The Use of ACSL in the Teaching of Process Dynamics and Control

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The use of industrial tools and methods in any engineering course is desirable, and should be encouraged to be utilized at the earliest point in any curriculum. During the past five years many industrial firms that are in the business of developing and marketing simulation software have made their products available to educational institutions either at no cost or for a nominal fee. The corporations that have initiated this policy cover both steady state and dynamic simulators. The distribution of simulators used in chemical engineering is heavily weighted toward the steady state, because that is how the majority of process design and analysis is accomplished. This distribution is currently undergoing a change, but the use of steady state simulators still predominates.

The subject of process dynamics and control in the chemical engineering curriculum had in the past relied heavily on transform mathematics and analog computers to perform the dynamic analysis of process equipment and the associated control schemes. The advent of faster digital computers has replaced the analog computer and the hybrid computers in performing dynamic analysis. The area of transform mathematics is still important, but today it should not dominate.

This paper focuses on the use of dynamic simulators in the chemical engineering curriculum, with specific emphasis in process dynamics and control. Two dynamic simulation codes were considered: Advanced Computer Simulation Language from Mitchell and Gauthier Associates of Concord, MA, and CSSL-IV from Simulation Services of Chatsworth, CA. NJIT focused on ACSL because of its use by other universities.

This paper presents a program that rapidly introduces the Advanced Computer Simulation Language (ACSL) to the undergraduate chemical engineering student, which then permits him to perform dynamic analysis on various systems. After preparing the process model (which includes the appropriate differential equations), the student can then investigate the effect on numerical integration step size, and the model's dynamic behavior by varying the manipulative parameters. Subsequent papers will address the logical extensions, namely, introduce specific models of interest to chemical engineers, introduce the control scheme into the dynamic model, and finally study the effect of the control system coupled with the process.

Introduction

Process dynamics and control (PDC) in the chemical engineering curriculum is normally a fourth year course. The first question that needs to be answered is: What is process dynamics? The answer is, simply, the study of the time dependent behavior of the processes that have been covered in the various undergraduate courses. The processes can range from the simple filling of an open tank, to a reactive process coupled with a product recovery system. The second question that logically follows is: What is process control? Here the answer is the addition of sufficient instrumentation and control loops (feedback / feedforward to a controller and the associated valve, speed control device, etc) so that the process units performs as designed, as well as properly responding to changes in process variables and parameters.

The first formal exposure that the engineering student gets to the subject of dynamics is in his or her differential equations course, where the principles of physics are combined with the calculus to systematically solve time dependent equations. In the chemical engineering courses, the subject of dynamic behavior is usually briefly discussed in the stoichiometry, fluid mechanics, heat transfer, kinetics and mass transfer courses, but never enough to make the student comfortable with time dependent systems. The real initial exposure is left to the PDC course, and this I question as being inappropriate. The discussion of this point is left for another forum.

During the second and third years of the chemical engineering curriculum, the student hears from the fourth year students a continual stream of negative comments on the subject of 'process dynamics' and most of all on 'process dynamics and control'. This negative attitude is passed from student class to student class, year after year, so that the students entering the PDC course 'want nothing to do with it!' Part of the problem is that the course traditionally starts with a large segment of time spent on the mathematics of solving differential equations. With such a significant portion of the course spent on the details of solving the time dependent equations, the objective of the course in process dynamics and control is lost. No wonder, the student gets annoyed with the subject matter.

This paper addresses the general subject of dynamics. The objective is: (1) to introduce dynamics with the emphasis on developing the differential relationships and the associated boundary conditions, (2) to obtain the solution to the differential equation(s) with a minimal expenditure of effort, and (3) to provide the means to view the results not as a column of numbers but visually, using graphical displays (terminals and plotters).

Acclimation to Dynamics

To accomplish the first objective the easiest path to follow is to return to the material the engineering student first encountered, the development of mathematical models and the associated solution of the resulting equations ... the course in differential equations, usually given at the end of the two year calculus sequence.

Linear First Order Systems

The application oriented problems that were initially encountered were first order differential equations that dealt with particle dynamics (velocity dependence), heat flow, fluid flow, mixing of solutions or 'salt tanks', series electrical circuits (RL and RC), chemical reactions, etc. The ODE given greatest application emphasis is that of problems associated with 'falling bodies'. The following example is illustrative of this type of problem.

Example 1: Falling Body Problem.

A body of weight 64 lb (mass $m = 2$ slugs, with $g = 32$ ft/sec^2) is dropped from a height of 100 ft with an initial downward velocity $v_o = 10$ ft/sec (fps). The body encounters an air resistance proportional to its velocity v. If the limiting downward velocity is known to be 128 fps, then:

(a) The differential equation of motion ... v(t), is:

$$F = mg - kv = m\dot{v}$$

$$\dot{v} + \frac{k}{m} v = g$$

with v positive in the downward direction. From the given limiting velocity of 128 fps the value of the constant k is evaluated, $k = 0.5$.

(b) The expression for the velocity of the body as a function of time ... v(t), is:

$$v(t) = (v_o - mg/k)\exp(-kt/m) - mg/k$$

using the integrating factor exp (+kt/m) and the initial condition $v(0) = v_o = 10$ fps.

Substituting the numerical values into the expression for the velocity the following is obtained:

$$v(t) = -118\exp(-t/2) + 128$$

The electrical equivalent of the above dynamics problem is given in Example 2.

Example 2: Series RL Circuit.

A series RL-circuit has an electromotive force (emf) of E ($E = 5$ volts), a resistance R ($R = 50$ ohms), and an inductance L ($L = 1$ henry). There is no initial current in circuit. At time t=0 the voltage source is imposed by closing a switch.

(a) The differential equation for current flow ... i(t), is:

$$L\dot{i} + Ri = E$$

(b) The expression for the current flow ... i(t), is:

$$i(t) = \frac{E}{R} - \frac{E}{R}\exp(-Rt/L)$$

using the integrating factor ex (+Rt/L) and the initial condition $i(0) = i_o = 0$.

Substituting the numerical values into the expression for the current the following is obtained:

$$i(t) = 0.10\,(1.0 - \exp(-50t))$$

Linear Second Order Systems

Logically, second order systems are covered next. This application area covers harmonic oscillators, the simple pendulum, particle dynamics, population dynamics, deflections of beams, series electrical circuits (LC and RLC), etc. The ODE's given greatest emphasis are the class of problems associated with 'harmonic oscillators' and 'series RLC electrical circuits'. It should be noted that these two classes are analogs of each other. The following example is illustrative of 'harmonic oscillators'.

Example 3: Damped Spring Mass System.

A mass having a weight of 6.0 lb is loaded onto a damped spring system. The load point of the unloaded spring is the point of displacement reference, with the downward direction being positive. The initial displacement of the equilibrated system is 6 inches, from which the spring force constant, A, is determined to be 12.0 lb_f/ft. The drag force, which is proportional to the velocity, has a damping coefficient, k, equal to 1.5 lb_f/fps. The mass is displaced positively an additional 4 inches, and then released.

(a) The differential equation of motion ... x(t), is:

$$F = w - k\dot{x} - Ax = m\ddot{x},$$

$$w = mg$$

The initial conditions for the spring mass system are:

$$x = 0.0 \text{ ft, and } \dot{x} = 0.8333 \text{ ft/sec}$$

(b) The expression for the displacement of the mass as a function of time ... x(t), is:

$$x(t) = 0.5 + 1/9 \exp(-4t) [\, 3 \cos(4\sqrt{3}t) + \sqrt{3} \sin(4\sqrt{3}t)\,]$$

$$x(t) = 0.5 + 2\sqrt{3}/9 \exp(-4t) \sin(4\sqrt{3}t + \pi/3)$$

The damped oscillatory motion is bounded by two exponential curves. The equations of these limits are:

$$x_{top}(t) = 0.5 + 2\sqrt{3}/9 \exp(-4t)$$

$$x_{bot}(t) = 0.5 - 2\sqrt{3}/9 \exp(-4t)$$

The quasi period is given by $2\pi/\omega$ or $2\pi/(4\sqrt{3})$. The natural period of this spring mass system (no damping) is less ... $2\pi/8$, which is plausible since one would expect opposition to motion via damping to increase the time for a complete cycle.

The electrical equivalent of the above dynamics problem is given in Example 4.

Example 4: Series RLC Circuit Problem.

