# A COMPUTER CONTROLLED
# FLUID SUPPLY SYSTEM

by

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## ABSTRACT

A computer controlled fluid supply system was designed to permit fluid control of low pressure hydraulic fracturing simulations and related research. Interfacing of mechanical and electronic hardware led to a capable fluid supply system. PID control was implemented and tuned to provide adequate response under varying loads. Flexible data acquisition and control computer software permits user specification of desired pressure or flow variables while recording the fluid data and presenting it graphically. Tests conducted to evaluate the system's capabilities demonstrated that constant flow rate could be achieved, but at the cost of steady-state error and poor load rejection, while pressure control was found to be satisfactory in holding a constant pressure with varying flow. Also, pressure control of a varying setpoint was employed, with good performance in following a complex trajectory.

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While I have benefitted from numerous discussions in the Laboratory, both technical and civil in nature, sincerest appreciation is due to Keith Morris and Jim Papadopoulos for their interest, insight, and expertise in dealing with the not infrequent technical problems that arose.

A project of this involvement typically spawns various levels of frustration. Fortunately, the concern and support expressed to me by numerous friends kept my thoughts in perspective and myself in higher spirits than might otherwise have been possible. I especially want to thank Phoebe Lovett for her emotional support throughout this thesis work and the past year.

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# I. INTRODUCTION

## A. Background and motivation

As the oil and gas industries strive ever harder to access and tap underground energy resources, new technologies to improve mining productivity are being researched and implemented. Chief among these technologies is hydraulic fracturing, a method that is being utilized increasingly in resource extraction. Hydraulic fracturing employs the injection of pressurized fluids and slurries into a rock formation. The pressurized medium can induce significant stresses in a rock field to initiate growth of cracks through which liquid and gaseous resources can flow to the wellbore for expeditious extraction. This process is particularly useful in stimulating the energy yield of many existing low permeability reserves.

The Resource Extraction Laboratory at M.I.T. has been actively pursuing hydraulic fracturing research, using both computer and laboratory simulations to verify and improve current analytical descriptions of the process. A number of simple, well-defined experiments have been initiatied within the Laboratory to obtain data to advance the understanding of hydraulic fracture. Both low (10-100 psi) and high pressure (1000-50,000 psi) experiments are found to have a role in simulating the hydrofracture process. For these experiments to be meaningful, there is a great need for a method of experimentation that provides accurate experimental results by careful regulation of input variables and proper measurement of the various responses.

The objective of this thesis is the development and implementation of a low pressure fluid supply system to provide data acquisition and control of hydraulic fracturing and associated (e.g. rheology) exeriments. As an integral part of any hydrafrac simulation, such a system is capable of greatly increasing the rate and ease of experimentation while providing more consistent results. Such a servocontrol and data acquisition system facilitates the exploration of a number of different experiments, complementing the intermediate pressure (1000 psi) servocontrol system already developed by McGrail (1981). With these tools, researchers in the Laboratory will be able to contribute to broaden the base of knowledge from which to expand the present technology of hydraulic fracturing.

## B. Sample hydraulic fracturing experiments

1. Interface separation experiment. One prominent application of an accurate low pressure fluid supply system in the Laboratory is the interface separation experiment (see Figure 1) described by Cleary (1981). In this simulation of hydrafrac, a cylinder of rubber encased in a steel cylinder is compressed by air pressure and pressed onto a polished plate of PMMA through which a borehole has been drilled. Fluid is injected through the borehole into the rubber-PMMA interface at a pressure slightly greater than the confining stress

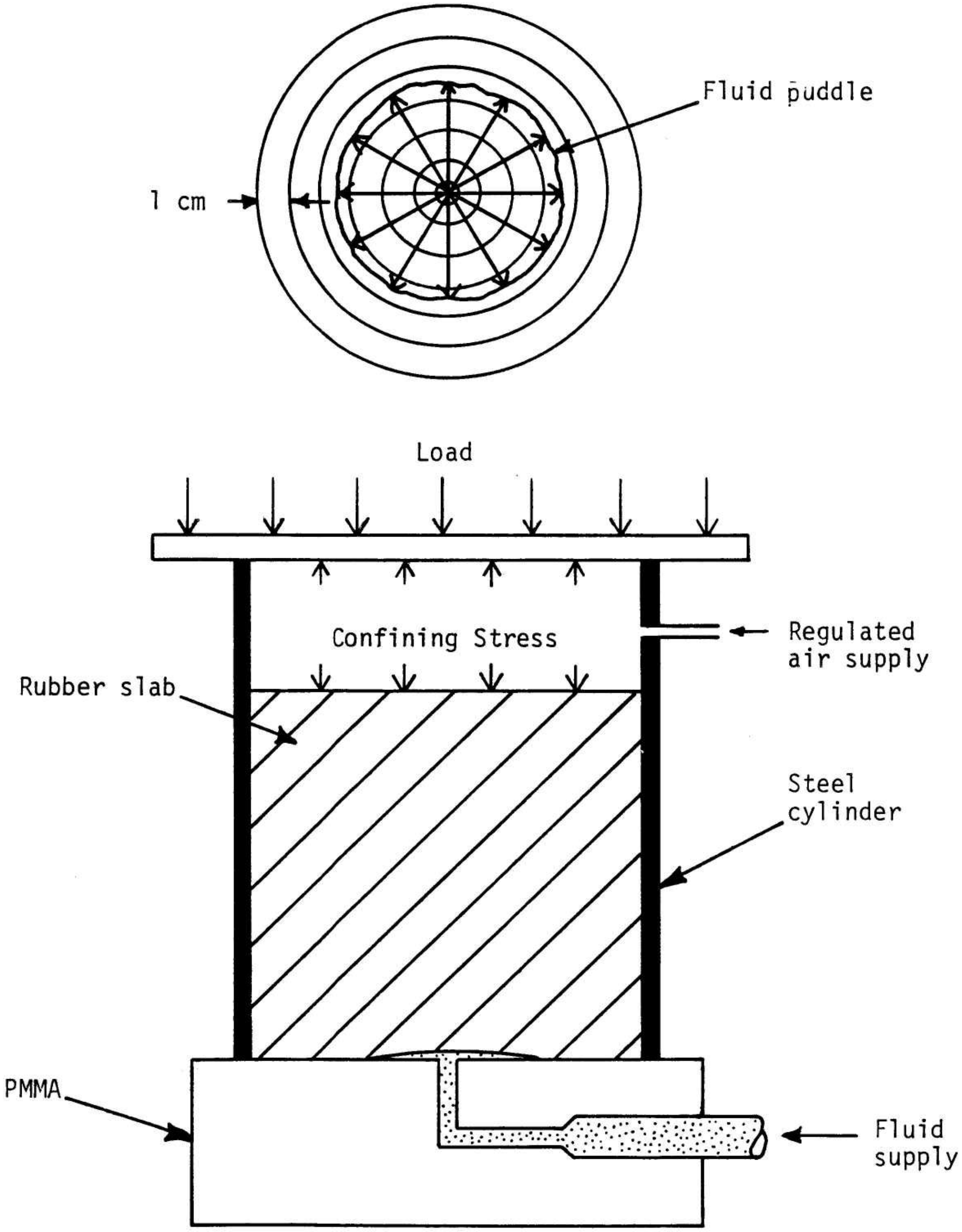


Figure 1. Interface separation experiment.

exhibited by the rubber cylinder. The spreading fluid is analogous to crack propagation and is a true repeatable demonstration of hydrafrac, which has been shown by Cleary (1980) to be dependent primarily on the injection fluid pressure and viscosity (scaled to modulus) and on the tectonic stresses of the underground field (represented here by the confining stress imposed upon the rubber cylinder), with only weak dependence on the fracture toughness of the material.

The great utility of this technique, with its excellent repeatibility, lies in the capability of readily observing and varying a number of hydrafracture parameters, especially the confining stress and injection pressure (with monitoring of flow and vice versa). It is these important capabilities which justify an automated data acquisition and control system.

2. Fluid rheology experiments. The study of fluid flow, in an effort to investigate properties of fracturing fluids, is another area of research in the Resource Extraction Laboratory which has immediate need for precise fluid flow control. While a mumber of rheology experiments are under consideration (see Cleary, 1981), one particular simulation is the parallel plate rheometer of Figure 2. This experiment is similar to the interface separation experiment, in that two polished blocks of PMMA are used, but in this case they are separated by shimstock, leaving a channel through which fluids injected through a borehole can flow. Once again an automated

