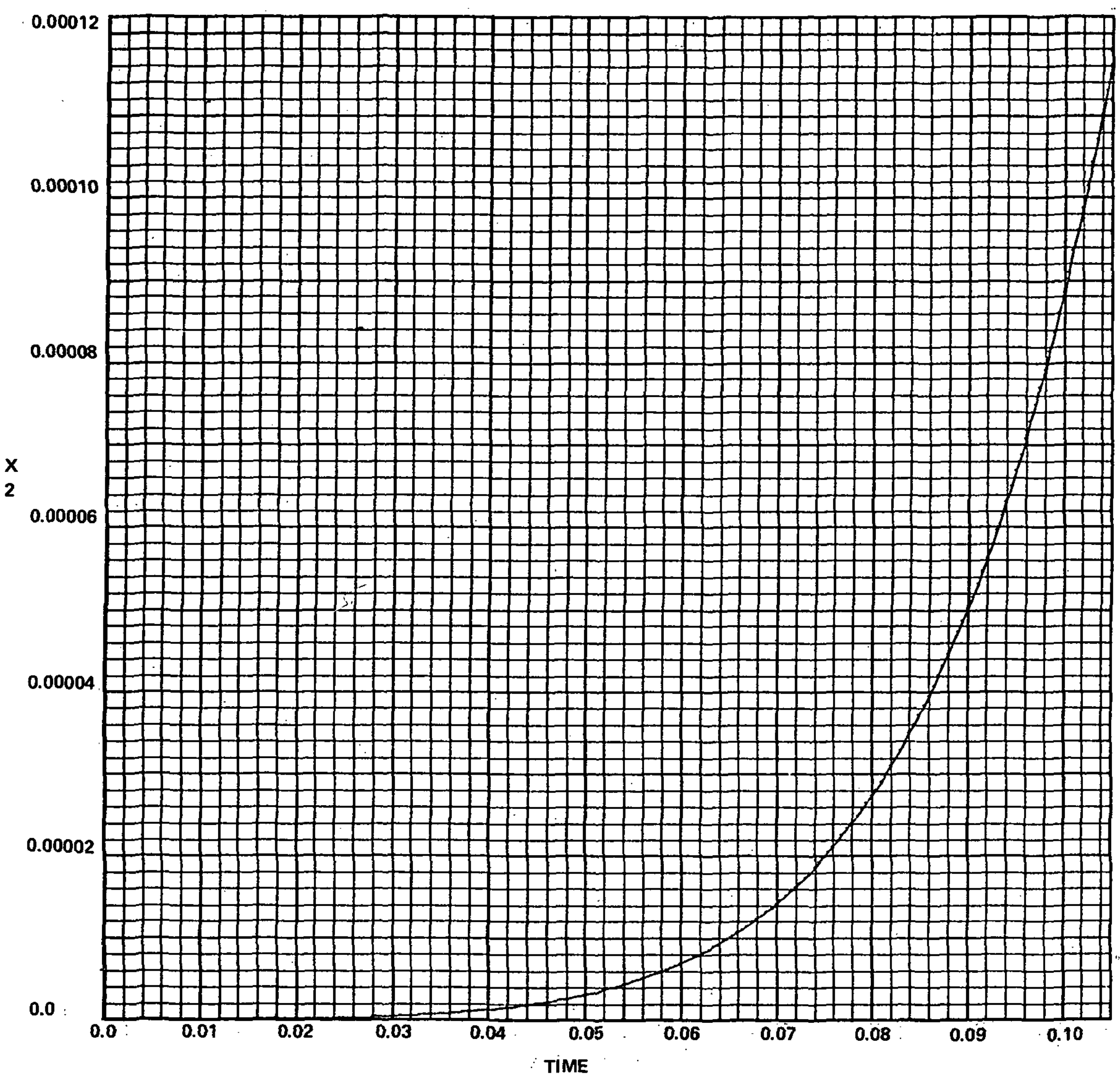
JOB NO- 620270

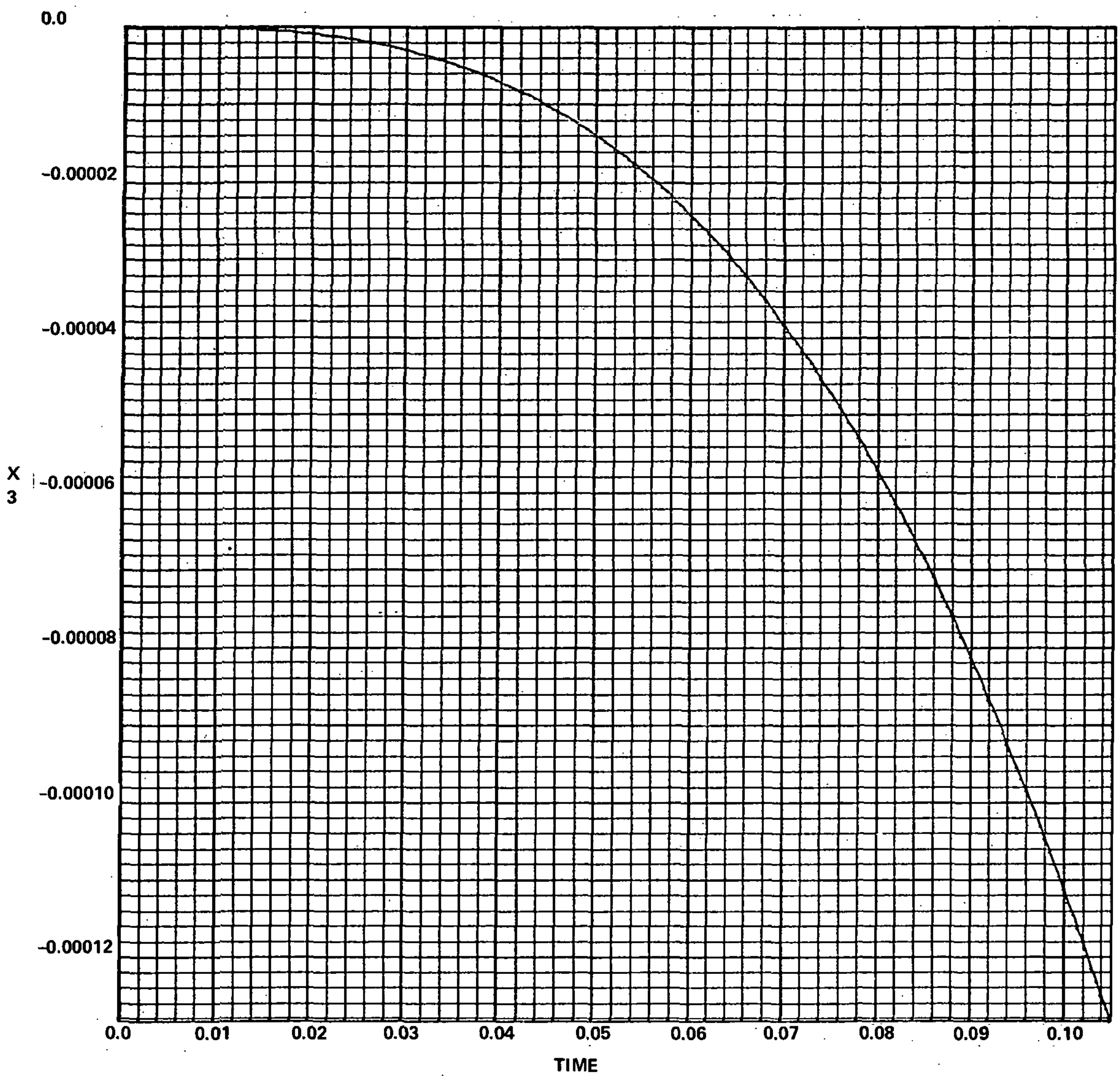
SEQ NO- 6289

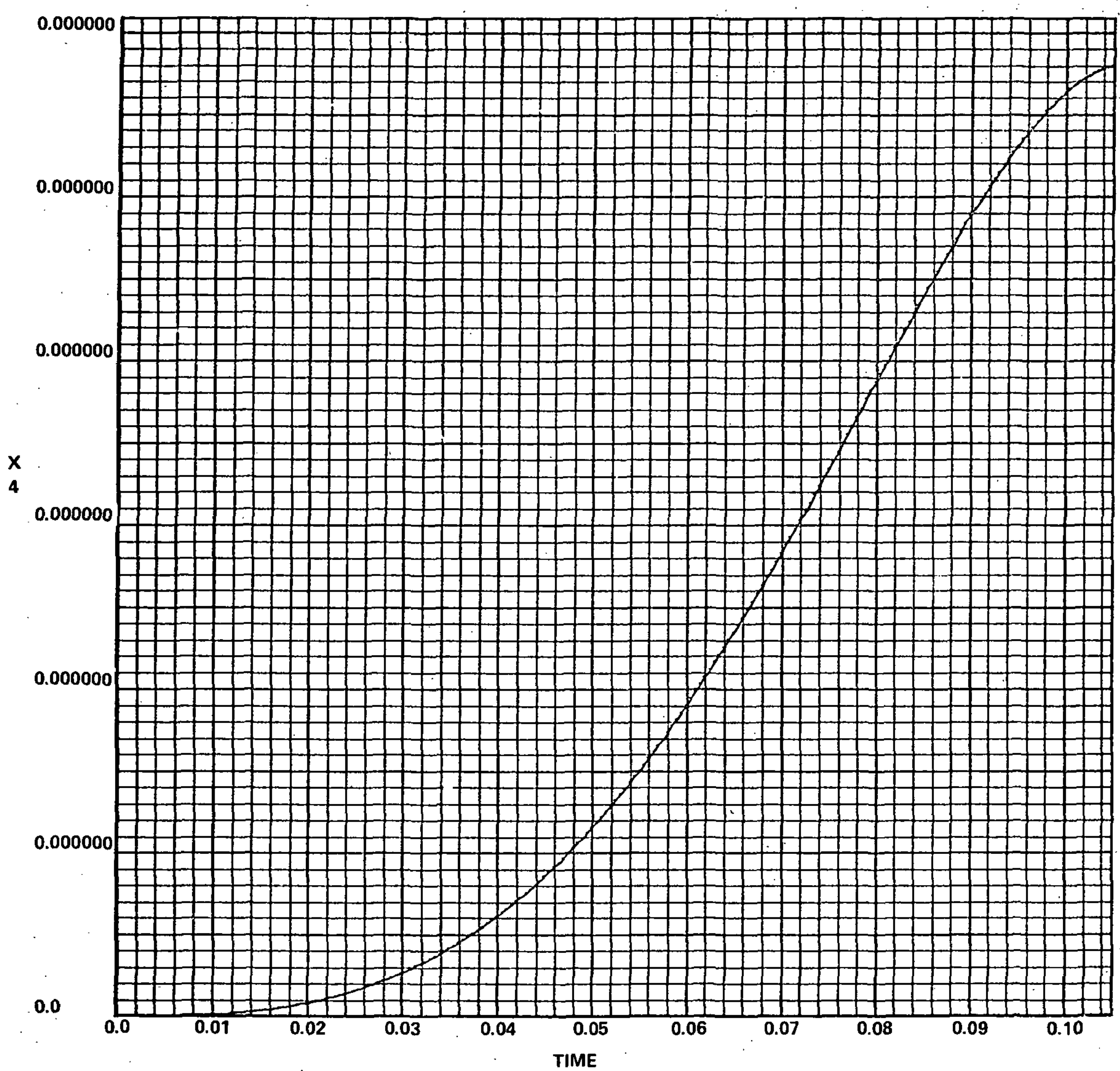
DATE- 06-11-72