An RLC-circuit has a resistance of R ohms (R = 10), a capacitance C farads (C = 10^{-2}) and inductance of L henrys (L = 0.5), with an 'emf' of E volts (E = 12) applied at time zero (0). Assuming no initial current in the circuit and no initial charge on the capacitor, then:

(a) The differential equation for the RLC circuit is:

$$L\dot{i} + Ri + \frac{q}{C} = E$$

or

$$L\ddot{i} + R\dot{i} + \frac{i}{C} = 0$$

The initial conditions for the RLC circuit are:

$$i = 0.0 \quad \text{and} \quad q = 0.0$$

(b) The expression for the current through the circuit is:

$$i(t) = 12/5 \exp(-10t) \sin(10t)$$

(c) The expression for the charge on the capacitor is:

$$q(t) = 3/25\, [1.0 - \exp(-10t) (\sin(10t) + \cos(10t))]$$

$$q(t) = 3/25\, [1.0 - \exp(-10t) \sin(10t + \pi/4)]$$

Systems of Linear Differential Equations

The extension of single variable systems is to those of coupled systems involving systems of ordinary differential equations, which have to be solved simultaneously. Examples of such systems are coupled oscillators and pendulums, rotational motion of multiple flywheels on the same shaft, series connected 'salt' tanks with recycle streams, coupled chemical reactions, complex electrical circuits, curves of pursuit, etc.

The systems that get preferential treatment in a differential equations course are those associated with mechanical systems (coupled oscillators and pendulums), series connected mixing tanks, and complex electrical circuits. Here it might be well to consider two examples, one in the area of particle dynamics and the second addressing mixing tanks ('salt tanks').

Example 5: Two Springs Connected in Series.

Two vertically oriented spring mass systems are connected in series. The top end of spring #1 is fixed while the top end of spring #2 is attached to the mass #1. The displacement of each mass is relative to the equilibrated spring loaded system. The equilibrated system is perturbed with mass #1 having a velocity of +1 ft/sec (fps) and mass #2 having a velocity of -1 fps.

(a) The differential equations for coupled spring mass system are:

$$m_1\ddot{x}_1 = -k_1x_1 + k_2(x_2 - x_1)$$

$$m_2\ddot{x}_2 = -k_2(x_2 - x_1)$$

The initial conditions for the spring mass system are:

$$\dot{x}_1 = 1.0, \qquad x_1 = 0.0,$$

$$\dot{x}_2 = -1.0, \qquad x_2 = 0.0$$

The constants associated with the coupled system are:

$$k_1 = 6.0, \qquad m_1 = 1.0,$$

$$k_2 = 4.0, \quad \text{and} \quad m_2 = 1.0$$

(b) The expressions for the vertical displacement of the two masses are:

$$x_1(t) = -\sqrt{2}/10 \sin(\sqrt{2}t) + \sqrt{3}/5 \sin(2\sqrt{3}t)$$

$$x_2(t) = -\sqrt{2}/5 \sin(2t) - \sqrt{3}/10 \sin(2\sqrt{3}t)$$

Example 6: Two Salt Tanks in Series.

Tank A contains 50 gallons of water in which 25 pounds of salt are dissolved. A second tank, B, contains 50 gallons of pure water. Liquid is pumped in and out of the tanks at the following rates:

Tank A: in ... 3 gpm fresh feed of pure water
in ... 1 gpm recycle to Tank A from Tank B
out ... 4 gpm to Tank B

Tank B: in ... 4 gpm from Tank A,
out ... 1 gpm recycle from Tank B to Tank A
out ... 3 gpm of product

For the tanks, the rate of change of the salt in the tank is the aggregate of the product of the flow rate and the associated concentration.

$$\Delta\text{Salt} = \sum(\text{flow*conc})_{in} - \sum(\text{flow*conc})_{out}$$

$$\dot{x}_1 = (3\text{ gpm})(0\text{ lb/gal}) + (1\text{ gpm})(\frac{x_2}{50}\text{ lb/gal}) - (4\text{ gpm})(\frac{x_1}{50}\text{ lb/gal})$$

$$\dot{x}_2 = (4\text{ gpm})(\frac{x_1}{50}\text{ lb/gal}) - (3\text{ gpm})(\frac{x_2}{50}\text{ lb/gal}) - (1\text{ gpm})(\frac{x_2}{50}\text{ lb/gal})$$

(a) The differential equations which describe the number of pounds of salt in tanks A and B ($x_1(t)$ and $x_2(t)$) are:

$$50\dot{x}_1 = -4x_1 + x_2$$

$$50\dot{x}_2 = +4x_1 - 4x_2$$

The initial conditions for the salt tank system are:

$$x_1 = 25.0 \quad \text{and} \quad x_2 = 0.0$$

(b) the time dependent equations for $x_1(t)$ and $x_2(t)$ are:

$$x_1(t) = 25/2\ [\exp(-3t/25) + \exp(-t/25)]$$

$$x_1(t) = 25\ [-\exp(-3t/25) + \exp(-t/25)]$$

Solution of Differential Equations

The development of differential equations requires the development of a free-body-diagram for particle dynamics, differential flow diagrams for solution systems, current/charge diagrams for electrical systems, etc. These diagrams and the subsequent analysis generate the differential equations, along with the necessary boundary condition(s). The prime time consuming effort is obtaining a solution of the differential equation(s). Obtaining a solution in equation form is one thing, but understanding the time dependence is an exercise that one has to go through. Without plotting the input function and the response (output) as a function of time, the exercise is just a set of numbers that, do not have any real meaning, except for the simplest of functions.

How does one cope with such a situation? The solution to the time dependent differential equation(s) is required, as well as an understanding of the results. The student gets bogged down in the details of the whole course in process dynamics and control by spending inordinate amounts of time solving (or trying to solve) differential equations. The answer is straight forward ... develop the differential relationships and the initial conditions, but leave the solution methodology and mechanics to someone else. Fortunately there exist computer codes that will accomplish this task. The code developed by Mitchell and Gauthier Associates of Concord, MA ... ACSL (Advanced Computer Simulation Language) ... is currently being implemented into the process dynamics and control course to address this issue.

Overview of ACSL

ACSL is a Continuous Simulation Language (CSSL) which follows the standards established by the Technical Committee on CSSL under the auspices of Simulation Councils, Inc. (The Society for Computer Simulation) in Simulation 9 (Dec 1967) pp 281-303. The educational feature of ACSL is that the user can readily acclimate to the protocol of the language. With the availability of a template for the ACSL input, a set of documented illustrative examples, a set of introductory notes, and a reference manual, one can readily use the simulation program. This continuous simulation language has been developed expressly for the purpose of modelling systems described by time dependent, nonlinear differential equations with transfer functions.

The main features of the ACSL language are free format, function generation capability, and independent error control on each integrator. Flexibility is provided for plotting the behavior of the various models under a number of external forcing functions. The ACSL program has incorporated into the executable code the necessary drivers for Tektronix terminals, DEC VT-240 / 241 Regis terminals, and HP plotters.

The free format feature of the ACSL code permits an algebraic input of the differential equations and their initial conditions. The ACSL statements supplied by the user are in two distinct groups. The first defines the model or structure of the system being simulated, while the second changes model parameters, starts runs, controls which plots to make, etc. The latter section contains the run time commands which describe the analysis to be performed. The ACSL input is translated into a sorted set of Fortran statements that are subsequently compiled and linked with the desired integrator routine and the I/O routines.

Figure 1 contains a skeleton overview of the ACSL command sections, with descriptive comments ... the majority of which were provided by E. Mitchell and J. Gauthier.

Use of ACSL

The use of ACSL requires that a systematic approach be used in the preparation of the input to ACSL. A 'template' has been recommended by Joe Gauthier, and found to be extremely helpful in organizing the translation of the mathematics of the model into the ACSL programming language. Figure 2 describes the ACSL template with comments to assist the user.

Use of the ACSL simulation language requires that one must have available a computer that will execute the code. This presents no problem since the code associated with ACSL is available on numerous computers as well as IBM PC's. The terminals that are connected to the computer should have graphics capability in order to make full use of the system. Hard copy plotters are also necessary for formal documentation.

Solution of Previously Cited Examples Using ACSL

For the previous cited examples, the solution was obtained by classical means. The following is a repeat of the solution of these examples using ACSL on a DEC VAX 11/785 digital computer.

The spacing 'comment statements' in the ACSL translator input and in the ACSL command file have been deleted for editorial purposes.

Example 1: Falling Body Problem.

A body of weight 64 lb (mass $m = 2$ slugs, with $g = 32$ ft/sec^2) is dropped from a height of 100 ft with an initial downward velocity $v_o = 10$ ft/sec (fps). The body encounters an air resistance proportional to its velocity v. If the limiting downward velocity is known to be 128 fps, then:

(a) The differential equation of motion ... v(t), is:

$$F = mg - kv = m\dot{v}$$

$$\dot{v} + \frac{k}{m} v = g$$

with v positive in the downward direction. From the given limiting velocity of 128 fps the value of the constant k is evaluated, k = 0.5.