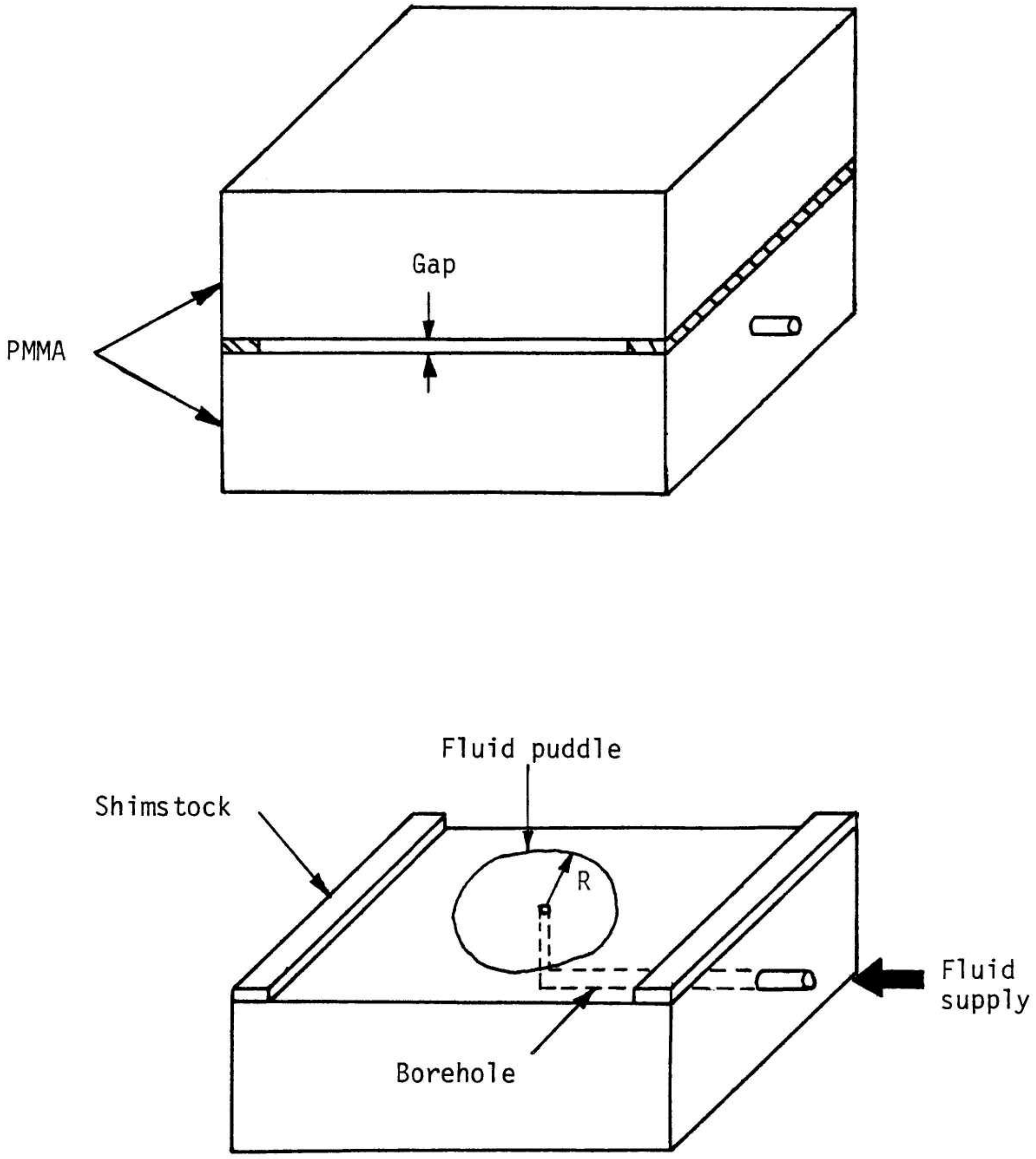


Figure 2. Parallel plate rheometer.

measurement and fluid control system leads to more meaningful and facile analysis, this time for the rheological properties of fluids used in hydraulic fracturing and other underground injection processes.

# II. THEORETICAL ANALYSIS OF THE CONTROL STRATEGY

## A. Continuous controller design

The closed-loop control system can be represented schematically as in Figure 3, with the dynamics of the servovalve-amplifier-VCS system modeled as the transfer function G(s). This section will outline the procedure used in determining the controller function D(s).

Early attempts were made to control the system with proportional feedback, in which the control signal M(s) (refer to Figure 3) is proportional to the error E(s) between the setpoint R(s) and the output C(s). This approach resulted in response with large steady-state error or offset, while increasing the gain of the controller drove the system to instability. As a major need in the experimentation is confidence in the system attaining the setpoint specified, proportional control was deemed inadequate.

A second approach utilizes proportional, integral, and derivative (PID) closed-loop control. (see Dorf, 1980; Harrison, 1978; and Ogata, 1970) In this strategy, the output of the controller is dependent upon (1) a constant times the error; (2) the integral of the error signal, which eliminates steady-state error; and (3) the time rate of change of the error, which effectively adds corrective action when the error is moving away from zero and decreases corrective action when the error is headed towards zero. The continuous form of the PID controller is then

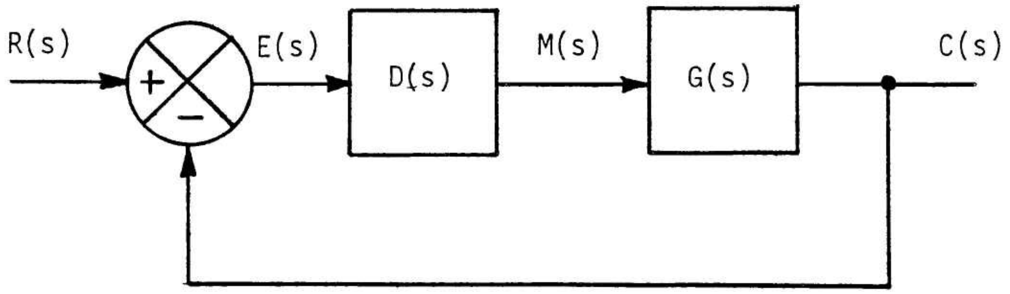


Figure 3. Closed-loop system block diagram.

$$D(s) = K(1 + 1/T_i s + T_d s) \qquad (1)$$

where $K$ = controller gain
$1/T_i$ = reset rate
$T_d$ = pre-act time

The reset rate can be thought of as the number of times per minute that the integral control acts upon the error signal if the eror is constant. The pre-act time is the amount of correction delivered by the derivative mode for each percent per minute rate of change of the error signal.

Determination of the above parameters embodies much of control engineering. The technique used here, described by Ziegler and Nichols (1942), is particularly convenient for determining the controller for a system in which the dynamics of the plant to be controlled are not known.

This method uses the concept of neutral stability. This is achieved by placing the system under proportional control and increasing the controller gain until the output is oscillating, with the amplitude of oscillations neither growing to gross instability nor decreasing to a stable output. With the knowledge of this oscillatory gain $K_u$ and measurement of the period of the oscillations $P_u$, the PID parameters are found as:

$$\begin{aligned} K &= 0.6\ K_u \\ T_i &= 0.5\ P_u \\ T_d &= 0.125\ P_u \end{aligned} \qquad (2)$$

Use of this Ziegler-Nichols criterion is expected to yield a closed-loop step response of damped oscillations with subsequent oscillations being reduced by a factor of four while providing much better steady-state error specifications than proportional control.

## B. Discrete realization of the continuous controller

The implementation of a continuous control system through a digital computer requires transformation techniques to account for sampling time delays and discretized integrations. A number of such transformations are available (refer to Franklin and Powell, 1980 and Stearns, 1975) and five were conducted and evaluated. The transformation found to be most satisfactory was the step-invariant simulation which uses techniques to assure that the step response of the discrete system is identical to that of the continuous system. The discrete controller can be summarized as

$$D(z) = \frac{\mathcal{Z}\{\mathcal{L}^{-1}[D(s)\ I(s)]\}}{I(z)} \qquad (3)$$

where $I(s)$ = Laplace transform of a unit step input
$I(z)$ = z-transform of a unit step input
$\mathcal{L}^{-1}$ = inverse Laplace transform
$\mathcal{Z}$ = z-transform

Referring to Equation (1) and tabulated transforms as in Dorf (1980),

$$D(z) = K\,\frac{z-1}{z}\,\mathcal{Z}\{\mathcal{L}^{-1}[\frac{1}{s} + \frac{1}{T_i s^2} + T_d]\}$$

$$D(z) = K\frac{(z-1)}{z} \cdot \left[\frac{z}{z-1} + \frac{T/T_i \; z}{(z-1)^2} + \frac{T_d}{T}\right]$$

$$D(z) = K \left(\frac{z^2(T_d/T + 1) + z(T/T_i - 1 - 2T_d/T) + T_d/T}{z-1}\right)$$

The useful form of this equation is a difference equation where

$$m(k) = m(k-1) + K[(1+T_d/T) \cdot e(k) + (T/T_i - 1 - 2T_d/T) \cdot e(k-1) + T_d/T \cdot e(k-2)] \quad (4)$$

where $T$ = sampling time
$m(k)$ = control signal at time $kT$
$e(k)$ = error signal at time $kT$

This difference equation can be easily formulated within the control program as functions of the previous control signal m(k-1) and the current and previous error signals e(k), e(k-1), and e(k-2).

# III. EXPERIMENTAL PROCEDURE

## A. Equipment

1. Overall system desription and operation. Figure 4 depicts the entire system when ready for experimentation. Fluid power for the simulation is provided by servo-valve regulation of filtered shop air or bottled gas. This regulated fluid supply power is transferred through a precision volume change and separation (VCS) device to the injection fluid and the interface experiment.