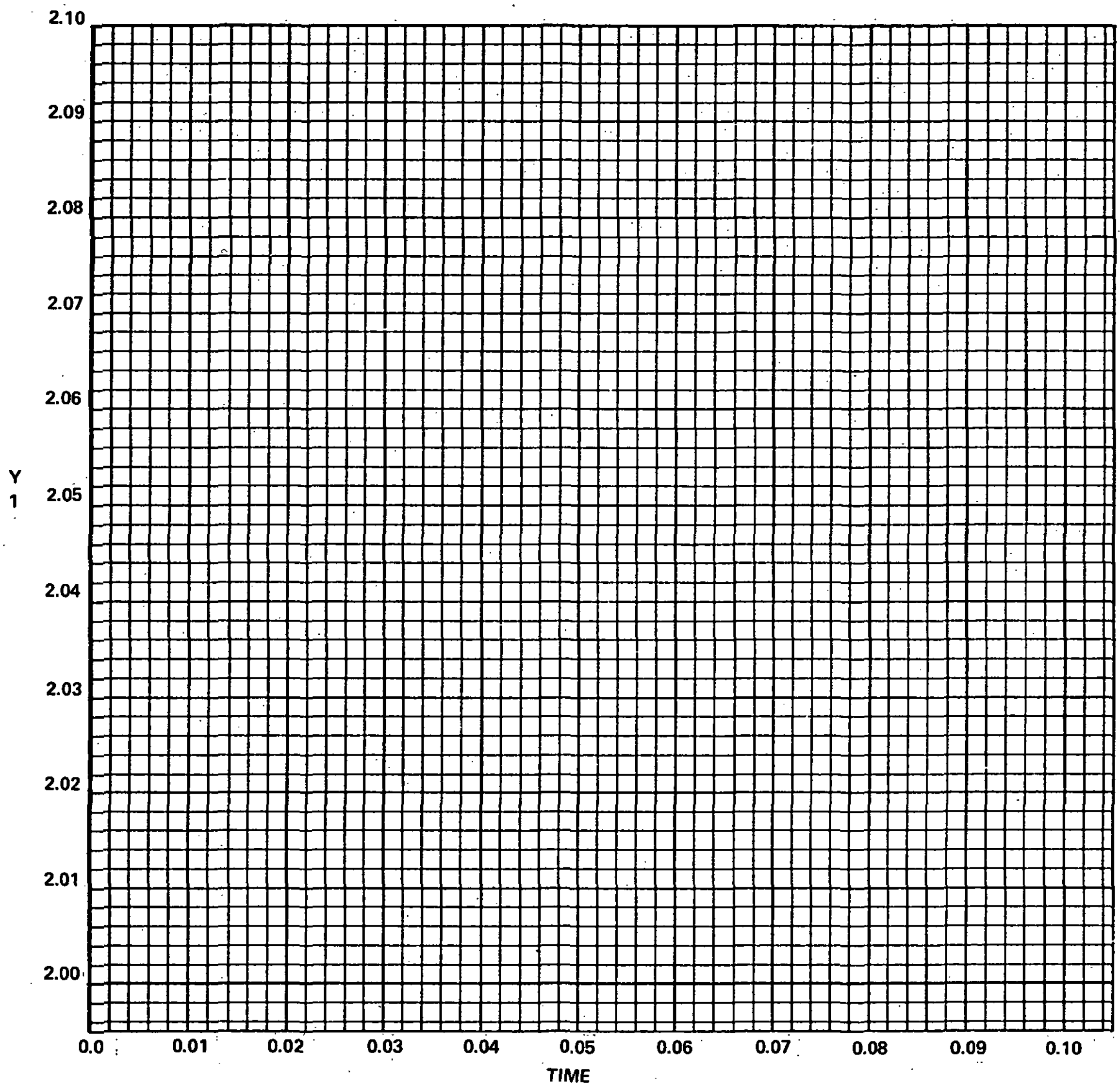
TIME- 08-39-58


0.0
-0.00001
-0.00002
-0.00003
-0.00004
-0.00005
-0.00006
X
1
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME

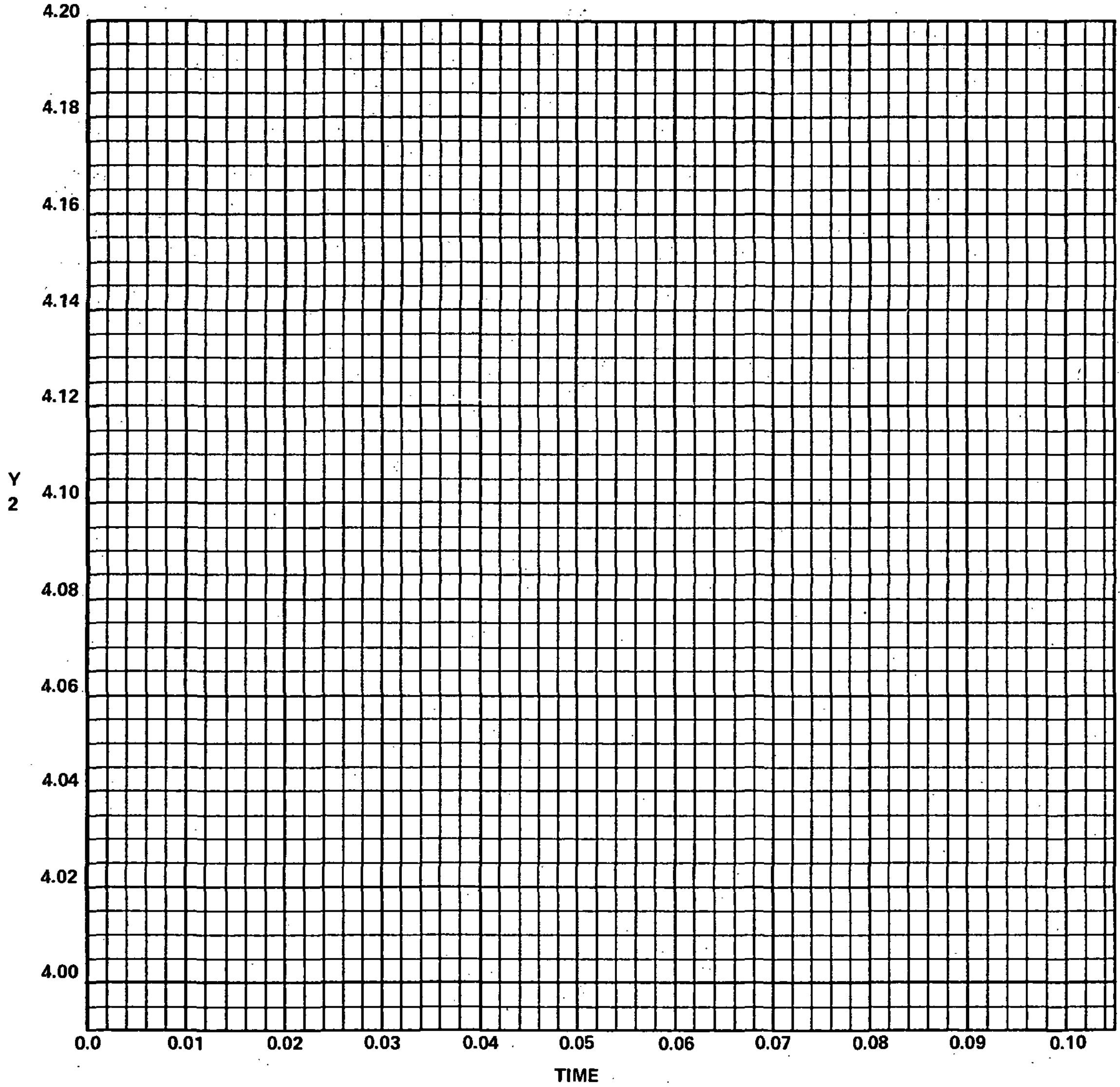

0.00012
0.00010
0.00008
X
2
0.00006
0.00004
0.00002
0.0
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME

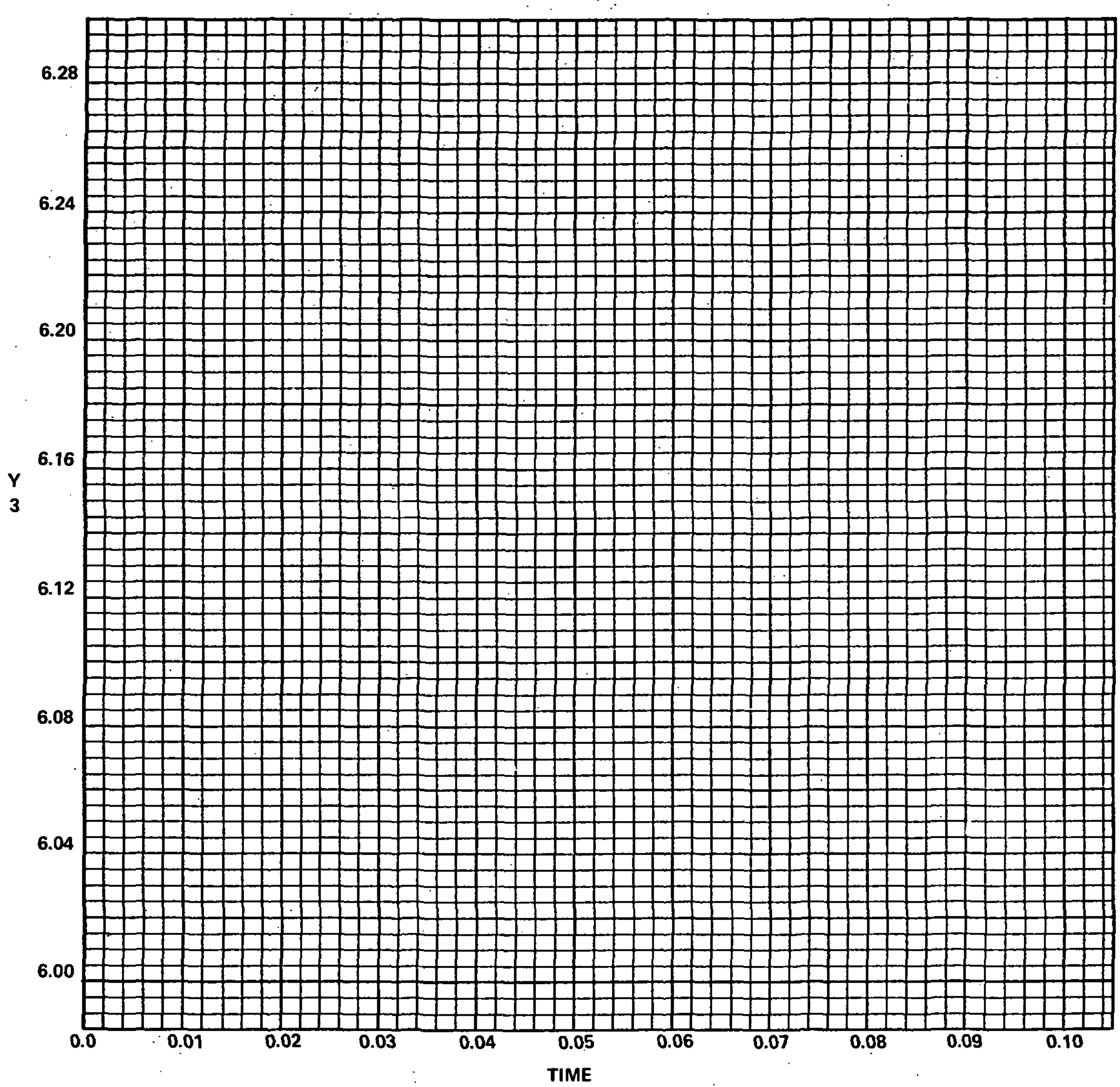

0.0
-0.00002
-0.00004
-0.00006
-0.00008
-0.00010
-0.00012
X
3
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME

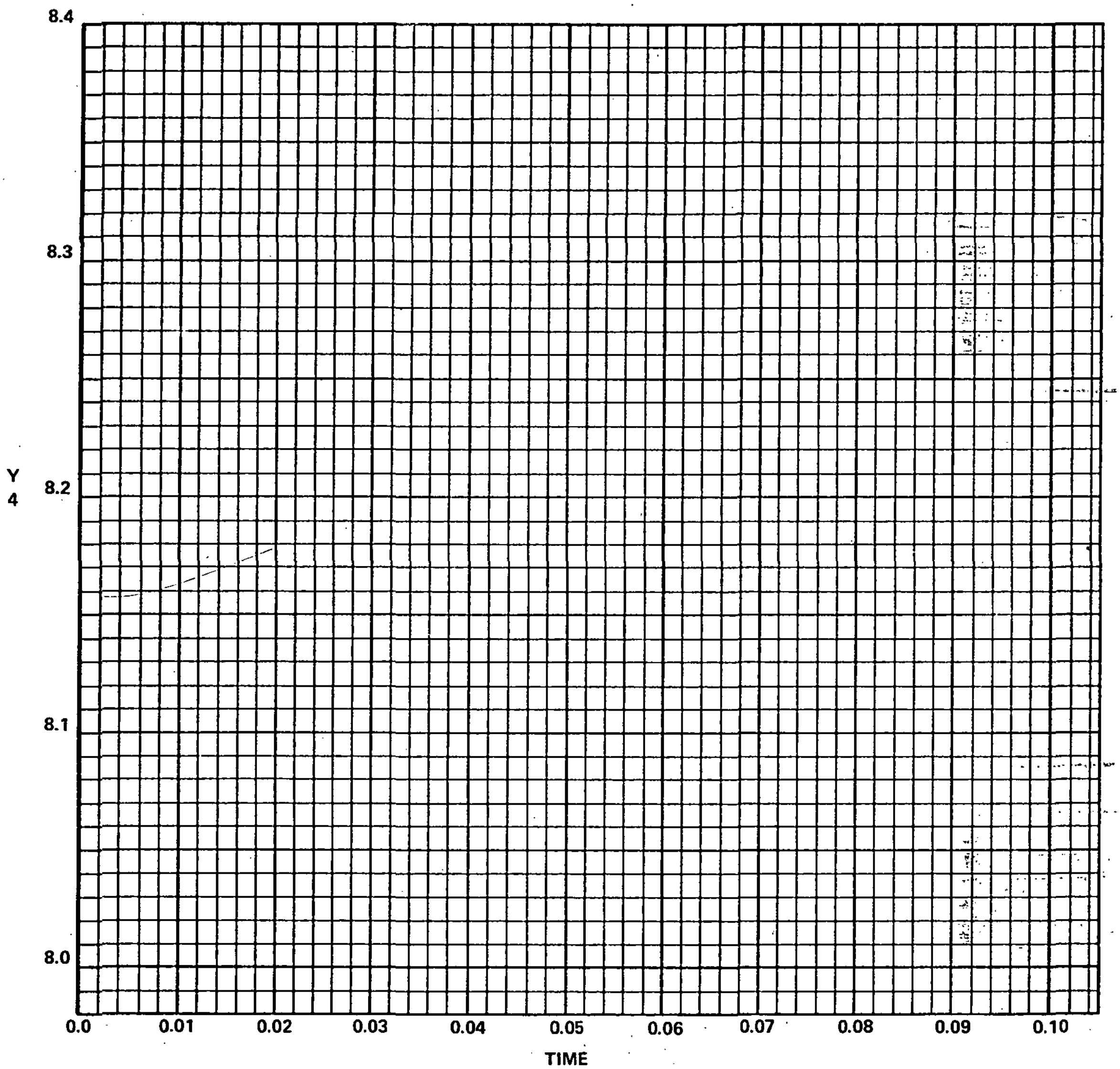

0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.0
X
4
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME



Y
1
2.10
2.09
2.08
2.07
2.06
2.05
2.04
2.03
2.02
2.01
2.00
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME


4.20
4.18
4.16
4.14
4.12
Y
2
4.10
4.08
4.06
4.04
4.02
4.00
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME


6.28
6.24
6.20
6.16
Y
3
6.12
6.08
6.04
6.00
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME


8.4
8.3
Y
4
8.2
8.1
8.0
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME

END JØB- RPTLD4

NAME-BALENT

DIST. CODE-BIN212

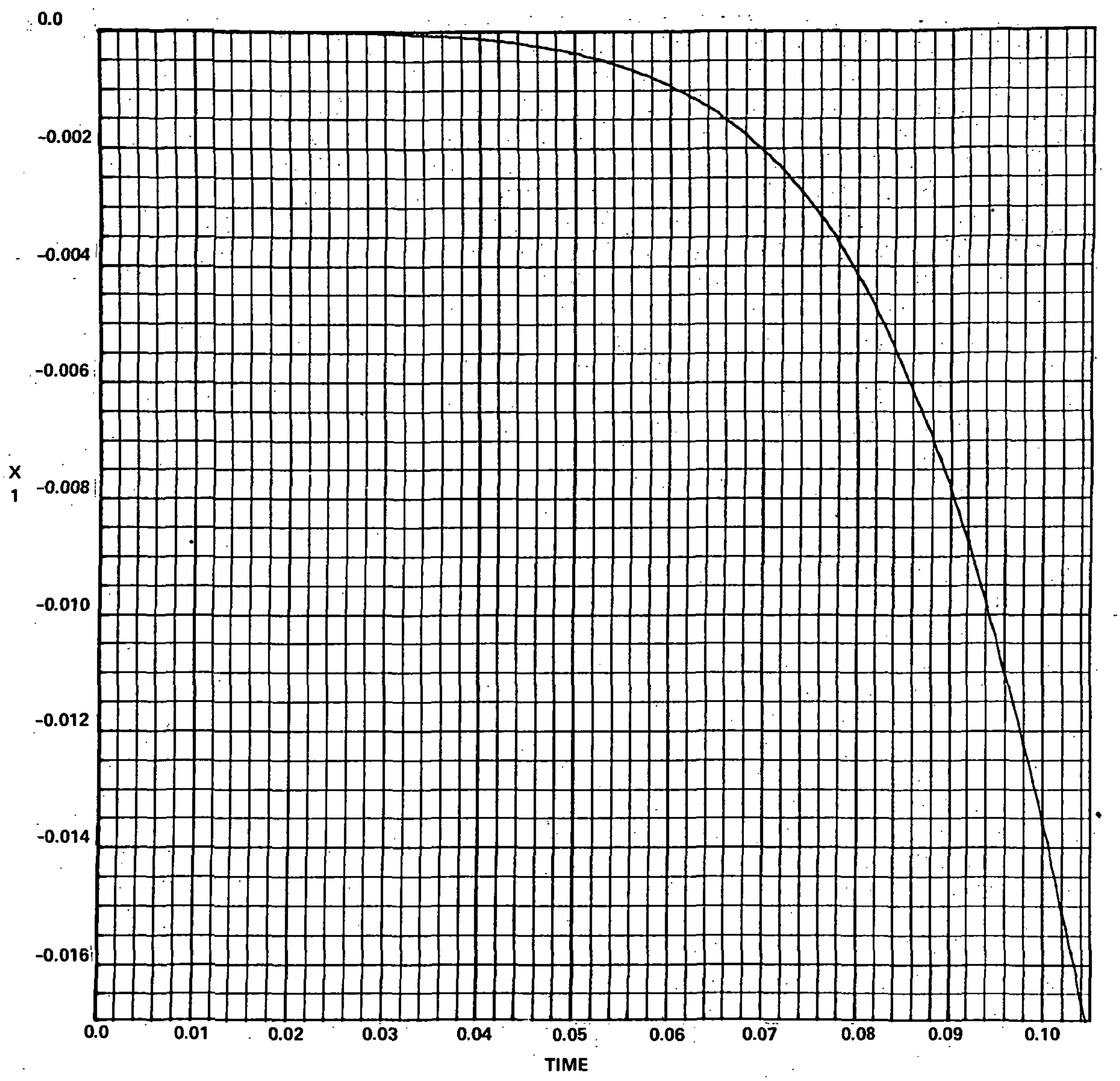
RUN ID-RPTLD6

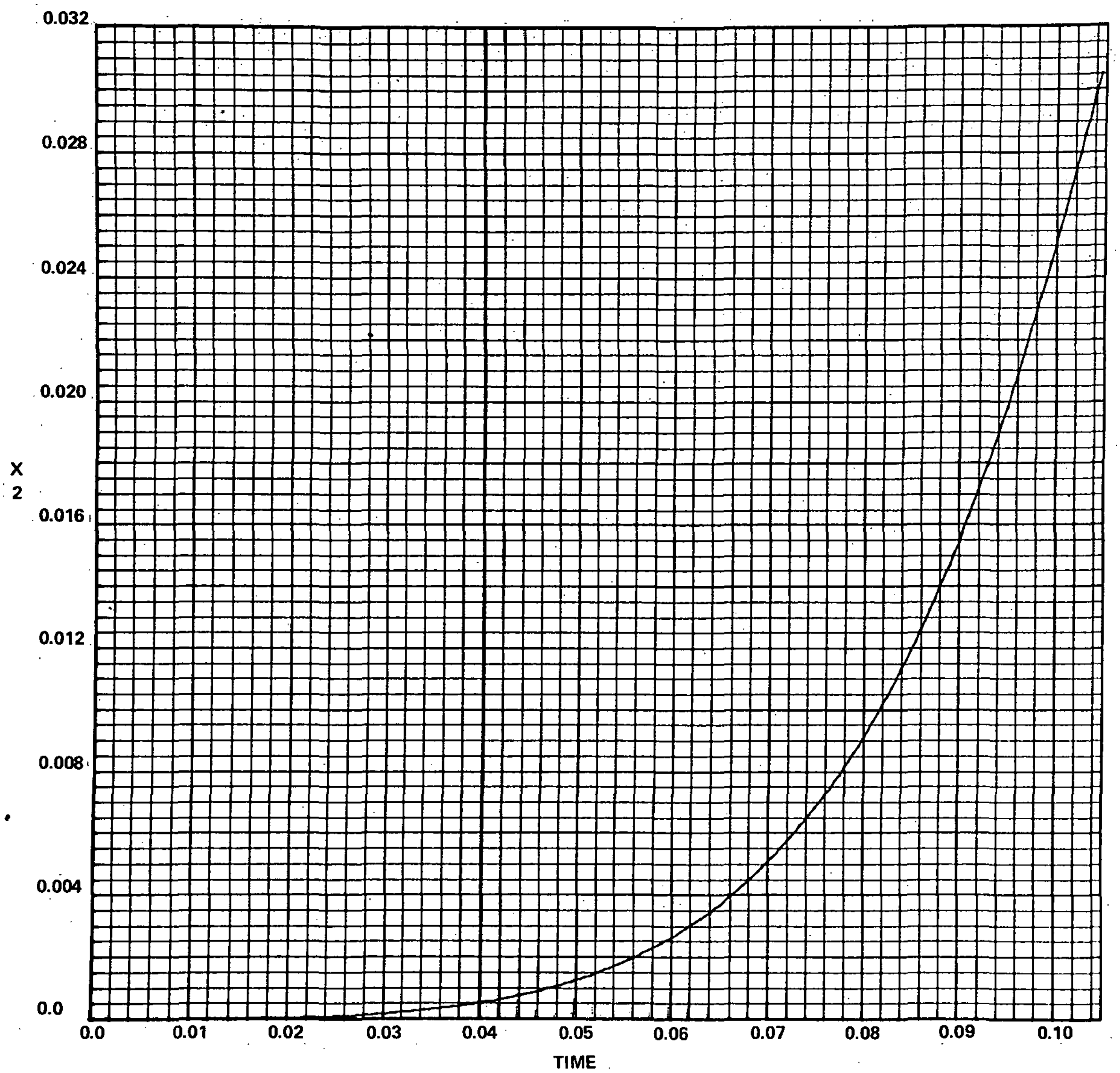
JOB NO-620270

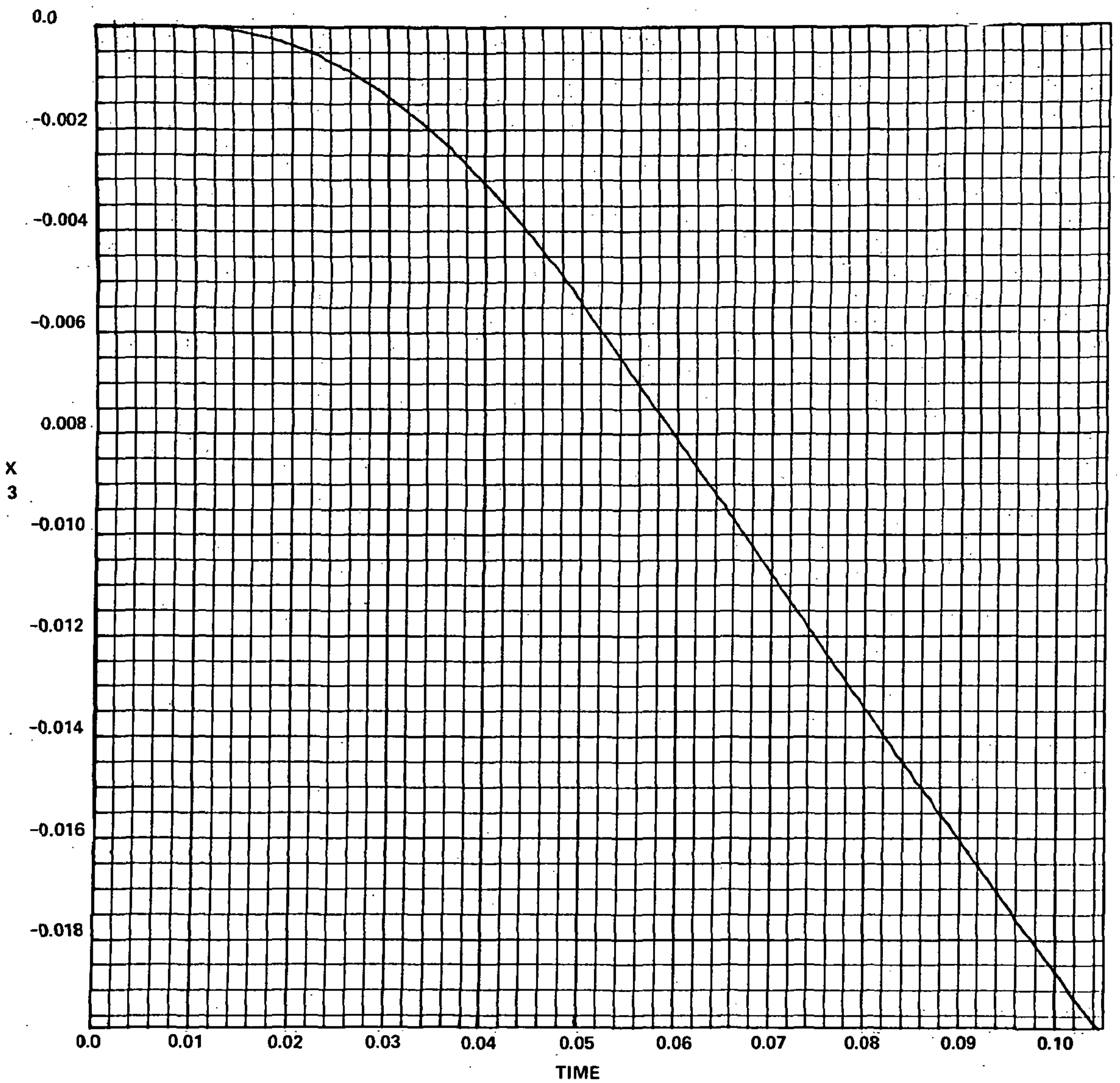