(b) The following ACSL program statements are placed in the file EX1.CSL ... to be processed by the ACSL procedure file, generating the executable EX1.EXE:

```
PROGRAM EX1
     " --- Falling body problem sub"
     "     ject to a drag force pro-"
     "     portional to the velocity."
     " --- Units of time are seconds."
     CONSTANT    G=32.0, W=64.0, M=2.0
INITIAL
     " --- Define preset variables."
     CONSTANT    VIC=0.0, K=0.5
     " --- Time scale to be 20.0 sec-"
     "     onds."
     CONSTANT    TSTP=19.9
     " --- Communication interval,max-"
     "     imium time step, and CINT"
     "     divisor."
     CINTERVAL   CINT=0.01
     NSTP=1
END $ " OF INTERVAL "
DERIVATIVE
     " --- Another way of changing "
     "     the independent variable "
     "     T , is by integrating T,"
     "     and storing the results in"
     "     TIME."
     TIME = INTEG ( 1.0, 0.0 )
     " --- Acceleration is the force"
     "     divided by the mass."
     VD = (W - K*V) / M
     " --- Integrate acceleration for"
     "     velocity"
     V = INTEG ( VD, VIC )
     " --- Specify the required ter-"
     "     mination condition."
     TERMT ( T.GE.TSTP )
END $ " OF DERIVATIVE SECTION "
END $ " OF PROGRAM "
```

(c) The following ACSL run time data statements are placed in the file EX1.DAT, to be executed using the ACSL command 'set cmd = 7', which transfers input to ACSL to logical unit 7:

```
" --- Set high volume printer switch"
set hvdprn = .t.
" --- Set graphic display to a VT 240"
"     / 241 terminal using DEC Regis"
" ... set devplt=2 ... "
" --- Set graphic display to a HP"
"     7475A Plotter"
set devplt=3
set title = "Example # 1 ... Falling"
            " Body Problem"
" --- Values to screen"
output t, v, vd, 'nciout'=200
" --- Values to File RRR, FOR008.DAT"
prepar t, v, vd
start
" --- Return for input from Keyboard"
set cmd = 5
```

(d) The following is the edited output from ACSL ... file EX1.OUT:

V = velocity, and VD = acceleration

T 0.	V 0.	VD 32.0000000
T 2.00	V 50.36410	VD 19.4090000
T 4.00	V 80.91140	VD 11.7721000
T 6.00	V 99.43930	VD 7.14017000
T 8.00	V 110.6770	VD 4.33073000
T 10.0	V 117.4930	VD 2.62672000
T 12.0	V 121.6270	VD 1.59319000
T 14.0	V 124.1350	VD 0.96631600
T 16.0	V 125.6560	VD 0.58610000
T 18.0	V 126.5780	VD 0.35548800
T 19.9	V 127.1160	VD 0.22107300

(e) Figures 3 and 4 present the velocity and acceleration distributions with respect to time for the falling body problem over a 20.0 second period. These drawings were prepared by ACSL via a Hewlett Packard plotter.

Example 2: Series RL Circuit.

A series RL-circuit has an electromotive force (emf) of E (E = 5 volts), a resistance R (R= 50 ohms), and an inductance L (L = 1 henry). There is no initial current in circuit. At time t=0 the voltage source is imposed by closing a switch.

(a) The differential equation for current flow ... i(t), is:

$$L\dot{i} + Ri = E$$

(b) The following ACSL program statements are placed in the file EX2.CSL ... to be processed by the ACSL procedure file, generating the executable EX2.EXE:

```
PROGRAM EX2
     " --- Series RL-circuit with a "
     "     constant voltage E. At"
     "     time zero, the series "
     "     circuit is closed. "
     " --- Units of time are seconds."
     CONSTANT    R=50.0, L=1.0, E=5.0
INITIAL
     " --- Define preset variables."
     CONSTANT    IIC=0.0
     " --- Time scale to be 0.10"
```

```
        TIME = INTEG ( 1.0, 0.0 )
        " --- Define the acceleration "
        XDD = (W-K*XXX-K*XD-A*X) / (W/G)
        "--- Integrate acceleration for"
        "    velocity, and then the ve-"
        "    locity for position."
        XD  = INTEG ( XDD, XDIC )
        X   = INTEG ( XD , XIC  )
        XTOP  =  0.5 + 2.0/9.0 * ...
                 SQRT(3.0) * EXP(-4.0*T)
        XBOT  =  0.5 - 2.0/9.0 * ...
                 SQRT(3.0) * EXP(-4.0*T)
        "--- Specify the required ter-"
        "    mination condition."
        TERMT ( T.GE.TSTP )
   END $ " OF DERIVATIVE SECTION "
   END $ " OF PROGRAM "
```

(c) The following ACSL run time data statements are placed in the file EX3.DAT, to be executed using the ACSL command 'set cmd=7', which transfers input to logical unit 7:

```
"    Runtime Commands for Example # 3"
"--- Set high volume printer switch"
set hvdprn = .t.
" --- Set graphic display to a VT 240"
"     / 241 terminal using DEC Regis"
' ... set devplt=2 ... '
" ----- Set graphic display to a HP"
"       7475A Plotter"
set devplt=3
set title = 'Example # 3: Damped ...
             Spring Problem'
" --- Values to screen"
output t, xdd, xd, x, 'nciout'=20
" --- Values to File RRR, FOR008.DAT"
prepar t, xdd, xd, x, xtop, xbot
start
" --- Return to input from Keyboard"
' ... set cmd = 5 ... '
'-'
RANGE "ALL"
set plt=1
PLOT "XAXIS"=TIME, X,XD
set plt=2
PLOT "XAXIS'=TIME, X,XTOP,XBOT,'SAME'
set plt=3
PLOT "XAXIS"=XD, X
STOP
```

(d) The following is the edited output from ACSL ... file EX3.OUT:

X = Displacement XD = Velocity XDD = Acceleration

```
T 0.   XDD-21.333  XD 0.      X 0.8333
T 0.1  XDD-5.7299  XD-1.3183  X 0.7543
T 0.2  XDD 3.6749  XD-1.3599  X 0.6125
T 0.3  XDD 6.3655  XD-0.8104  X 0.5018
T 0.4  XDD 4.9151  XD-0.2249  X 0.4513
T 0.5  XDD 2.2099  XD 0.1320  X 0.4489
T 0.6  XDD 0.0712  XD 0.2373  X 0.4692
T 0.7  XDD-0.9195  XD 0.1854  X 0.4911
T 0.8  XDD-0.9805  XD 0.0846  X 0.5047
T 0.9  XDD-0.5983  XD 0.0040  X 0.5088
T 1.0  XDD-0.1766  XD-0.0339  X 0.5069
```

```
RANGE "ALL"
     TIME 0.              1.00000000
      XDD-21.3333000  6.36555000
      XD -1.45672000  0.23750300
      X   0.44566000  0.83333300
     XTOP 0.50705000  0.88490000
     XBOT 0.11510000  0.49295000
```

(e) Figure 6 presents both the displacement and the velocity of the oscillating mass. Figure 7 presents the displacement of the mass along with the exponential bounds. The phase plane plot is given by Figure 8, and indicates that the system is very nearly critically damped.

Example 4: Series RLC Circuit Problem.

An RLC-circuit has a resistance of R ohms (R = 10), a capacitance C farads (C = 10^{-2}) and inductance of L henrys (L = 0.5), with an electromotive force (emf) of E volts (E = 12) applied at time zero (0). Assuming no initial current in the circuit and no initial charge on the capacitor, then:

(a) The differential equation for the RLC circuit is:

$$L\dot{i} + Ri + \frac{q}{C} = E$$

or

$$L\ddot{i} + R\dot{i} + \frac{i}{C} = 0$$

The initial conditions for the RLC circuit are:

$$i = 0.0 \quad \text{and} \quad q = 0.0$$

(b) The following ACSL program statements are placed in the file EX4.CSL ... to be processed by the ACSL procedure file, generating the executable EX4.EXE:

```
PROGRAM EX4
     " --- Series RLC-circuit with a "
     "     constant voltage E.  At"
     "     time zero, the series cir-"
     "     cuit is closed with no "
     "     charge on the capacitor. "
     " --- Units of time are seconds."
INITIAL
     " --- Define the circuit con-"
     "     stants"
     CONSTANT    R=10.0,  L=0.5, ...
                 C=1.0E-2,  V=12.0
     " --- Define preset variables."
     CONSTANT    IIC=0.0,  QIC=0.0
     " --- Time scale to be 1.0 min"
     CONSTANT    TSTP=0.999
     " --- Communication interval,"
     "     maximum time step, and"
```

```
     "     CINT divisor."
     CINTERVAL   CINT=0.0001
     NSTP=1
END $ " OF INITIAL "
DERIVATIVE
     " --- Another way of changing"
     "     the independent variable T"
     "     is by integrating T, and"
     "     storing the results in"
     "     TIME."
     TIME = INTEG ( 1.0, 0.0 )
     " --- Circuit definition of the"
     "     rate of change of the cur-"
     "     rent. "
     IDOT = ( V - Q/C - R*I ) / L
     " --- Integrate to obtain cur-"
     "     rent."
     I = INTEG ( IDOT, IIC )
     " --- Integrate current to ob-"
     "     tain the charge."
     Q = INTEG ( I, QIC )
     " --- Specify the required ter-"
     "     mination condition."
     TERMT ( T.GE.TSTP )
END $ " OF DERIVATIVE SECTION "
END $ " OF PROGRAM "
```