The MINC-11 laboratory computer acquires data from two transducers: a DCDT (direct current displacement transformer) mounted on the VCS device (monitoring flow) and a pressure transducer monitoring the interface fluid pressure. This data will be used to calculate a correction signal based a user-supplied preset pressure or flow value, which is then used to control the gas transfer through the servovalve. This closed-loop control will continually monitor the experiment to control the desired parameters.

a. Computer. The computer used for the data acquisition and control of the system is the MINC-11 laboratory computer manufactured by Digital Equipment Corporation; it is essentially a small PDP-11 type computer. It has two floppy disc drives and may be programmed in FORTRAN, BASIC, or MACRO-11, an assembly language. Data acquisition and control modules such as the analog to digital converter (A/D), the

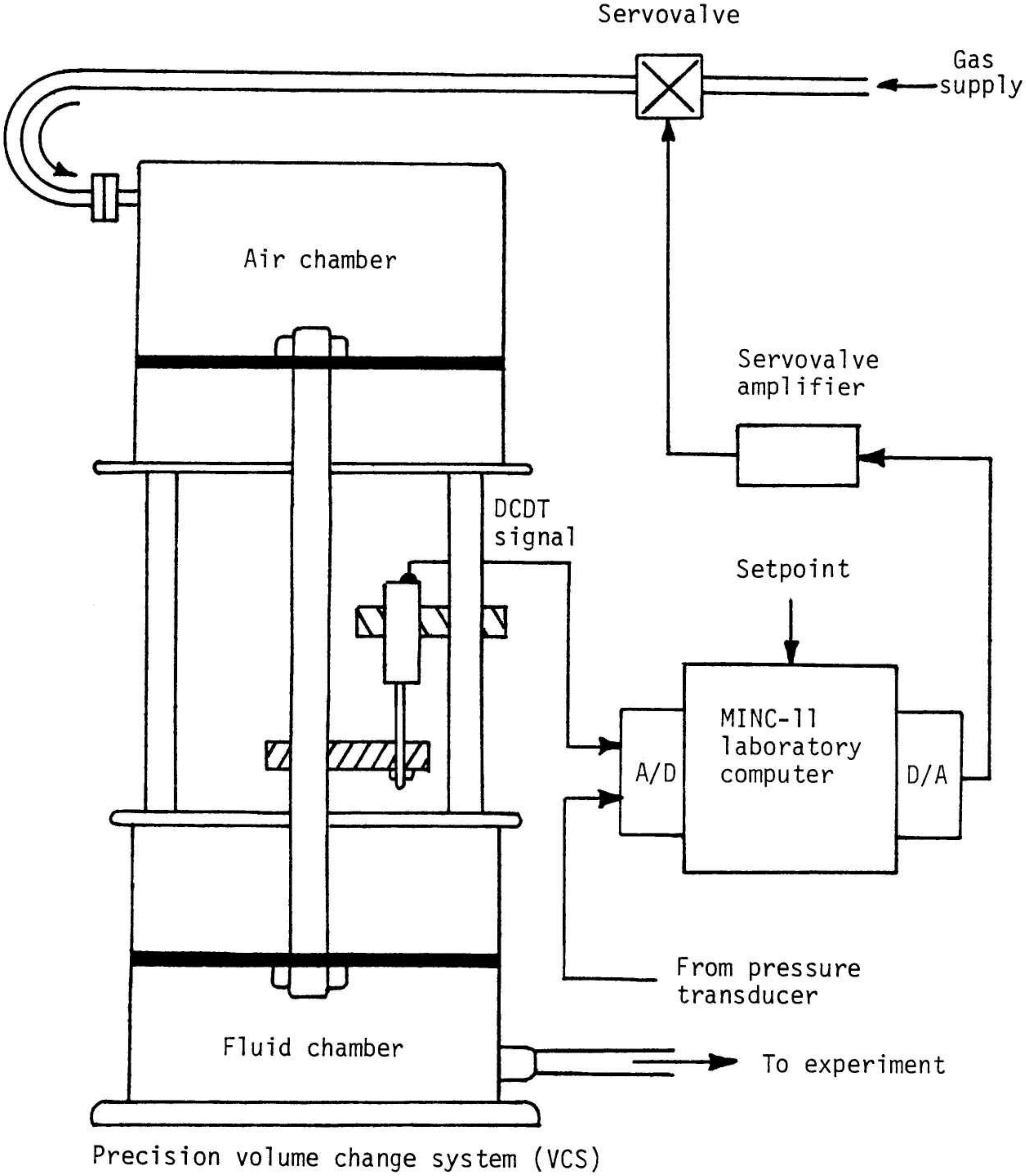


Figure 4. Overall system schematic.

digital to analog converter (D/A) and real time clock have been mounted integrally to the computer. The complete unit is mobile, as the terminal can be stored on the cart to move the computer to the location of an experiment. The data storage of the computer is roughly 12,000 data points in the main memory and 256,000 data points on disc.

b. Servovalve. To provide the accurate control required, a fast-response servovalve is needed. Typical industrial two-stage hydraulic and pneumatic valves provide enhanced power handling capabilities but with decreased response. Due to the low fluid power requirements of this low pressure system, a single stage servovalve was deemed sufficient to provide the pressures and flows anticipated while its simpler design aided the response characteristics.

A Hydraulic Servocontrols Corporation (Buffalo, NY) Model 58C servovalve was chosen (Figure 5). This single stage, nozzle-flapper valve is driven by a torque motor attached to the flapper. The position of the flapper is determined by a low-level DC, electrical current signal to the torque motor coil. The position of the flapper can thus be quickly and accurately controlled via the MINC-11 D/A.

c. Servovalve control amplifier. An amplifier (Figure 6) was designed and constructed to provide the servovalve coil with sufficient current based upon the voltage signal of the MINC D/A. The upper half of the diagram represents the voltage regulator, incorporated into the amplifier to provide

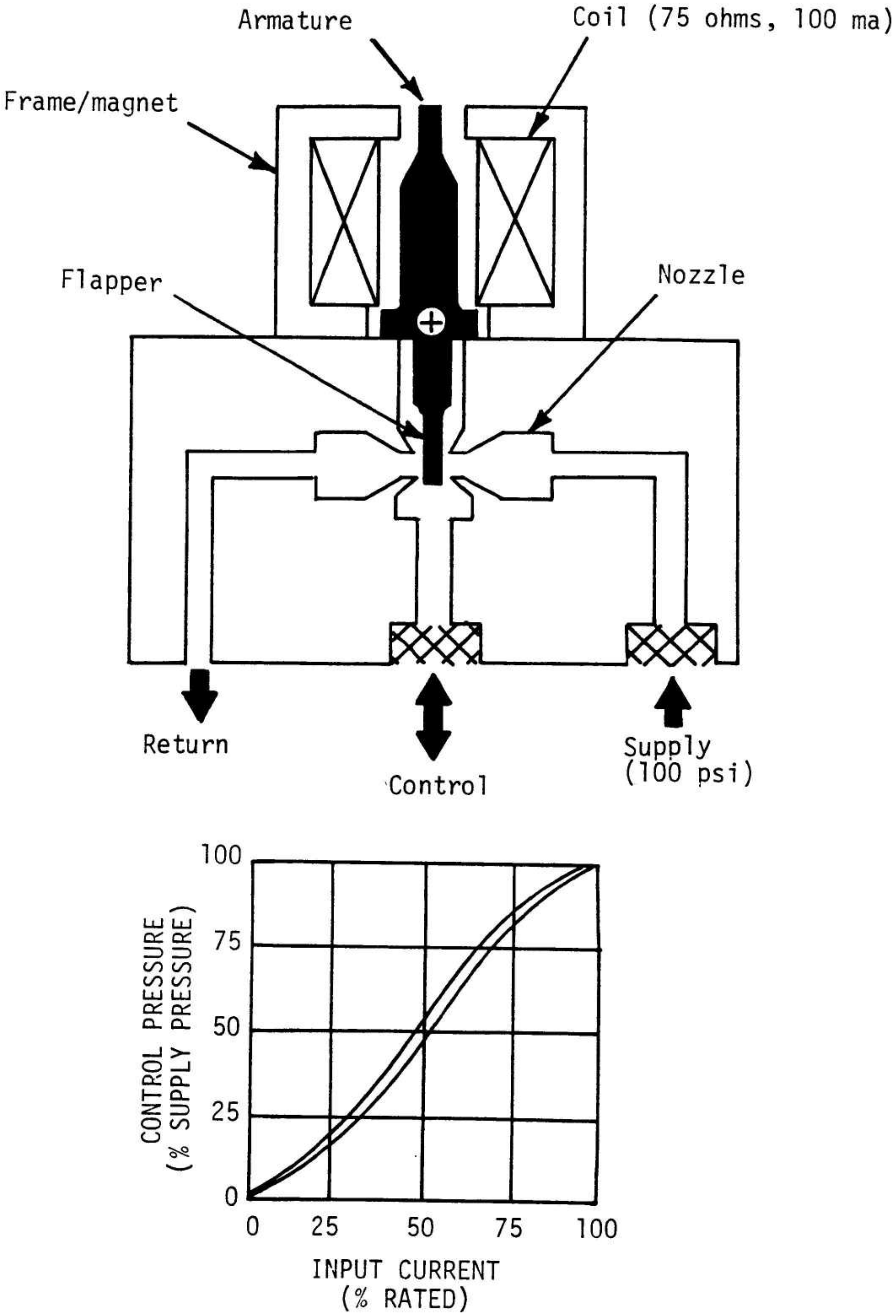
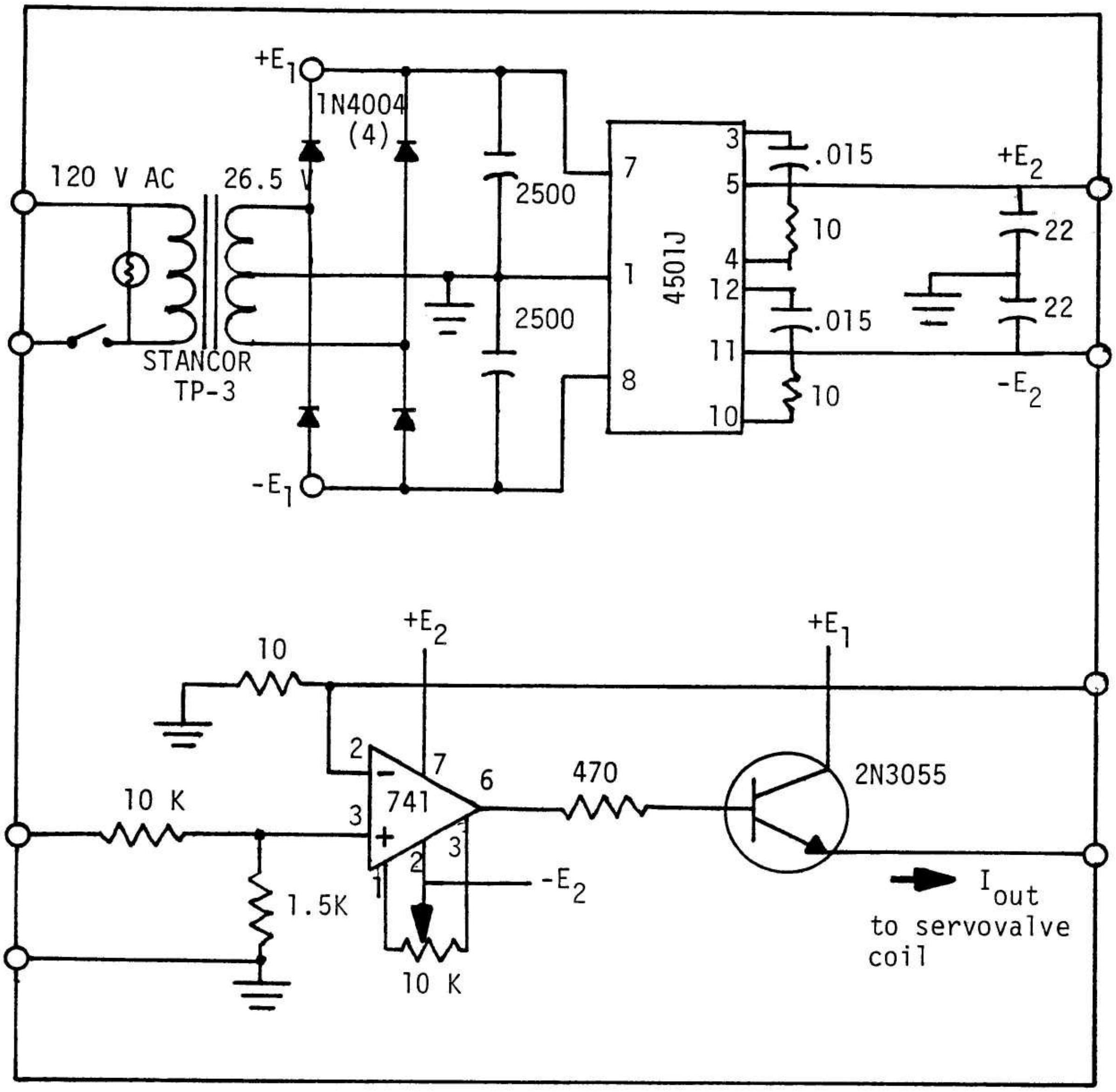