SEQ NO-4151

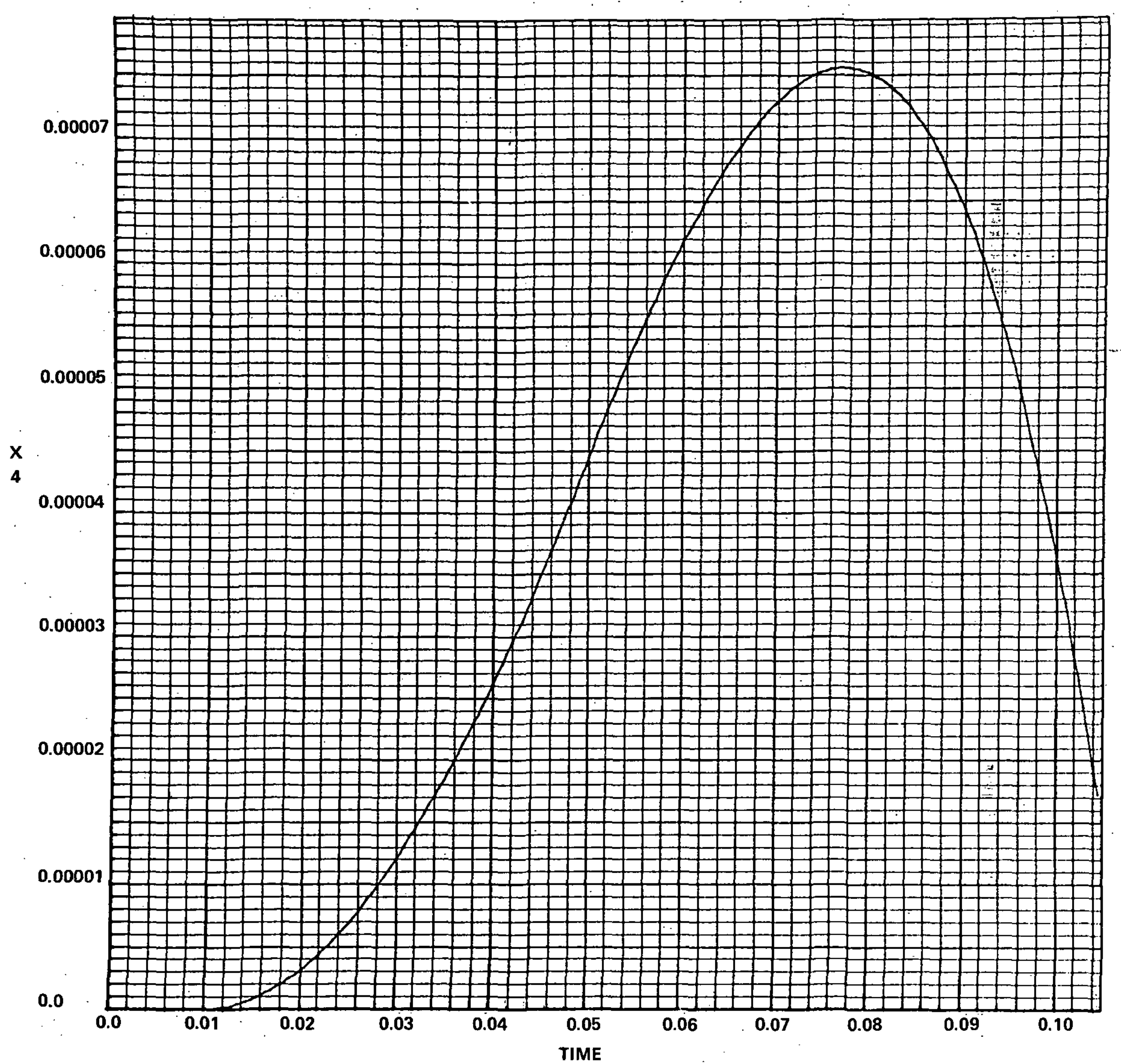
DATE-06-15-72

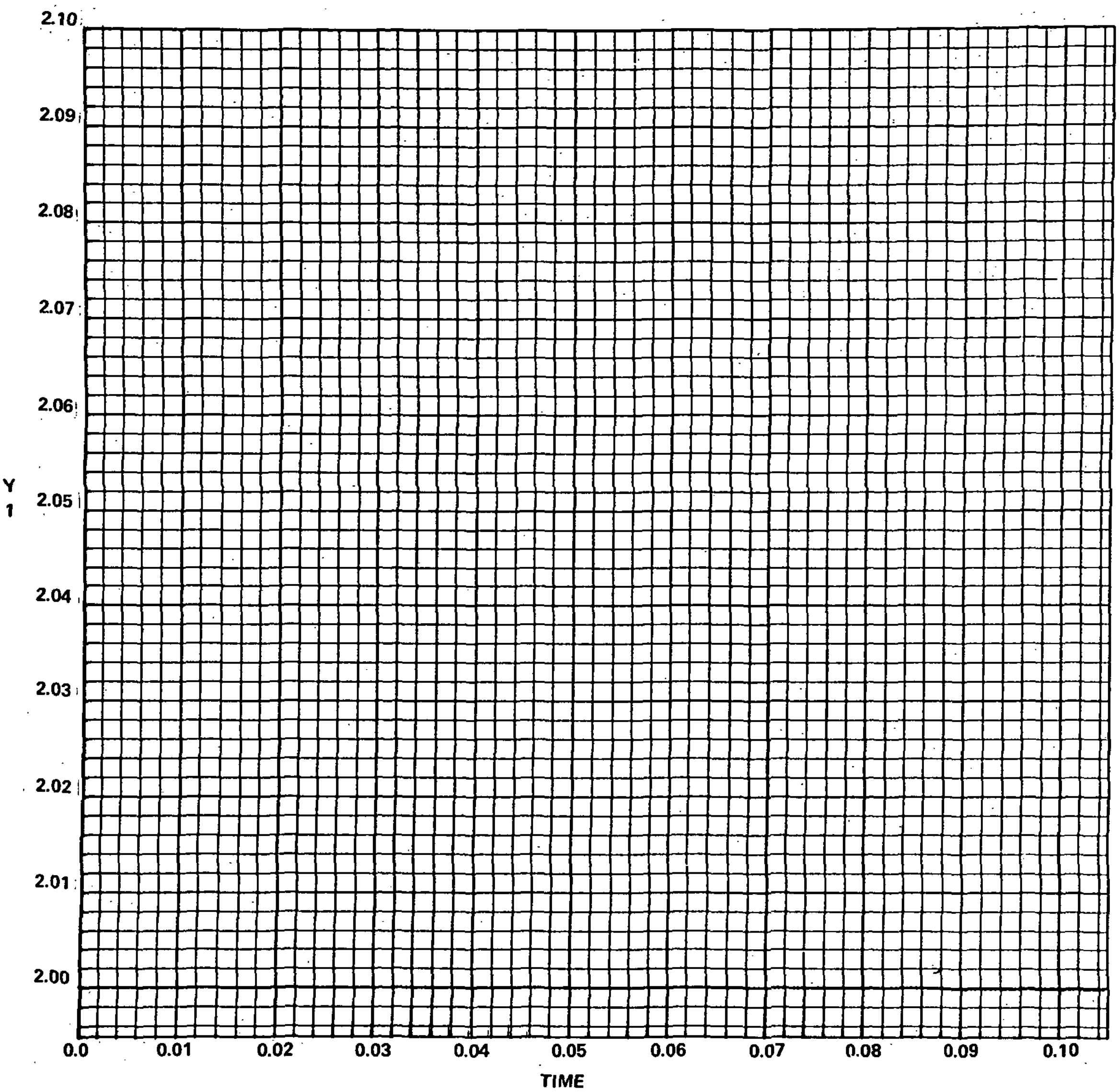
TIME-07-01-00

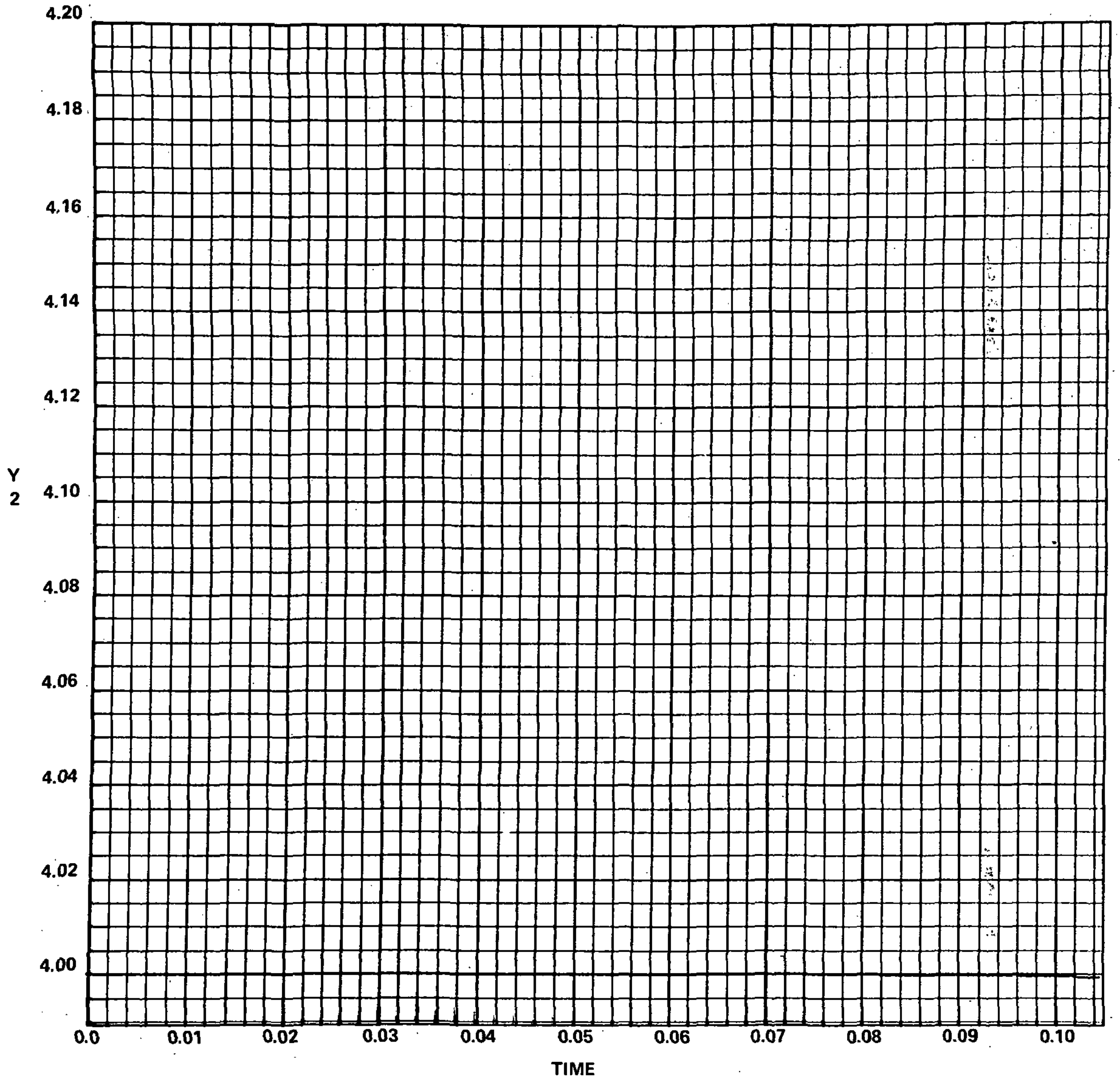

0.0
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
-0.014
-0.016
X
1
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME


0.032
0.028
0.024
0.020
X
2
0.016
0.012
0.008
0.004
0.0
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME

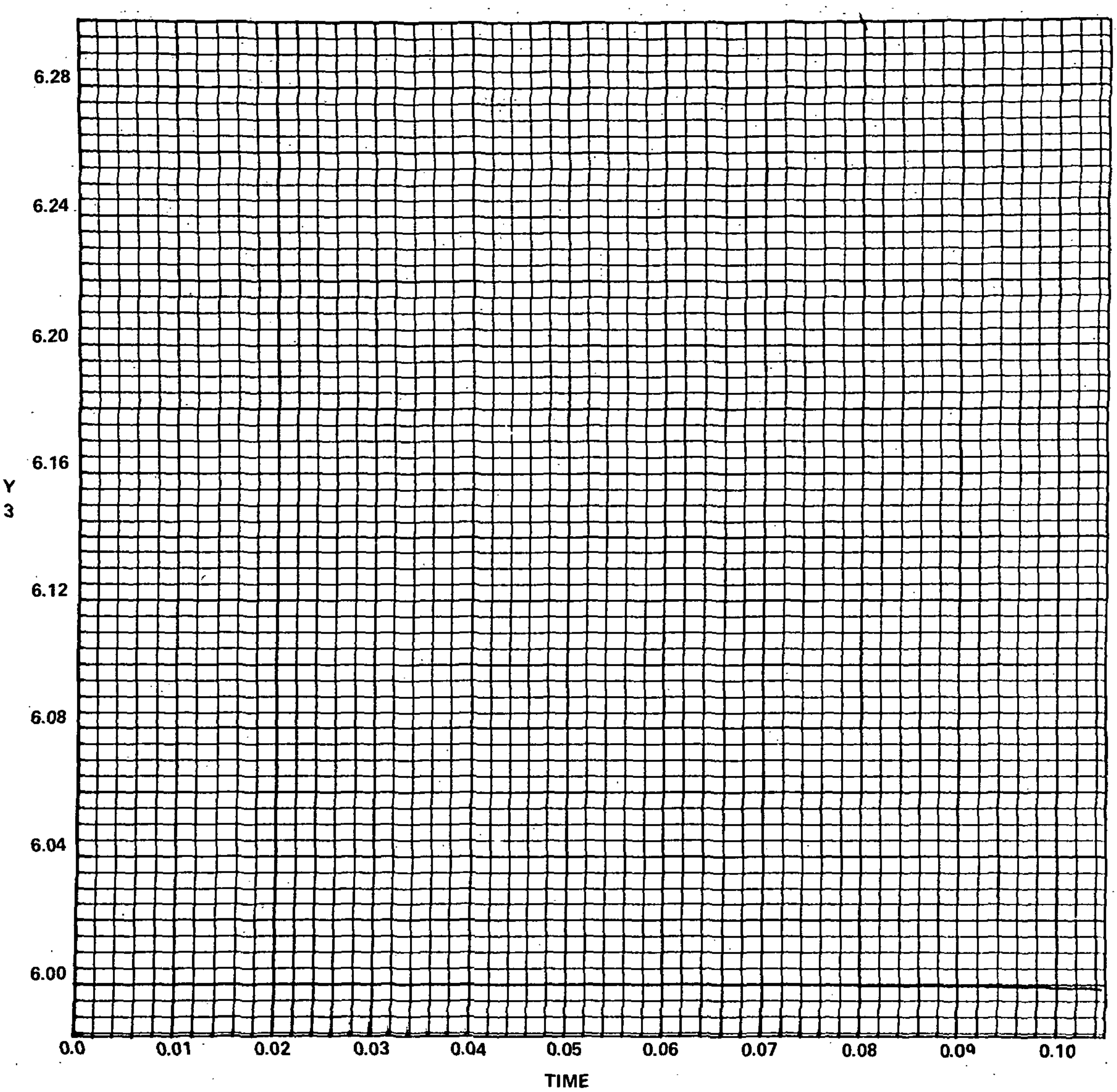

0.0
-0.002
-0.004
-0.006
0.008
-0.010
-0.012
-0.014
-0.016
-0.018
X
3
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME

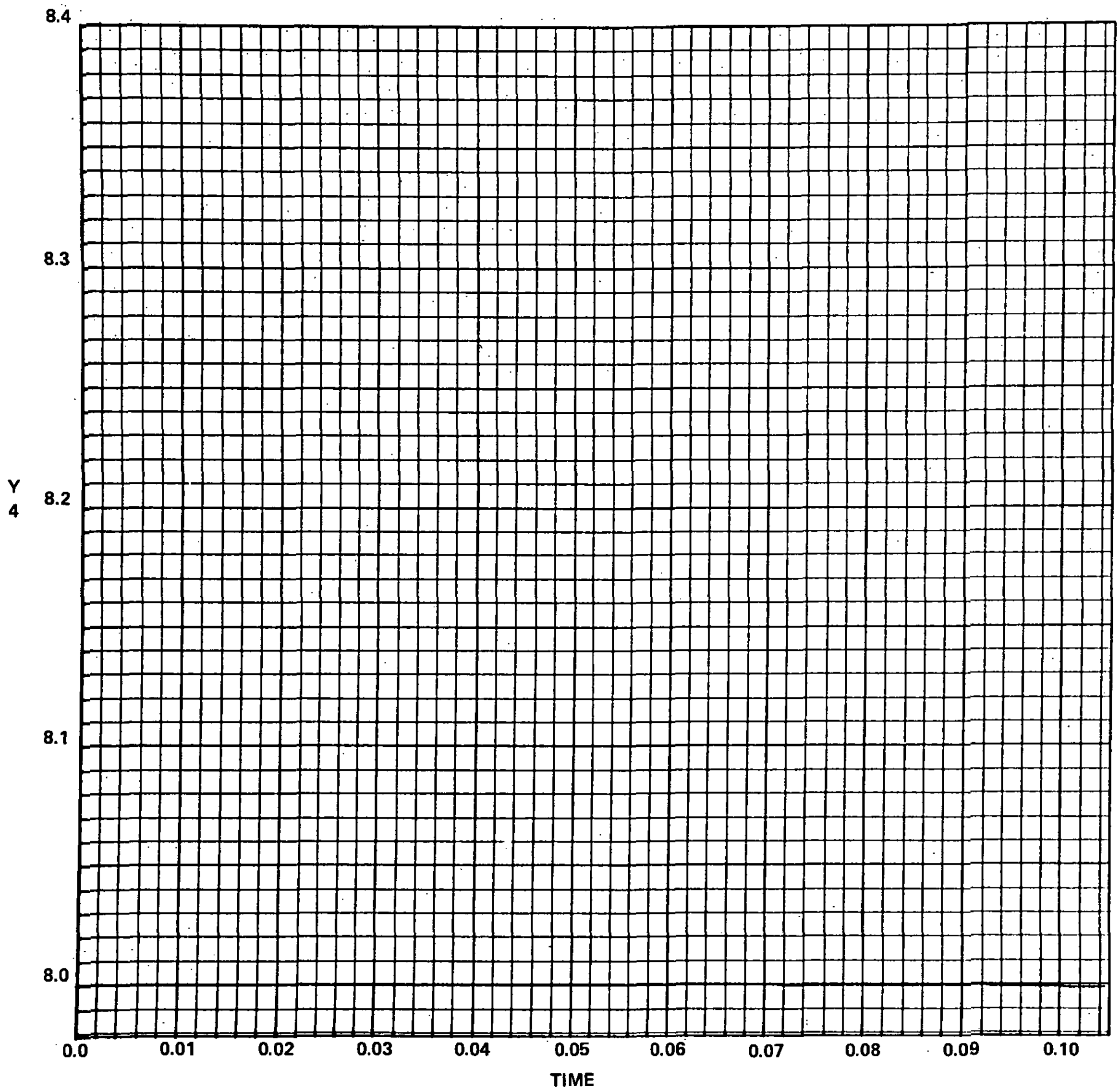

0.00007
0.00006
0.00005
X
4
0.00004
0.00003
0.00002
0.00001
0.0
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME


2.10
2.09
2.08
2.07
2.06
2.05
2.04
2.03
2.02
2.01
2.00
Y
1
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME



4.20
4.18
4.16
4.14
4.12
4.10
4.08
4.06
4.04
4.02
4.00
Y
2
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME


6.28
6.24
6.20
6.16
Y
3
6.12
6.08
6.04
6.00
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME


8.4
8.3
Y
4
8.2
8.1
8.0
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
TIME

END JØB- RPTLD6

REFERENCES

1. Wuenscher, H.: Development of a Tooling Concept for Manufacturing Operations in Space (Serpentuator). Pictorial Status Report, SRT Code 905-31-21-03-62 (OMSF), Marshall Space Flight Center, Huntsville, Ala., July, 1967.

2. Trauboth, H.; and McCollum, W.: MARSYAS Users Manual. Computation Laboratory, Marshall Space Flight Center, Huntsville, Ala., January, 1973.

3. Trauboth, H.; and Prasad, N.: MARSYAS – A Software Engineering System for the Digital Simulation and Analysis of Physical Systems. International Federation of Automatic Control (IFAC), Budapest Symposium on Digital Simulation of Continuous Processes (DISCOP), Györ, Hungary, September, 1971.

4. Trauboth, H.; and Prasad, N.: MARSYAS – A Software System for the Digital Simulation of Physical Systems. Proceedings of the Spring Joint Computer Conference, Atlantic City, N.J., 1970, pp. 223-235.

5. Prasad, N.; Blum, H.; and Wisnia, H.: Addition of Newton's Method for the Solution of Nonlinear Loops. MARSYAS Specifications, vol. VI, Digital Simulation Systems, Inc., New York, N.Y., 1971.

6. Buntyn, T. J.; Dyer, M. E.; and Austin, S. L.: AMTRAN Users Manual. Interim Report SE-COMP-1399, Teledyne/Brown Engineering Co., Huntsville, Ala., September, 1971.

7. Wood, L. H.; Reinfelds, J.; Seitz, R. N.; and Clem, P. L., Jr.: The AMTRAN System. Datamation, vol. 12, no. 10., 1966, p. 22.

8. Singh, S. P.: Structural Properties of Large-Scale Dynamical Systems, Ph.D. dissertation, University of Notre Dame, June, 1972.

9. Singh, S. P.; and Liu, R.: Existence of State-Equation Representation of Linear Large-Scale Dynamical Systems. Electrical Engineering Department Memorandum EE7205b, University of Notre Dame, November, 1972.

NASA-Langley, 1973 —— 8

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

SPECIAL FOURTH-CLASS RATE
BOOK

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
451

U.S.MAIL

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546