(c) The following ACSL run time data statements are placed in the file EX4.DAT, to be executed using the ACSL command 'set cmd=7', which transfers input to logical unit 7:

```
"   Runtime Commands for Example # 4"
" --- Set high volume printer switch"
set hvdprn = .t.
" --- Set graphic display to a VT 240"
"     / 241 terminal using DEC Regis"
' ... set devplt=2 ... '
" ----- Set graphic display to a HP"
"       7475A Plotter"
set devplt=3
set title = 'Example # 4: Series ...
            RLC-Circuit'
" --- Values to screen"
output t, idot, i, q, 'nciout'=200
" --- Values to File RRR, FOR008.DAT"
prepar t, idot, i, q
" ----- Return to input from Keyboard"
' ... set cmd = 5 ... '
'-'
RANGE "ALL"
set plt=1
PLOT "XAXIS"=time, i,q
set plt=2
PLOT "XAXIS"=i,q
STOP
```

(d) The following is the edited output from ACSL ... file EX4.OUT:

```
T 0.   IDOT 24.000  I 0.      Q 0.
T 0.1  IDOT-2.6590  I 0.7429  Q 0.0590
T 0.2  IDOT-4.3051  I 0.2953  Q 0.1119
T 0.3  IDOT-1.3515  I 0.0168  Q 0.1250
T 0.4  IDOT 0.0453  I-0.0332  Q 0.1231
T 0.5  IDOT 0.2009  I-0.0155  Q 0.1205
T 0.6  IDOT 0.0737  I-0.0016  Q 0.1197
T 0.7  IDOT 0.0021  I 0.0014  Q 0.1198
T 0.8  IDOT-0.0091  I 8.0E-0  Q 0.1199
T 0.9  IDOT-0.0039  I 1.3E-0  Q 0.1200
T 1.0  IDOT-3.E-04  I-6.E-05  Q 0.1200

RANGE "ALL"
         T 0.              0.99900000
      IDOT-4.98911000   24.0000000
         I-0.03343690   0.77375200
         Q 0.              0.12518600
```

(e) Figure 9 illustrates both the current through the circuit and the charge buildup on the capacitor. Figure 10 presents the phase plane plot which indicates that the circuit is nearly critically damped.

Example 5: Two Springs Connected in Series.

Two vertically oriented spring mass systems are connected in series. The top end of spring #1 is fixed while the top end of spring #2 is attached to the mass #1. The displacement of each mass is relative to the equilibrated spring loaded system.

The equilibrated system is perturbed with mass #1 having a velocity of 1 ft/sec (fps) and mass #2 having a velocity of -1 fps.

(a) The differential equations for coupled spring mass system are:

$$m_1\ddot{x}_1 = -k_1x_1 + k_2(x_2 - x_1)$$

$$m_2\ddot{x}_2 = -k_2(x_2 - x_1)$$

The initial conditions for the spring mass system are:

$$\dot{x}_1 = 1.0, \quad x_1 = 0.0,$$

$$\dot{x}_2 = -1.0, \quad x_2 = 0.0$$

The constants associated with the coupled system are:

$$k_1 = 6.0, \quad m_1 = 1.0,$$

$$k_2 = 4.0, \quad m_2 = 1.0$$

(b) The following ACSL program statements are placed in the file EX5.CSL ... to be processed by the ACSL procedure file, generating the executable EX5.EXE:

```
PROGRAM EX5
     " --- Two vertical spring mass"
     "     systems connected in"
     "     series.  The top spring is"
     "     fixed and the second "
     "     spring is connected to the"
     "     first mass.  At the end of"
```

```
     "     the second spring is mass"
     "     number two. "
     " --- Units of time are seconds."
INITIAL
     " --- Define the spring mass"
     "     constants"
     CONSTANT    M1=1.0,  M2=1.0, ...
                 K1=6.0,  K2=4.0
     " --- Define preset variables."
     CONSTANT  X1IC=0.0, X2IC=0.0, ...
               X1DIC=1.0, X2DIC=-1.0
     " --- Time scale to be 10.0 sec."
     CONSTANT    TMAX=9.999
     " --- Communication interval,"
     "     maximum time step, and"
     "     CINT divisor."
     CINTERVAL   CINT=0.005
     NSTP=1
END $ " OF INITIAL "
DERIVATIVE
     " --- Another way of changing"
     "     the independent variable T"
     "     is by integrating T, and"
     "     storing the results in"
     "     TIME."
     TIME = INTEG ( 1.0, 0.0 )
     " --- Equations of motion for"
     "     the spring mass system."
     X1DD = ( -K1*X1+K2*(X2-X1) ) / M1
     X2DD = ( -K2*(X2-X1) ) / M2
     " --- Integrate to obtain the"
     "     velocity."
     X1D = INTEG ( X1DD, X1DIC )
     X2D = INTEG ( X2DD, X2DIC )
     " --- Integrate to obtain the ...
           displacement. "
     X1 = INTEG ( X1D, X1IC )
     X2 = INTEG ( X2D, X2IC )
     " --- Specify the required ter-"
     "     mination condition."
     TERMT ( T.GE.TMAX )
END $ " OF DERIVATIVE SECTION "
END $ " OF PROGRAM "
```

(c) The following ACSL run time data statements are placed in the file EX5.DAT:

```
"    Runtime Commands for Example # 5"
" --- Set high volume printer switch"
set hvdprn = .t.
"--- Set graphic display to a VT 240"
"    / 241 terminal using DEC Regis"
' ... set devplt=2 ... '
"----- Set graphic display to a HP"
"      7475A Plotter"
set devplt=3
set title = 'Example # 5: Two ...
    Springs Connected In Series'
" --- Values to screen"
output t, x1, x2, 'nciout'=200
"-"
"--- Values to File RRR, FOR008.DAT"
prepar t, time, x1, x1d, x2, x2d
start
" --- Return to input from Keyboard"
' ... set cmd = 5 ... '
RANGE "ALL"
set plt=1
PLOT "XAXIS"=time,x1
set plt=2
PLOT x2
set plt=3
PLOT "XAXIS"=x1d,x1
set plt=4
PLOT "XAXIS"=x2d,x2
STOP
```

(d) The following is the edited output from ACSL ... file EX5.OUT:

```
T 0.      X1 0.           X2 0.
T 1.00    X1-0.24948500   X2-0.22448600
T 2.00    X1 0.16469800   X2-0.19126900
T 3.00    X1-0.15916100   X2 0.39483800
T 4.00    X1 0.41574400   X2-6.2772E-04
T 5.00    X1-0.44635600   X2-0.02744220
T 6.00    X1 0.20951800   X2-0.39016900
T 7.00    X1-0.20323700   X2 0.26322300
T 8.00    X1 0.31877900   X2 0.17642300
T 9.00    X1-0.10475700   X2-0.00449048
T 10.0    X1-0.16911500   X2-0.26899300

RANGE "ALL"
       T 0.            9.99900000
    TIME 0.            9.99900000
      X1-0.47965100    0.48723800
     X1D-1.39834000    1.36848000
      X2-0.43042400    0.45050300
     X2D-1.00000000    0.96448300
```

(e) Figures 11 and 12 presents the displacement for both oscillating masses. From these figures the period of the system is observed to be 40.0 seconds. Figures 13-16 present the displacement and phase plane plot for both masses over a 10.0 second time period.

Example 6: Two Salt Tanks in Series.