Figure 5. Servovalve.



Notes:
1. All resistors 1 watt, 5%.
2. Resistance in ohms.
3. Capacitance in microfarads.
4. Amplifier sensitivity - 12 milliamps/volt.

Figure 6. Servovalve amplifier.

a regulated 15 volt supply ($\pm E_2$) for the operational amplifier. The voltage regulation circuit also provides 18 volts ($+E_1$) unregulated, for the transistor collector. The amplifier circuit, essentially a voltage-controlled current source, has been calibrated to allow full usage of the D/A 10 volt output, thereby increasing the available resolution of the control. With a rated coil current of 100 milliamps for the servovalve, the 10 volt input will allow an overhead margin of nearly 15 milliamps with which to control the position of the valve's flapper. Thus, a 0-10 volt calculated D/A control signal will deliver a 0-115 milliamp control current to the servovalve coil. An offset null circuit has been provided to permit nulling of the operational amplifier voltage output at zero input voltage.

d. Precicion volume change device. The interface between the pressurized gas and the injection fluid is accomplished through a precision volume change system (refer to Figure 4) manufactured by Geotechniques International, Inc. (Middleton, MA), in conjunction with a low friction separator. This device consists of two chambers separated by pistons with a common shaft, guided by a linear bearing. A rolling diaphragm (Bellofram) provides a fluid seal between each piston and chamber. Thus, as the upper chamber is pressurized, loading transmitted through the shaft also pressurizes the lower chamber, usually containing a liquid such as water. The fluid separator provides fluid power transfer to the injection fluid while allowing fluid flow to be accurately measured.

e. Transducers. Two transducers are utilized in this application: (1) a pressure transducer, typically 0-100 psi range with output of approximately 0-100 millivolts; and (2) a DCDT with approximately a four inch stroke and signal gain of about 2 volts/inch. The pressure transducer is very straightforward and simple to use but the DCDT requires some precautions in its use. The DC output is a rectified AC signal which exhibits an AC ripple. The ripple was found to preclude the gathering of any meaningful data and was also found to influence the signal from the pressure transducer. In order to reduce these effects, a low-pass filter is used to filter the DCDT output, with very good results.

f. Data acquisition, graphics, and control software. Software has been developed to provide significant operator control of the apparatus. The user can indicate a number of experiment parameters, (pressure or flow control, sampling frequency, and channel choices are a few options available.) The strip chart mode of graphics operation is available as is the opportunity to retain the experimental data for post-simulation interpretation.

## B. Test methods

This system has been designed so as to simplify the experimental process for the user. To this end, it complements the data acquisition capabilities previously developed in the Laboratory. Transducer excitation and reading is performed by a transducer box mounted on the rear of the MINC-11. This box supplies both 5.5 and 12 volt regulated excitation voltages with individual jacks being connected to various A/D channels as indicated on the box. Output jacks and a channel selector switch allows the use of other data recording devices such as strip charts, oscilloscopes, and multimeters.

Filling the lower chamber of the VCS device is done most conveniently before attaching the regulated air supply from the servovlave. An adapter has been constructed to allow filling from a water with a threaded faucet. Water should be forced through the adapter until no trapped air bubbles are visible. This adapter tube should be attached to the output tube of the VCS by the fittings provided and after opening the valve next to the outlet, slowly flow water into the lower chamber taking care not to increase the flow too much. The piston will rise until the upper limit of the travel is reached. Any air introduced into the chamber can now be expelled by tilting the device to cause the air bubbles to move to the bottom side of the VCS opposite the tube connected to the water supply. There is a small release valve at the side which should be opened slightly to force the air out by the water pressure. This release valve, the outlet valve, and the water supply should now be closed and the adapter tube removed from the filled VCS.

The air supply, typically bottled gas, is connected through existing tubing to the supply pressure port (indicated) in the servovalve manifold with the controlled pressure from the servovalve connected to the top of the VCS. Connections to the servovalve amplifier from the valve and D/A of the MINC are simplified through the use of two 2-pin Molex connectors, one of which is male and the other female to prohibit incorrect connections. With the VCS now filled with water and all connections made and electronics supplied with power, the system can be connected to the experiment.

Software to support the system is stored on the floppy disc titled "VCS Pressure/Flow Control," which should be inserted into the MINC disc drive. To start the program, type "RUN VCS". Execution of the program results in the following responses, all requiring input from the user:

```
"ENTER A/D CHANNELS (PRESSURE FIRST, THEN POSITION)"
  -simply enter the value of the A/D channels selected
   for the experiment, probably 0-7

"DISC STORAGE OF DATA DESIRED? (1=YES, 0=NO)"
  -if no, the next two responses will be omitted

"ENTER DATA FILE NAME"
  -maximum name length is 6 characters with a 3-character
   extension (e.g. SYSTEM.DAT)

"ENTER DATA FILE POINT DIVISOR:
     1=WRITE EVERY PAIR TO FILE
     2=WRITE EVERY OTHER PAIR TO FILE
     3=WRITE EVERY THIRD PAIR TO FILE
     ETC..."
  -allows user to save disc space

"ENTER SAMPLING PERIOD"
  -minimum period is 0.07 seconds
```

"ENTER PRESSURE TRANSDUCER GAIN (MILLIVOLTS/PSI)"
-should be known from transducer callibrations (typically about 1 mv/psi)

"ENTER POSITION TRANSDUCER GAIN (MILLIVOLTS/CC)"
-with VCS characteristics of 0.0375 cm/cc and DCDT gain of 931 mv/cm, typical value is 34.9 mv/cc

"ENTER 0 FOR PRESSURE CONTROL, 1 FOR FLOW CONTROL"
-if 1,skip next response, otherwise skip second response

"ENTER DESIRED PRESSURE (PSI)"
-maximum of 90% of supply pressure

"ENTER DESIRED FLOW RATE (CC/SEC)"
-maximum of approximately 35 cc/second

"ENTER MAXIMUM PRESSURE EXPECTED (PSI)"

"ENTER MAXIMUM FLOW EXPECTED (CCS)"
-both used in scaling of data for strip chart mode

"TO TAKE INITIAL ZERO READING, SET PRESSURE AND FLOW TO ZERO AND ENTER 0, OTHERWISE ENTER 1"
-if 1, skip next two responses, else

"PRESSURE TRANSDUCER ZERO = (e.g. 1.008) MILLIVOLTS"
"POSITION TRANSDUCER ZERO = (e.g. -7056.332) MILLIVOLTS"

"ENTER 0 TO RE-ZERO TRANSDUCERS, ENTER 1 TO PROCEED"
-if 0, return to take zero reading; the values printed above should be verified against knowledge of the approximate zeros and it is useful to re-zero the transducers a few times to lend confidence to the value

"*** TYPE "S" TO END SESSION ***"
"PAUSE -- TYPE RETURN TO START"
-carriage return begins sampling and control in strip chart mode, "S" will terminate the test

The system is now under computer control. When using pressure control, initial response will be a damped, but significant overshoot before the output stabilizes at the set point. For this reason, it is best to delay opening the outlet valve to the experiment until after the output has stabilized. For best results, the valve should be opened slowly to avoid any oscillations or drop in pressure. Both transducer outputs should be visible on the terminal strip chart. To end the test type "S" (no carriage return needed); the terminal will clear the strip chart and type

```
"DO YOU WANT TO RUN AGAIN?  (1=YES, 0=NO)"
  -typing 1 allows another test without re-executing
   entire program and will return to initial response;
   0 ends program
```

If sampling time is too small, a synchronization error will result and a response will be typed

```
"SYNCHRONIZATION HAS BEEN LOST!"
"*** TYPE RETURN ***"
  -next response will ask if the user wants to run again
```

If disc storage of data is used, it is possible to plot both transducer curves with the program "TWOPLT". After typing "RUN TWOPLT", responses will be

```
"ENTER PRIMARY VARIABLE (0 FOR PRESSURE, 1 FOR FLOW)"
  -the primary variable refers to that variable which is
   plotted in reference to the y axis scaling, the second
   variable will be scaled to fit the plotted page, but
   will not be consistent with the y axis scaling

"ENTER DATA FILE NAME"
  -enter name of data desired to plot (e.g. SYSTEM.DAT)

"MIN, MAX Y AXIS VALUES = (minimum,maximum)
 ENTER -1 TO USE THESE VALUES OR ENTER NEW VALUES"

"MAX X AXIS VALUE = (seconds)
 ENTER -1 TO USE THIS VALUE OR ENTER NEW VALUE"

"ENTER X AXIS LABEL, THEN Y AXIS LABEL (MAX 20 CHARS)"
  -e.g. TIME (SECONDS)
        PRESSURE (PSI) or TOTAL VOLUME (CC)
```

"ENTER NUMBER OF X AXIS TIC MARKS, Y AXIS TIC MARKS"
-divides respective axes

When the program is finished, a plot file HIPLOT.PLT has been created. To use the plotter, prepare it with paper and a pen, turn it on and type the command file HIPLOT.COM to obtain plotted output of the experiment.

## IV. RESULTS AND DISCUSSION

### A. Ziegler-Nichols criterion test

The Ziegler-Nichols criterion as described in the theoretical anlysis requires that the system be driven to neutral stability under closed-loop proportional control. Noting this unstable proportional gain $K_u$ and measuring the period of oscillation $P_u$, the PID parameters can be evaluated. Figure 7 is a representative graph of this phenomenon with the values indicated. Thus, from Equation 2, the controller parameters are:

$$\begin{aligned} K &= 0.6\ K_u = 0.84 \\ T_i &= 0.5\ P_u = 0.08 \\ T_d &= 0.125\ P_u = 0.02 \end{aligned}$$

Experimentation with these values demonstrated that all values provoked the system to oscillate. Further tuning of the parameters resulted in lowering slightly the controller gain, the reset rate (the inverse of $T_i$), and the pre-act time to 0.8, 0.09, and 0.015 respectively.

### B. Constant flow control

Tests were conducted using flow control mode (Figure 8). While relatively constant flow rate was achieved, there was a significant steady-state error from the desired flow rate. Flow control also was particularly susceptible to load changes from varying the outlet valve position.

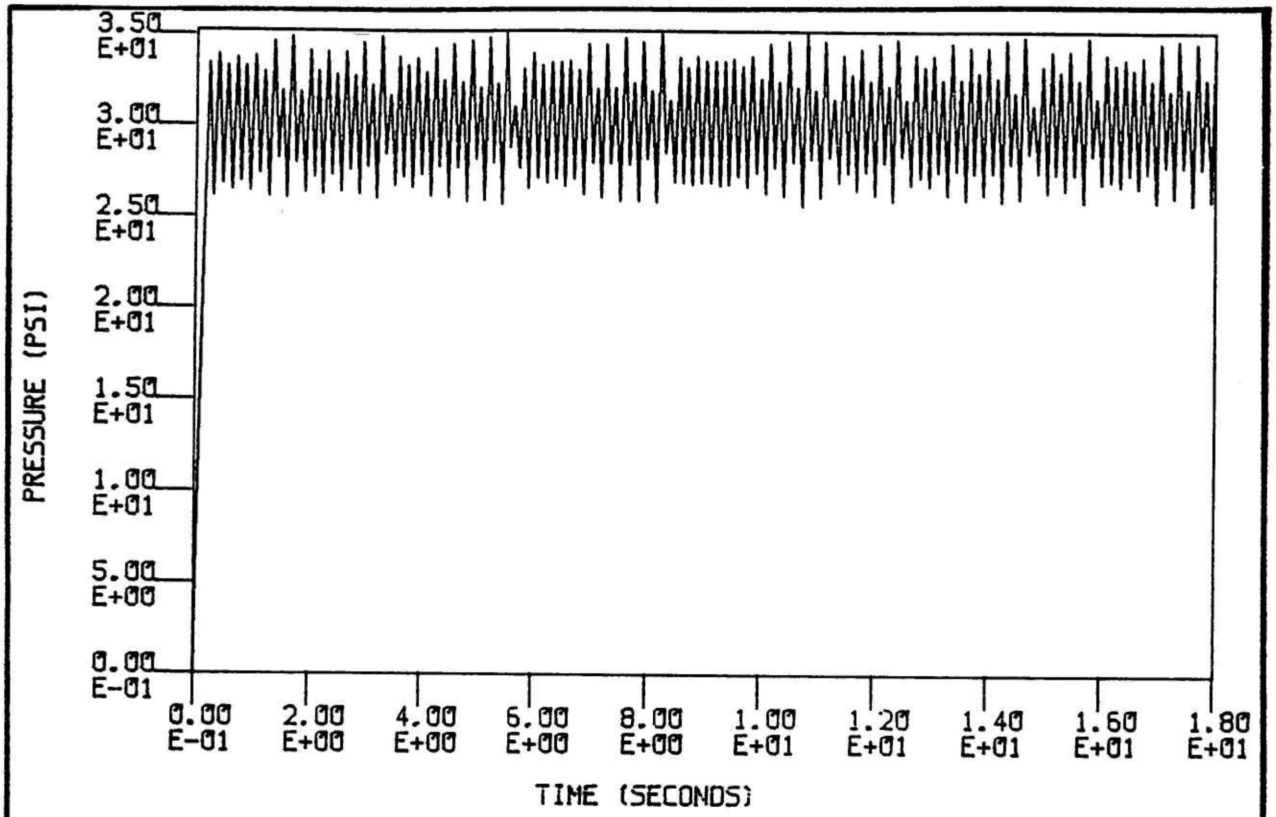


Figure 7. Ziegler-Nichols test.

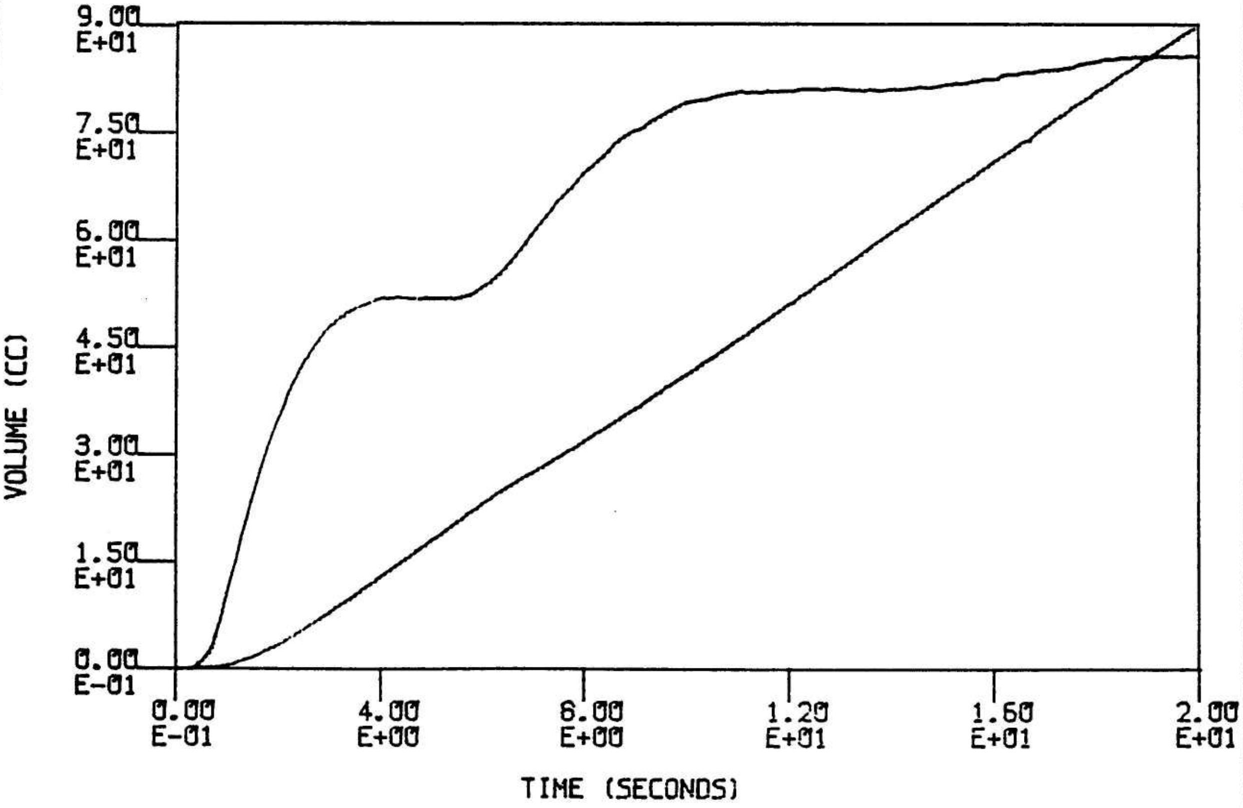


Figure 8. Constant flow test.

### C. Constant pressure control

The system was tested for constant pressure control for both no-flow and varying flow conditions (see Figures 9 and 10). As can be seen in both figures, a large overshoot is present but does recede according to the Ziegler-Nichols criterion for the amplitude ratio. In the varying flow case, the experiment works best when the pressure is allowed to stabilize at the setpoint before opening the valve. While large variations in the flow rate will cause oscillations, cautious flow changes cause little or no excursion from the setpoint, yielding good pressure control. Note that closing of the valve, indicated in Figure 10 by the horizontal flow lines, causes greater overshoot of the pressure than the undershoot caused by opening of the valve. Possibly explanable by the inertia of the column fo flowing water being decelerated, this should not present a problem in experimentation, as closing of the valve does not typically occur until after the significant data has been gathered.