Tank A contains 50 gallons of water in which 25 pounds of salt are dissolved. A second tank, B, contains 50 gallons of pure water. Liquid is pumped in and out of the tanks at the following rates:

```
Tank A: in  ... 3 gpm of pure water
        in  ... 1 gpm recycle
        out ... 4 gpm

Tank B: in  ... 4 gpm from Tank A,
        out ... 3 gpm
        out ... 1 gpm recycle
```

For the tanks, the rate of change of the salt in the tank is the aggregate of the product of the flow rate and the associated concentration.

$$\Delta\text{Salt} = \sum(\text{flow*conc})_{in} - \sum(\text{flow*conc})_{out}$$

(a) The differential equations which describe the number of pounds of salt in tanks A and B ($x_1(t)$ and $x_2(t)$ respectively are:

$$50\dot{x}_1 = -4x_1 + x_2$$

$$50\dot{x}_2 = +4x_1 - 4x_2$$

The initial conditions for the salt tank system are:

$$x_1 = 25.0, \qquad x_2 = 0.0$$

(b) The following ACSL program statements are placed in the file EX6.CSL ... to be processed by the ACSL procedure file, generating the executable EX6.EXE:

```
PROGRAM EX6
     " --- Two salt tanks connected"
     '      in series. Tank #1 feeds"
     "      tank #2."
     "      F1 - feed to tank #1"
     "      F2 - feed from tank #1 to"
     "           tank #2"
     "      F3 - recycle"
     "      F4 - product from tank #2"
     " --- Units of time are minutes."
     ""
INITIAL
     " --- Define the tank constants"
     CONSTANT   F1=3.0, C1=0.0,   ...
                F2=4.0, F3=1.0,   ...
                F4=3.0,           ...
                V1=50.0,  V2=50.0
     " --- Define preset variables."
     CONSTANT    X1IC=25.0,  X2IC=0.0
     " --- Time scale to be 100.0 min"
     CONSTANT    TMAX=100.0
     " --- Communication interval,"
     "      maximum time step, and"
     "      CINT divisor."
     CINTERVAL   CINT=0.05
     NSTP=1
END $ " OF INITIAL "
DERIVATIVE
     " --- Another way of changing"
     "      the independent variable T"
     "      is by integrating T, and"
     "      storing the results in"
     "      TIME."
     TIME = INTEG ( 1.0, 0.0 )
     " --- Equations describing the"
     "      salt content of tanks #1"
     "      and #2. "
     X1D = F1*C1 + F3*X2/V2 - F2*X1/V1
       X2D  =  F2*X1/V1  -  F3*X2/V2  -
     F4*X2/V2
     " --- Integrate to obtain the"
     "      salt content. "
     X1 = INTEG ( X1D, X1IC )
     X2 = INTEG ( X2D, X2IC )
     " --- Specify the required ter-"
     "      mination condition."
     TERMT ( T.GE.TMAX )
END $ " OF DERIVATIVE SECTION "
END $ " OF PROGRAM "
```

(c) The following ACSL run time data statements are placed in the file EX6.DAT:

```
"    Runtime Commands for Example # 6"
" --- Set high volume printer switch"
set hvdprn = .t.
" --- Set graphic display to a VT 240"
"      / 241 terminal using DEC Regis"
' .... set devplt=2 ... '
" ----- Set graphic display to a HP"
"         7475A Plotter"
set devplt=3
set title = 'Example # 6: Two Salt ...
     Tanks In Series'
" --- Values to screen"
output t, x1, x2, 'nciout'=200
" --- Values to File RRR, FOR008.DAT"
prepar t, time, x1, x1d, x2, x2d
start
" ----- Return to input from Keyboard'
' ... set cmd = 5 ... '
RANGE "ALL"
set plt=1
PLOT "XAXIS"=time,x1,x2
set plt=2
PLOT "XAXIS"=x1d,x1
set plt=3
PLOT "XAXIS"=x2d,x2
STOP
```

(d) The following is the edited output from ACSL ... file EX6.OUT:

```
T 0.      X1 25.0000000  X2 0.
T 10.00   X1 12.1439000  X2 9.22815000
T 20.00   X1 6.75059000  X2 8.96527000
T 30.00   X1 4.10647000  X2 6.84676000
T 40.00   X1 2.62658000  X2 4.84167000
T 50.00   X1 1.72268000  X2 3.32141000
T 60.00   X1 1.14331000  X2 2.24928000
T 70.00   X1 0.76293600  X2 1.51463000
T 80.00   X1 0.51037400  X2 1.01736000
T 90.00   X1 0.34180100  X2 0.68258300
T 100.0   X1 0.22902200  X2 0.45773700

RANGE "ALL"
         T 0.            100.000000
      TIME 0.            100.000000
        X1 0.22902200    25.0000000
       X1D-2.00000000   -0.00916703
        X2 0.            9.62250000
       X2D-0.22222200    2.00000000
```

(e) Figure 17 illustrates the salt content in both tanks. Figures 18 and 19 present the phase plane plots for both tank A and tank B.

Summary

The objective of this paper was to introduce students in the chemical engineering process dynamics and control course to the use of ACSL to solve differential equations associated with various time dependent mathematical models. The tact used was to exploit examples that the student is familiar with, namely mechanical systems, electrical systems, and the mixing of solutions.

The examples presented were selected to give the student a working base to begin an earnest study of dynamics. The first part of this paper presented the classical solution to six (6) problems without any attempt to graphically describe the results, since this is the posture normally taken in a differential equations course.

The second part of the paper presented the solution to the same six problems using ACSL, with its standard solution methodology. Starting with the differential equation(s) and the associated initial condition(s), each example was coded and successfully solved. The time taken to obtain the solution to each example did not exceed one hour. During this time period the integration step size was studied, the results of the simulation were displayed on the graphics terminal, and a final simulation run was made to generate the appropriate hard copy plots.

With an appropriate introduction to the ACSL simulation language (accompanied by reference notes), and the availability of illustrative examples and a copy of the Reference Manual, the student should be able to solve problems within several days. The student's use of ACSL should be initiated via a supervised workshop where the machine dependent procedures associated with ACSL can be demonstrated and explained, and at the same time several of the illustrative examples can be used to reinforce the material presented. The ACSL Reference Manual contains some thirteen example problems complete with problem definition and solution.

Some comments at this time should be made on how to best utilize this commercial package. The most desirable mode would be an IBM-PC (or equivalent), since this gives each user direct control over both the program and the computer. The educational cost structure is $1,000 for the first year and $500 for subsequent years ... on a per machine basis. Utilizing a multiuser computer (such as a DEC VAX 11 / 785) the cost structure is the same, but some ten to fifteen students can use ACSL at the same time. For the annual fee Mitchell and Gauthier will provide limited technical support and also copies of the ACSL Reference Manual. The computational intensity of the integration routines in a multiuser interactive mode dictates that NJIT will move the program to a VAX 8800.

An acknowledgement is in order at this point to Steve Keeton of NJIT's Computer Services Department for assistance is clarifying the DEC Digital Control Language supplied by Mitchell and Gauthier, and also in setting up a dedicated port on the VAX for the HP plotter. The operational control language supplied by Mitchell and Gauthier is under review by S. Keeton for multiuser access.

The use of a HP 7475 plotter for more than a single student is not desirable because the paper has to be hand fed, one sheet at a time. A HP cartridge plotter has been selected for instructional support. The direct connection of a plotter to a computer for more than a single user requires that a spooler be developed so as to keep each individuals plots separate.

What's Next

The next phase of this effort is to prepare a set of appropriate examples from the chemical engineering curriculum emphasizing dynamics. The development of the mathematical model, and the solution of the differential equations using ACSL will prepared. These problems will be used in various workshop exercises and also as homework assignments.

The final phase will be the introduction of a control scheme into the process model. The objective is to observe how the control strategy interfaces with the process, and how the proper control action is established.

Figure 1: ACSL OVERVIEW

```
========================================

   PROGRAM

         { Pre-INITIAL Section }
         Statements executed once, at
         the beginning of simulation.

   INITAL

         { Initial Section }
         Statements contained here are
         executed each time START used.

   END $ " OF INITIAL "

   DYNAMIC

         DERIVATIVE name

               { Derivative Section }
               Statements needed to cal-
               culate derivatives are
               located here.

         END $ " OF DERIVATIVE "
```

```
        DISCRETE name

             ( Discrete Section )
             Statements executed period-
             ically.

        END $ " OF DISCRETE "

        ( Dynamic Section )
        Statements executed during every
        communication interval.

   END $ " OF DYNAMIC "

   TERMINAL

        ( Terminal Section )

   END $ " OF TERMINAL "

   END $ " OF PROGRAM "
-----------------------------------
```

Run Time Commands (Describes the Analysis)

```
   SET variable ...

   PREPAR list ...

   OUTPUT list ...

   START

   DISPLAY list ...

   PLOT list ...

   PRINT list ...

   STOP
```

Figure 2: A TEMPLATE FOR ACSL MODELS

```
   PROGRAM name

        ???

   INITIAL

        ???

   END $ " OF INITIAL "

   DYNAMIC

        CINTERVAL   CINT =  ???
        CONSTANT    TMAX =  ???

   DERIVATIVE name

        ALGORITHM    IALG = ???
        NSTEPS       NSTP = ???
        MAXTERVAL    MAXT = ???
        MINTERVAL    MINT = ???

        ???

   END $ " OF DERIVATIVE "

        ???

   END $ " OF DYNAMIC "

   TERMINAL

        TERMT (T .GE. TMAX)

        ???

   END $ " OF TERMINAL "

   END $ " OF PROGRAM "
```