### D. Pressure trajectory control

Figure 11 shows the results of pressure control with a changing setpoint. This demonstrates one of the more powerful capabilities of the system. Experimental results with complex varying pressure profiles provide a more advanced tool with which to evaluate hydraulic fracturing theory.

The trajectory used linearly increased the setpoint to a constant before entering into 3 cycles of a sinusoid and back

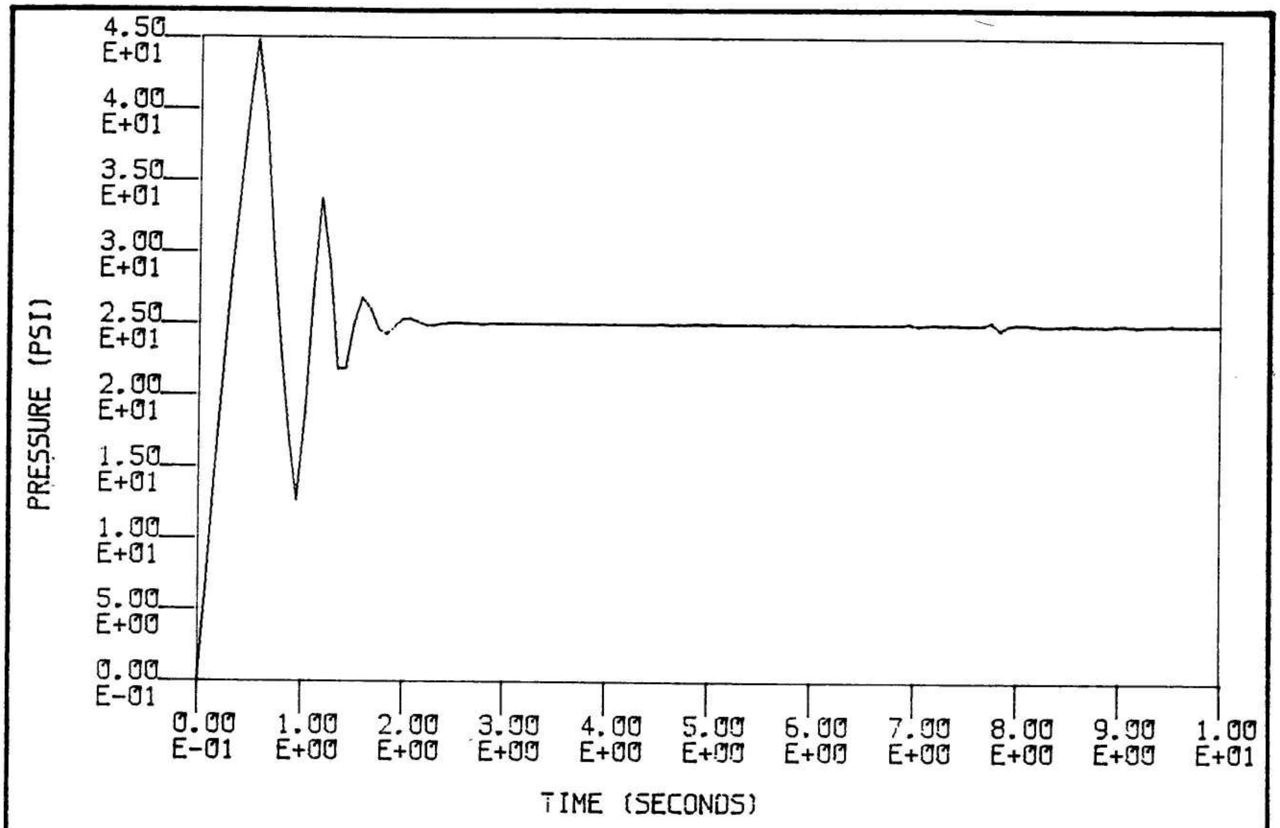


Figure 9. Constant pressure test (no flow).

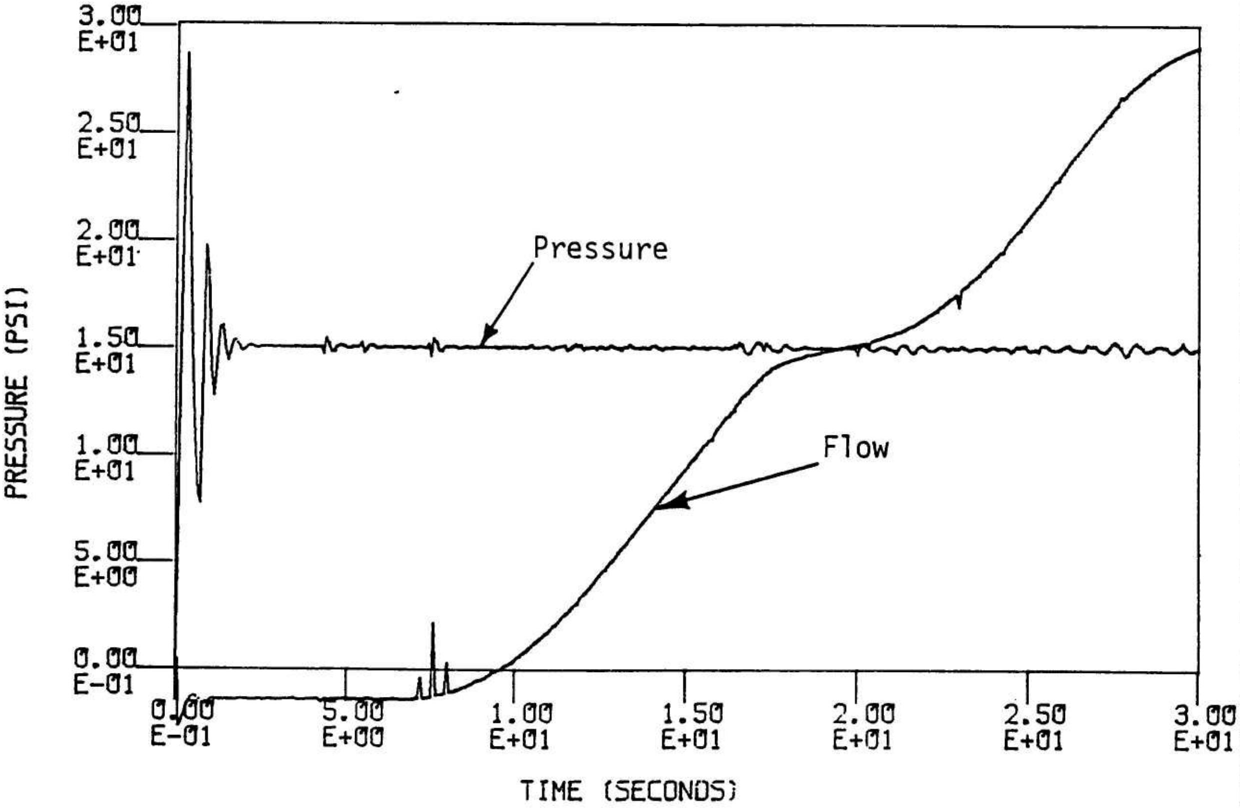


Figure 10. Constant pressure test (flow).

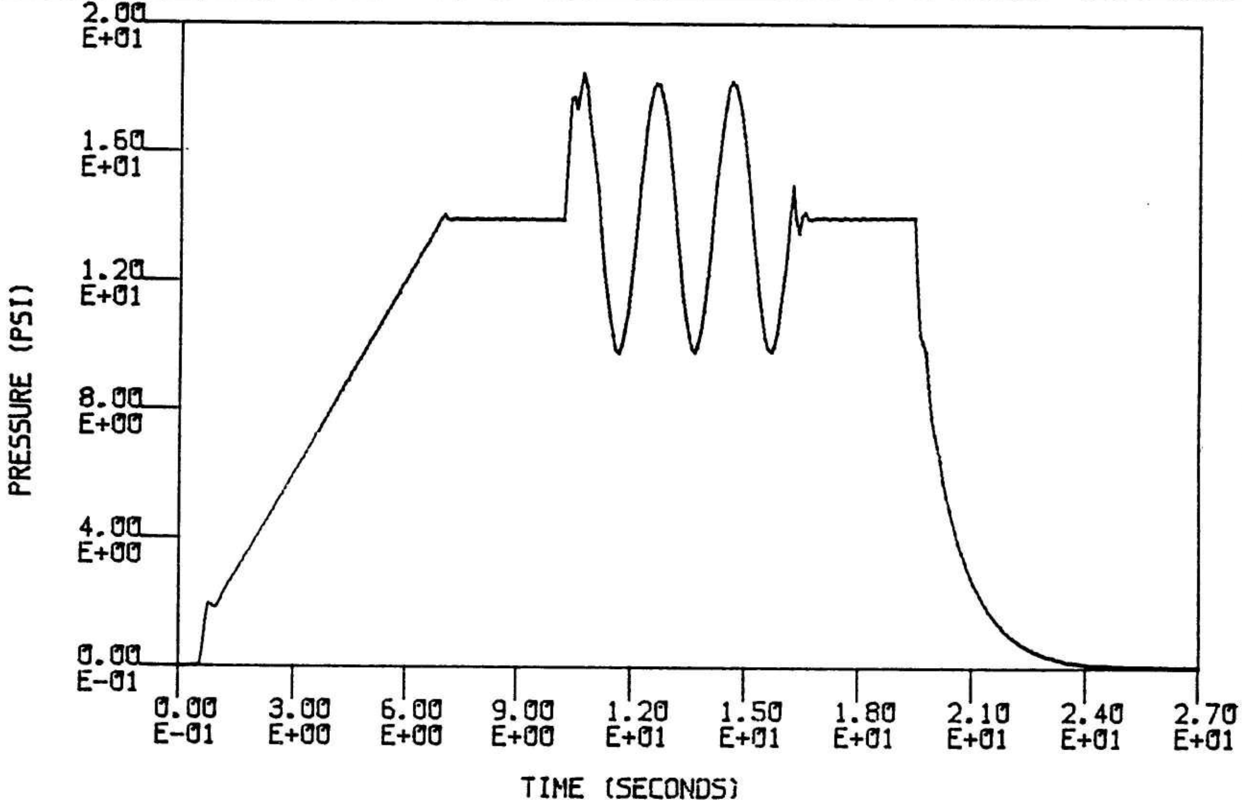


Figure 11. Pressure trajectory test.

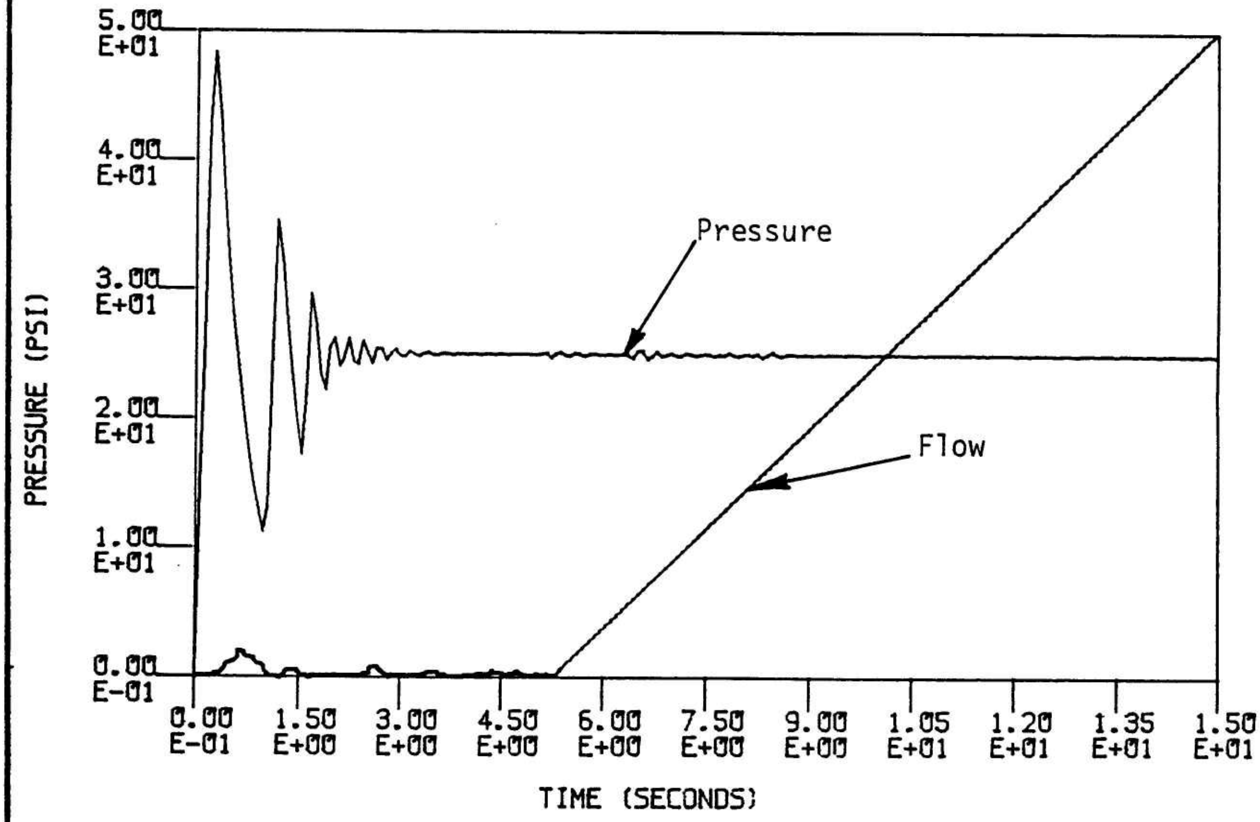


Figure 12. Interface separation constant pressure test.

to the constant before decaying to zero. The subroutine TRAJECT that was used can be found in the Appendix. There is a step at the beginning of the ramp cycle which is probably due to the servovalve's non-linearity at low control current (refer to Figure 5).

## E. DISLASH constant pressure control

The system was used in conjuntion with the DISLASH interface separation experiment described in the introduction and the results are shown in Figure 12. The variations in flow seen is the relative motion of the DCDT as the fluids are compressed within the VCS due to the oscillating pressure. There actually is no flow until the valve has been opened later in the test as the volume curve begins to increase.

# V. CONCLUSIONS AND RECOMMENDATIONS

## A. Conclusions

Pressure control was tested and enacted for a variety of cases. While initial overshoot is large in pressurizing the fluid, good pressure control was obtained by permitting the system to stabilize before initiating fluid flow. Variations in fluid flow can be compensated for provided the variations are not excessive. The system followed a planned trajectory to demonstrate capabilities in describing complex pressure profiles. While constant flow rate was achieved, current load rejection is inadequate to confidently use flow control.

## B. Recommendations

During development of the system, numerous obstacles were overcome in progressing to a working system. Some further problems have also been identified as potential areas to focus further development.

The poor flow control and large overshoot of the system are certainly faults that deserve more attention. More extensive analysis and modelling of the system might permit the design of a more complex and decisive control strategy. Considering that non-linearities are probably within the system (e.g. slight servovalve non-linearity), analysis using non-linear methods could also prove fruitful.

One problem area never adequately solved is the presence of electronic noise permeating the data signals. The noise emanates primarily from the DCDT and further filtering and/or isolation of the displacement transducer should be considered.

In applications where speed of sampling is a large concern, thought could be given to re-coding much or all of the control software in Macro-11, the MINC assembly language. While losing some of the convenience of a higher level language, this approach would be applicable when sampling rates of 100 Hz and higher are necessary.