Figure 3

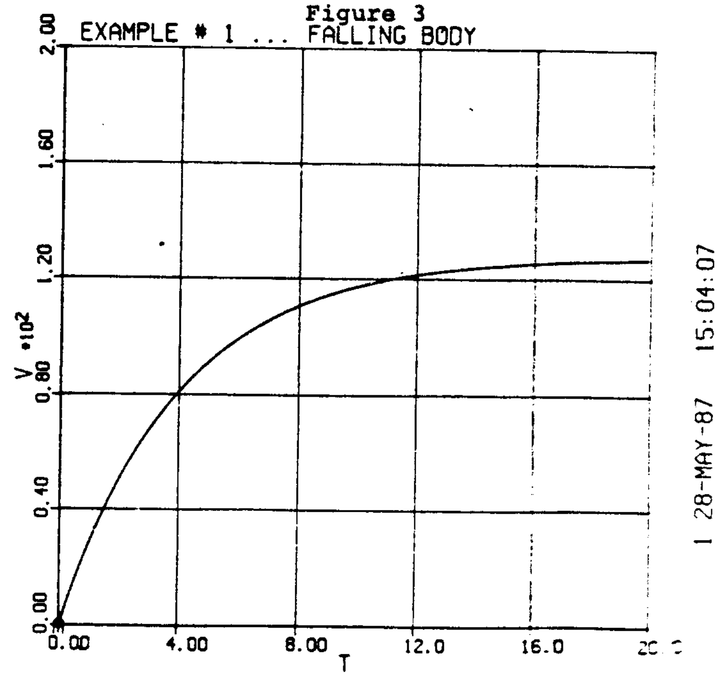

Figure 5

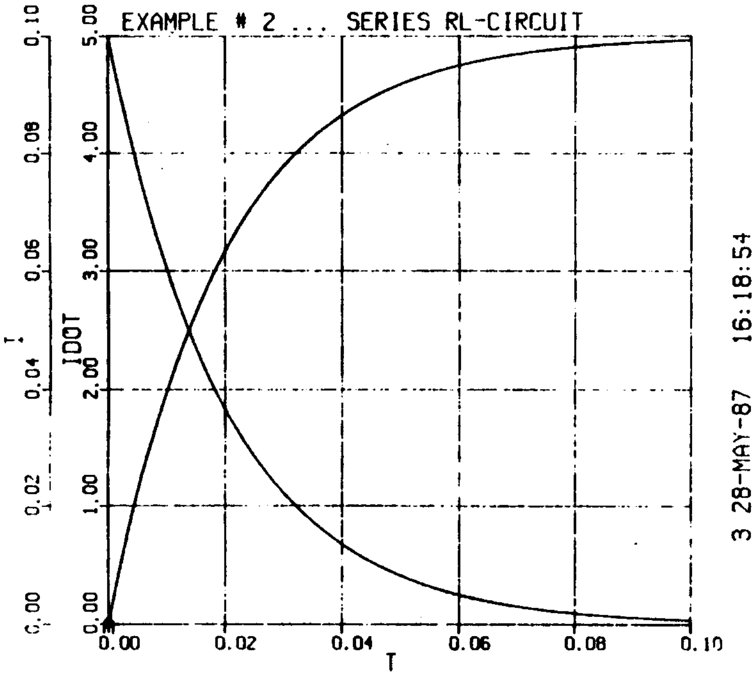

Figure 4

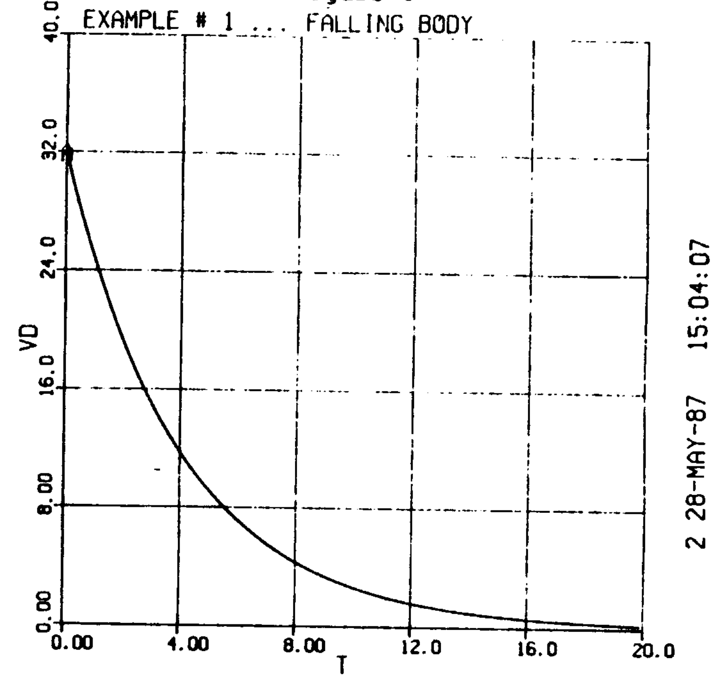

Figure 7

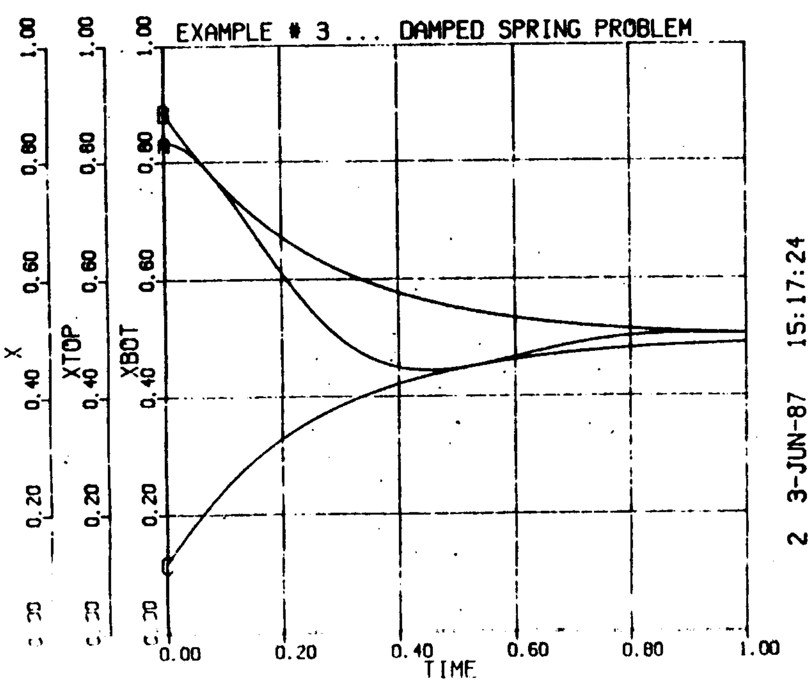

Figure 6

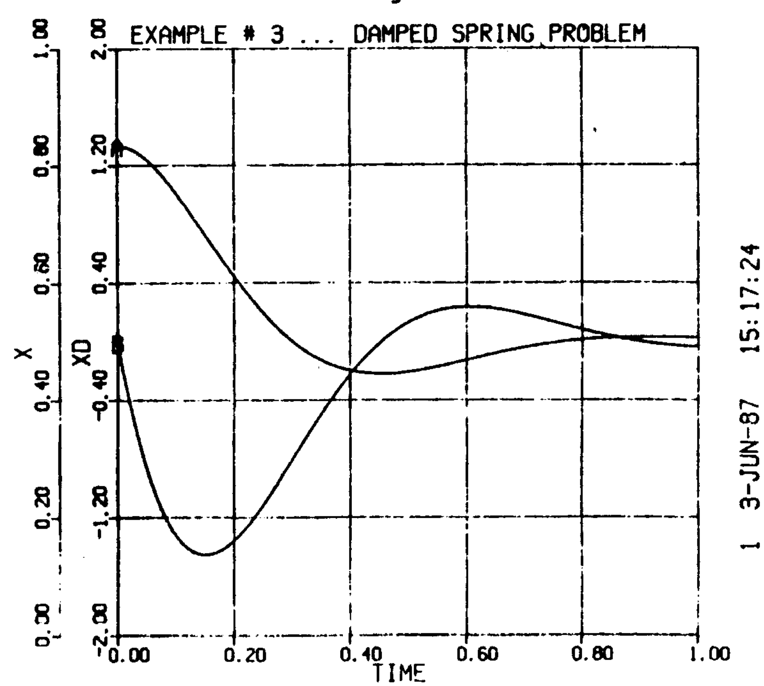

Figure 9

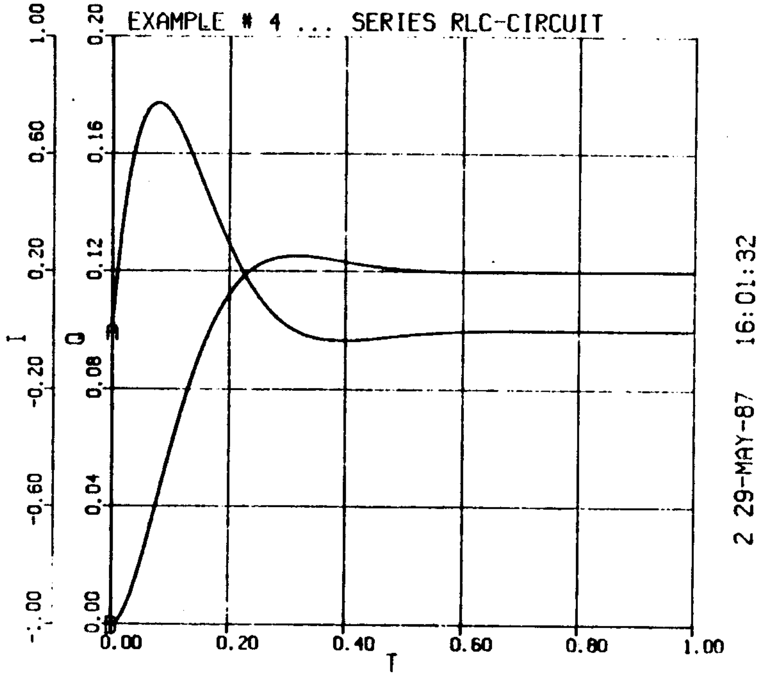

Figure 8

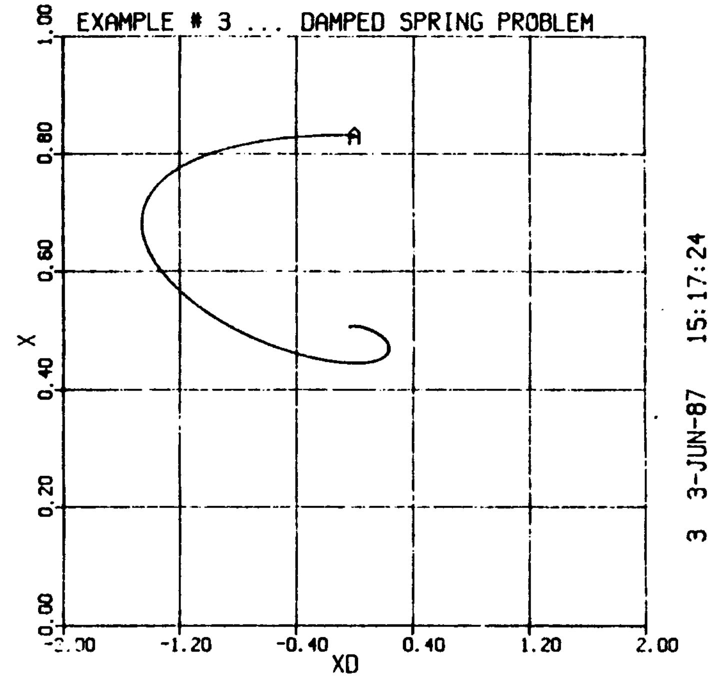

Figure 11

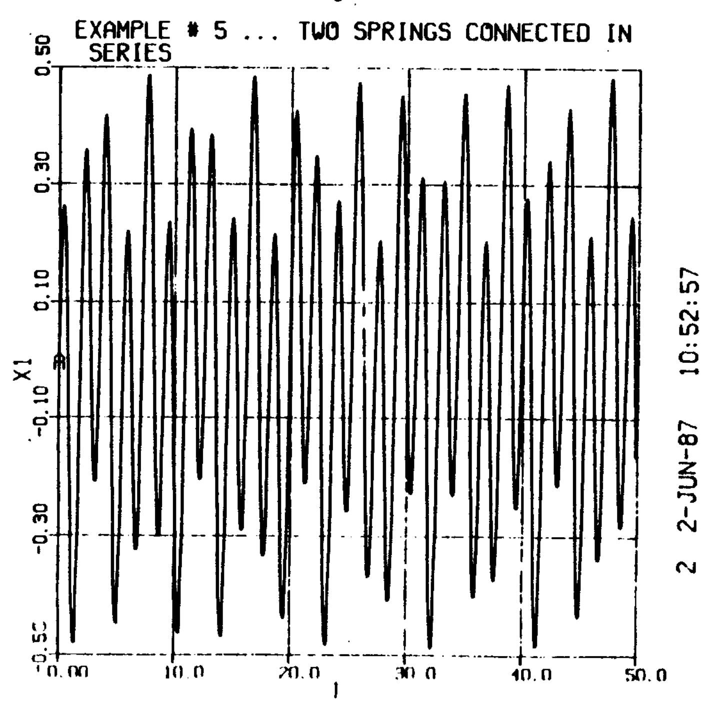

Figure 10

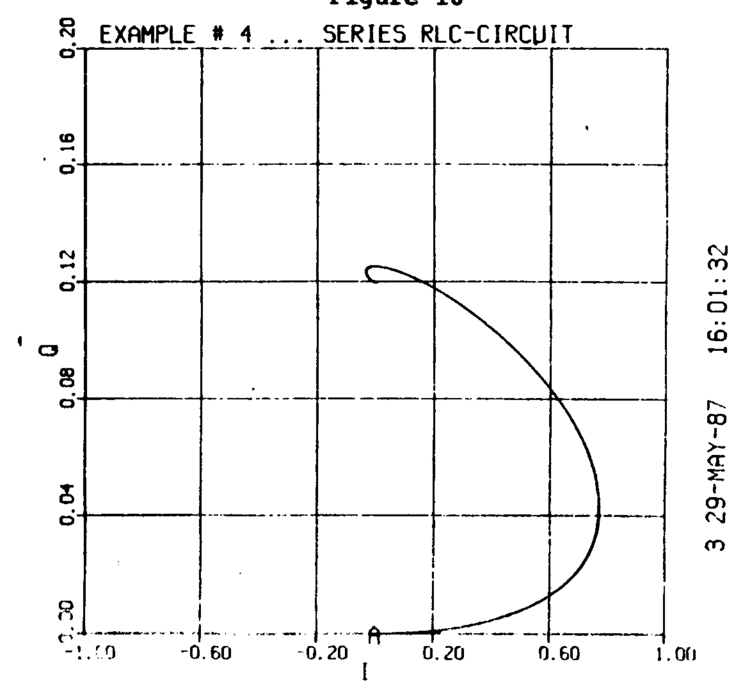

Figure 13

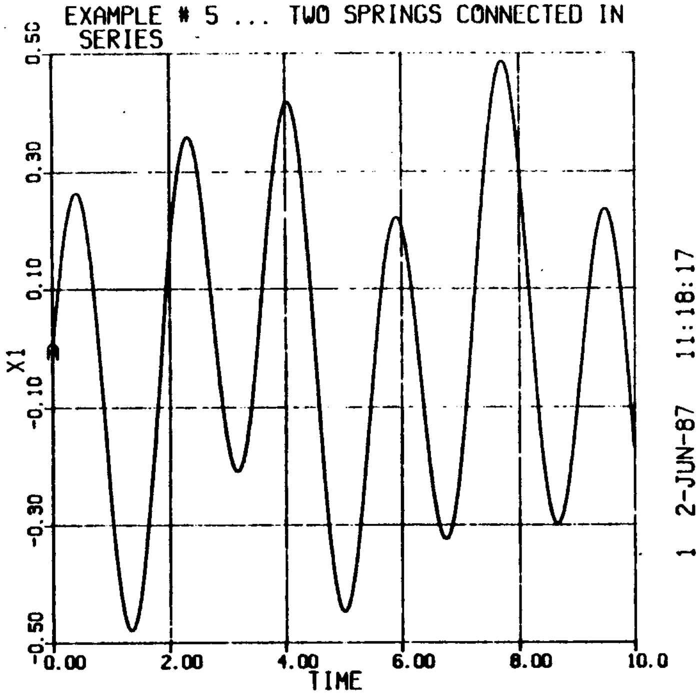

Figure 12

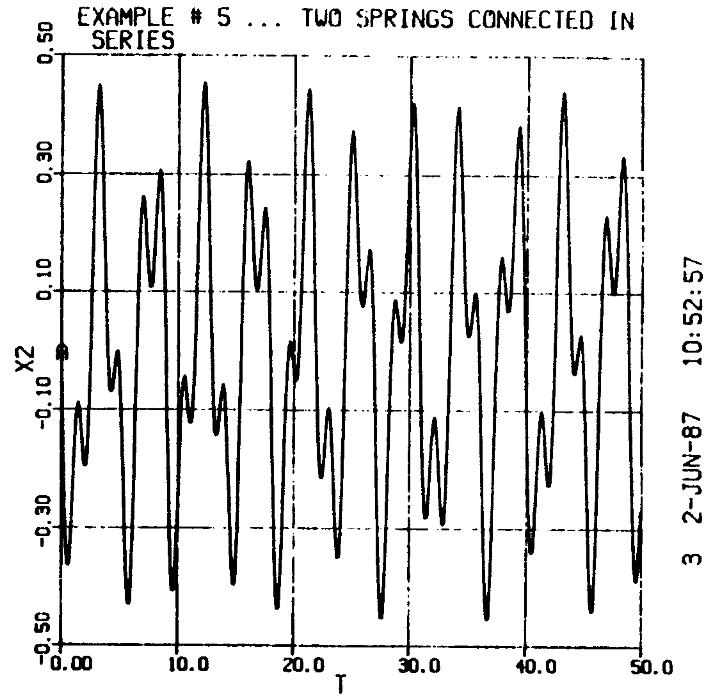

Figure 15

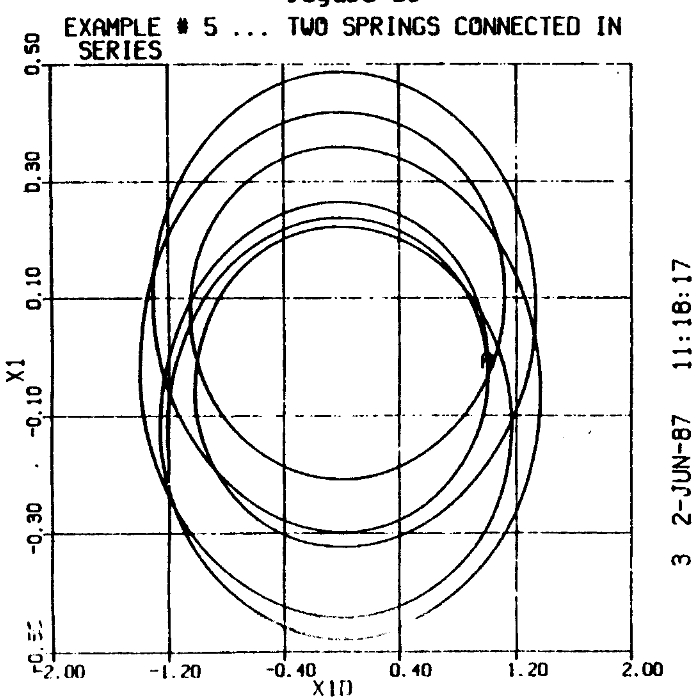

Figure 14

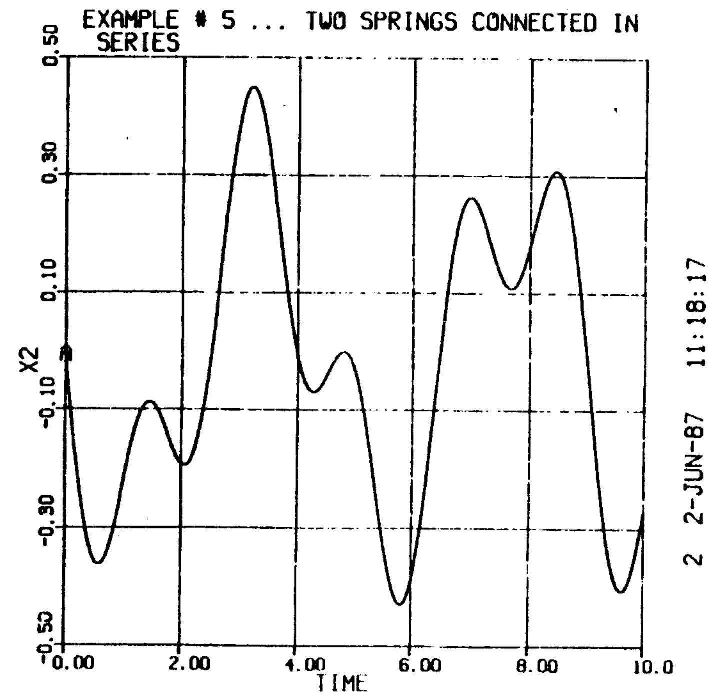

Figure 17

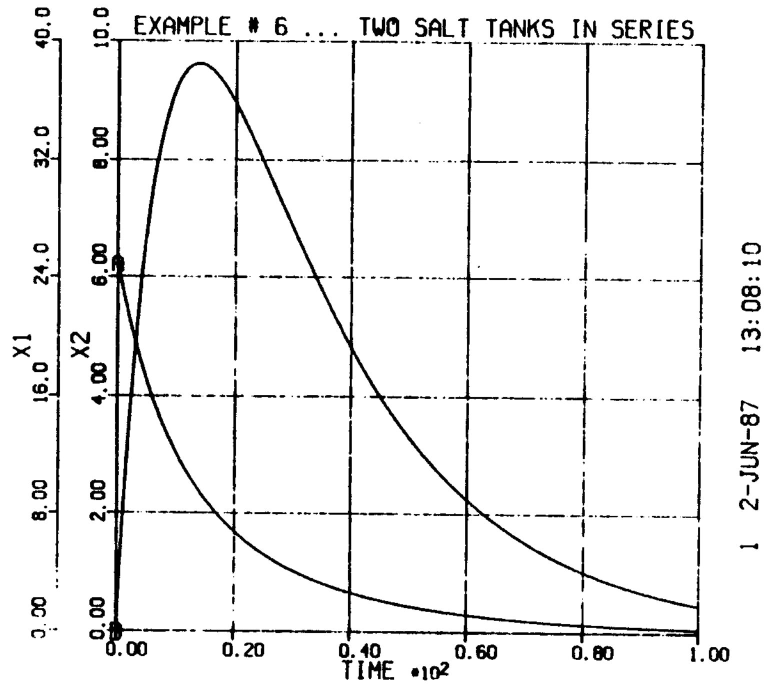

Figure 16

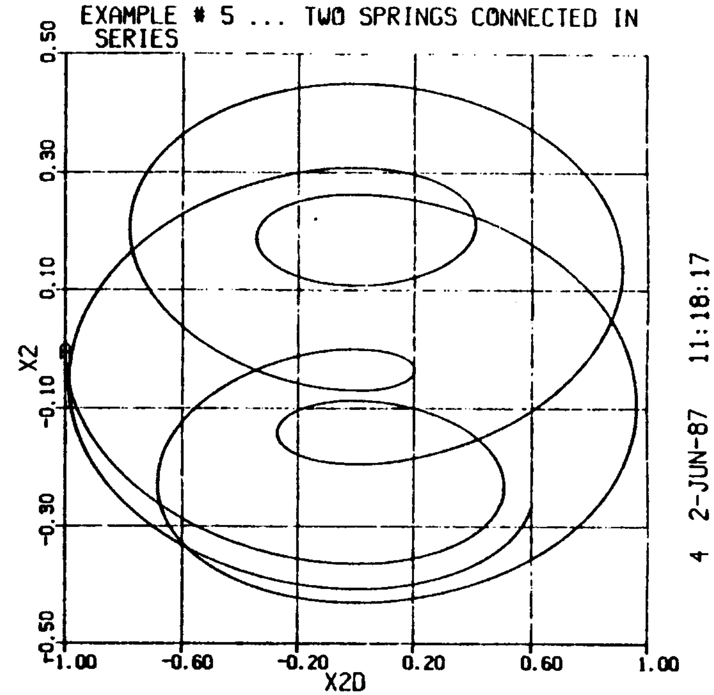

Figure 19

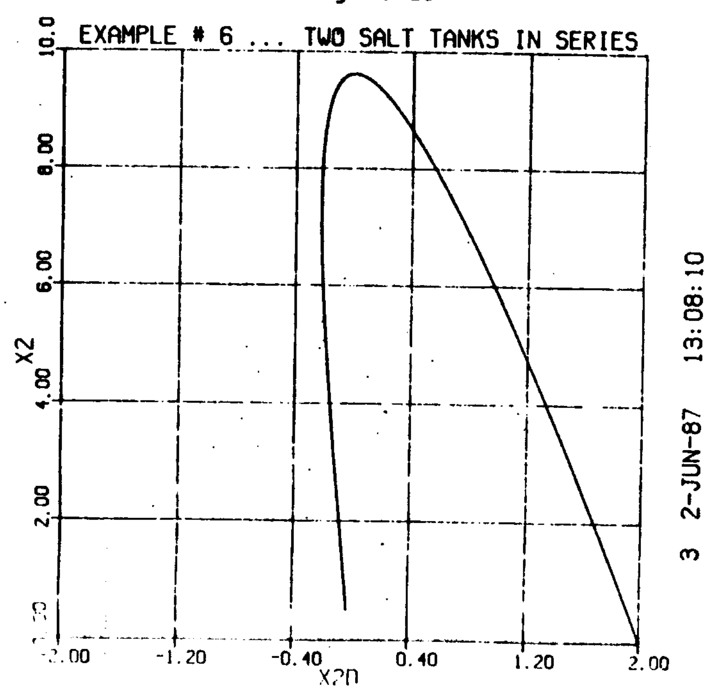

Figure 18