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# APPENDIX

## A. Listing of program VCS

```
C        *******************************************************
C        *                                                     *
C        *                    -PROGRAM VCS-                    *
C        *                                                     *
C        *   CONTROL SOFTWARE FOR LOW PRESSURE FLUID SUPPLY    *
C        *   SYSTEM USING PROPORTIONAL PLUS INTEGRAL PLUS      *
C        *   DERIVATIVE CONTROL OF FLOW OR PRESSURE.  DISCRETE *
C        *   TRANSFORMATION WAS ACCOMPLISHED BY USING A STEP-  *
C        *   INVARIANT SIMULATION OF THE CONTINUOUS CONTROLLER. *
C        *                                                     *
C        *******************************************************
C
C
C                  INITIALIZATION
C
10       COUNT=0.
         DIMENSION IBUF(30)
         INTEGER*2 FILNAM(5),PRZERO,FLZERO,DATBUF(11000)
         DATA G1,E1,E2/3*0./
         COUNT=0.
         FLZERO=0
         PRZERO=0
         ICOUNT=1
         ILOST=0
         INUM=0
         IOUT=0
         MODE=1
         TIME=0.
C
C                  INITIALIZE CONTROLLER PARAMETERS:
C                     GAIN=FEEDBACK CONTROL GAIN
C                     TI=INTEGRAL RESET TIME
C                     TD=DERIVATIVE PRE-ACT TIME
C
         GAIN=0.8
         TI=0.09
         TD=0.015
C
C                  ENTER A/D CHANNELS
C
         TYPE*,'ENTER A/D CHANNELS (PRESSURE FIRST, THEN POSITION)'
         ACCEPT*,ICHAN1,ICHAN2
C
C                  DISC STORAGE OF DATA?
C
         TYPE*,'DISC STORAGE OF DATA DESIRED?  (1=YES,0=NO)'
         ACCEPT*,IDISK
         IF (IDISK.EQ.0) GO TO 30
```

```
C
C                 ENTER DATA FILE NAME
C
      TYPE*,'ENTER DATA FILE NAME'
      ACCEPT 20,FILNAM
20    FORMAT(5A2)
      OPEN(UNIT=10,NAME=FILNAM,TYPE='NEW',FORM='UNFORMATTED')
C
C                 ENTER DATA FILE POINT DIVISOR
C
      TYPE*,'ENTER DATA FILE POINT DIVISOR:
     1  1=WRITE EVERY PAIR TO FILE
     1  2=WRITE EVERY OTHER PAIR TO FILE
     1  3=WRITE EVERY THIRD PAIR TO FILE
     1  ETC...'
      ACCEPT*,IDIV
C
C                 ENTER SAMPLING RATE
C
30    TYPE*,'ENTER SAMPLING PERIOD'
      ACCEPT*,DWELL
C
C                 ENTER TRANSDUCER GAINS
C
      TYPE*,'ENTER PRESSURE TRANSDUCER GAIN  (MILLIVOLTS/PSI)'
      ACCEPT*,PGAIN
      TYPE*,'ENTER POSITION TRANSDUCER GAIN  (MILLIVOLTS/CC)'
      ACCEPT*,FGAIN
C
C                 PRESSURE OR FLOW CONTROL?
C
40    TYPE*,'ENTER 0 FOR PRESSURE CONTROL, 1 FOR FLOW CONTROL'
      ACCEPT*,ICNTRL
      IF (ICNTRL.EQ.1) GO TO 50
      TYPE*,'ENTER DESIRED PRESSURE (PSI)'
      ACCEPT*,SETPSI
      GO TO 60
50    TYPE*,'ENTER DESIRED FLOW RATE (CC/SEC)'
      ACCEPT*,SETFLO
C
C                 ENTER STRIP CHART PARAMETERS
C
60    TYPE*,'ENTER MAXIMUM PRESSURE EXPECTED  (PSI)'
      ACCEPT*,PMAX
      TYPE*,'ENTER MAXIMUM FLOW EXPECTED  (CCS)'
      ACCEPT*,FMAX
C
C                 ZERO TRANSDUCERS
C
      TYPE*,'TO TAKE INITIAL ZERO READING, SET PRESSURE AND FLOW'
      TYPE*,'TO ZERO AND ENTER 0, OTHERWISE ENTER 1'
      ACCEPT*,IZERO
      IF (IZERO.NE.0) GO TO 120
70    ITZERO=0
```

```
          DO 80 I=1,4
            CALL FASTAD(2,ICHAN1,PRZERO)
            ITZERO=ITZERO + PRZERO
80        CONTINUE
          PRZERO=ITZERO/4
          ITZERO=0
C
          DO 90 I=1,4
            CALL FASTAD(0,ICHAN2,FLZERO)
            ITZERO=ITZERO + FLZERO
90        CONTINUE
          FLZERO=ITZERO/4
C
          PZERO=FLOAT(PRZERO)/81.92
          FZERO=FLOAT(FLZERO)/.8192
          TYPE 100,PZERO
100       FORMAT(' PRESSURE TRANSDUCER ZERO =',F9.3,' MILLIVOLTS')
          TYPE 110,FZERO
110       FORMAT(' POSITION TRANSDUCER ZERO =',F9.3,' MILLIVOLTS')
C
C                   RE-ZERO?
C
          TYPE*,'ENTER 0 TO RE-ZERO TRANSDUCERS, 1 TO PROCEED'
          ACCEPT*,IZERO
          IF (IZERO.EQ.0) GO TO 70
C
C                   START EXPERIMENT
C
120       TYPE*,'*** TYPE "S" TO END SESSION ***'
          PAUSE 'TYPE RETURN TO START'
C
C                   SET UP STRIP CHART
C
          CALL VTCLR
          DO 130 I=1,2
130       CALL GRSCAL(IBUF,0.,0.,0.,PMAX,I-1)
          CALL GRAF(IBUF,0,227+16)
          CALL INSTRP(2)
C
C                   INITIALIZE AND START CLOCK
C
          CALL XRATE(DWELL,IRATE,IPRSET)
          CALL CLOCK(MODE,IRATE,IPRSET)
          CALL START
C
C                   CHECK FOR SYNCHRONIZATION
C
140       CALL CSYNCH(ILOST)
          IF (ILOST.NE.0) GO TO 200
C
C                   CALL A/D CONVERSION
C
          CALL FASTAD(2,ICHAN1,IDATAP)
          IDATAP=IDATAP-PRZERO
```

```
      PSI=FLOAT(IDATAP)/PGAIN/81.92
      CALL FASTAD(0,ICHAN2,IDATAF)
      IDATAF=IDATAF-FLZERO
      FLOW=FLOAT(IDATAF)/FGAIN/.8192
C
C                 CALCULATE CORRECTION SIGNAL
C
      IF (ICNTRL.EQ.1) GO TO 150
      E=SETPSI-PSI
      GO TO 160
150   E=COUNT*DWELL*SETFLO-FLOW
160   CORECT=G1+GAIN*((1.+TD/DWELL)*E+(DWELL/TI-1.-2.*TD/DWELL)*E1
     1        +TD/DWELL*E2)
      E2=E1
      E1=E
      G1=CORECT
170  IF (CORECT.LT.0.) CORECT=0.
      IF (CORECT.GT.10.) CORECT=10.
      ICOREC=INT(CORECT*4096./10.2375)
C
C                 CALL D/A CONVERSION
C
      CALL SEND(3,ICOREC)
C
C                 SCALE DATA AND OUTPUT TO STRIP CHART
C
      IY1=INT(FLOW/FMAX*209.)+30
      IY2=INT(PSI/PMAX*209.)+30
      CALL ENABLE
      CALL STDATA(2,IY1,IY2)
      CALL DISABL
C
C                 ENTER DATA INTO BUFFER
C
      INUM=INUM+1
      IF(INUM.NE.IDIV) GO TO 180
      INUM=0
      DATBUF(ICOUNT)=IDATAP
      DATBUF(ICOUNT+1)=IDATAF
      ICOUNT=ICOUNT+2
      COUNT=COUNT+1.
C
C                 READ TERMINAL AND STOP IF USER HAS TYPED AN "S"
C
180   CALL CHARIN(I1)
      IF (I1.EQ."123) GO TO 190
      IF (ICOUNT-2.GE.11000) GO TO 190
      GO TO 140
```

```
C
C                    STORE DATA ON DISK
C
190        CALL SEND(3,0)
           IF (IDISK.EQ.0) GO TO 210
           WRITE(10) DWELL*IDIV
           WRITE(10) PGAIN
           WRITE(10) FGAIN
           WRITE(10) ICOUNT-2
           WRITE(10) (DATBUF(I),I=1,ICOUNT-2)
           GO TO 210
200        CALL VTCLR
           CALL SEND(3,0)
           TYPE*,'SYNCHRONIZATION HAS BEEN LOST!'
           PAUSE '*** TYPE RETURN ***'
C
C                    QUERY USER FOR ANOTHER TRIAL
C
210        CALL VTCLR
           TYPE*,'DO YOU WANT TO RUN AGAIN?  (1=YES,0=NO)'
           ACCEPT*,IRUN
           IF (IRUN.EQ.0) STOP 'END OF RUN'
           IF (IDISK.EQ.1) CLOSE(UNIT=10)
           CALL VTCLR
           GO TO 10
           STOP
           END
```

## B. Listing of program TWOPLT

```
C        *******************************************************
C        *                                                     *
C        *                   -PROGRAM TWOPLT-                  *
C        *                                                     *
C        *  THIS PROGRAM READS A DATA FILE CREATED BY "VCS.FOR"  *
C        *  AND CREATES A SINGLE PLOT FILE OF BOTH PRESSURE AND  *
C        *  FLOW AGAINST TIME, SCALING THE SECONDARY PLOT WITH   *
C        *  RESPECT TO THE PRIMARY VARIABLE SCALING.             *
C        *                                                     *
C        *******************************************************
C
         DIMENSION TIME(501),Y(501),TEMP(501),YMAX(2),YMIN(2)
         INTEGER*2 FILNAM(5),DATBUF(1500)
         BYTE XLBL(20),YLBL(20)
         MODE=1
         IOUT=0
         ILOST=0
         TIM=0.
         NPTS=0
         ONE=2
         YMAX(1)=0.
         YMAX(2)=0.
         NE=2
         NI=1
C
C                  PLOT PRESSURE OR FLOW AS PRIMARY VARIABLE?
C
         TYPE*,'ENTER PRIMARY VARIABLE (0 FOR PRESSURE, 1 FOR FLOW)'
         ACCEPT*,IPLOT
         IF (IPLOT.EQ.0) GO TO 10
         NE=0
         NI=-1
C
C                  ENTER DATA FILE NAME
C
10      TYPE*,'ENTER DATA FILE NAME'
         ACCEPT 20,FILNAM
20       FORMAT(5A2)
         OPEN(UNIT=20,NAME=FILNAM,TYPE='OLD',FORM='UNFORMATTED')
         REWIND 20
C
C                  READ DATA FILE
C
         READ(20) DWELL
         READ(20) PGAIN
         READ(20) FLGAIN
         READ(20) ICOUNT
         TYPE*,'*************** READING DATA ***************'
         READ(20) (DATBUF(J),J=1,ICOUNT)
         CLOSE(UNIT=20)
```

```
      PRESSR=PGAIN*81.92
      FLOW=FLGAIN*.8192
C
C               FILL TIME ARRAY
C
      DO 30 I=1,ICOUNT/2
        TIME(I)=DWELL*(I-1)
30    CONTINUE
C
C               GET DATA (FLOW OR PRESSURE)
C
      DO 40 K=1,NE,NI
        G=PRESSR
        ITAB=IPLOT+K
        IF(ITAB.EQ.2) G=FLOW
        DO 40 I=1,ICOUNT,2
          NPTS=NPTS+1
          IDATA=DATBUF(I+IPLOT+K-1)
          Y(NPTS)=FLOAT(IDATA)/G
40    CONTINUE
C
C               CALCULATE PRIMARY MAXIMUM AND MINIMUM Y VALUES
C
      IEND=ICOUNT/2
      DO 50 I=1,IEND
        IF(Y(I).GT.YMAX(1)) YMAX(1)=Y(I)
50    CONTINUE
      YMIN(1)=YMAX(1)
      DO 60 I=1,IEND
        IF(Y(I).LT.YMIN(1)) YMIN(1)=Y(I)
60    CONTINUE
      SAVE=YMIN(1)
      TYPE 70,YMIN(1),YMAX(1)
70    FORMAT(' ',' MIN,MAX Y AXIS VALUES=',F10.3,',',F10.3,
     1 /,'  ENTER -1 TO USE THESE VALUES OR ENTER NEW VALUES')
      ACCEPT*,YMIN(1)
      IF(YMIN(1).NE.-1.) GO TO 80
      YMIN(1)=SAVE
      GO TO 90
80    ACCEPT*,YMAX(1)
C
90    TYPE 100,TIME(ICOUNT/2)
100   FORMAT(' ',' MAX X AXIS VALUE=',F10.3,
     1 /,'  ENTER -1 TO USE THIS VALUE OR ENTER NEW VALUE')
      ACCEPT*,TMAX
      IF(TMAX.LT.0.)TMAX=TIME(ICOUNT/2)
C
      TYPE*,'ENTER X AXIS LABEL, THEN Y AXIS LABEL (MAX 20 CHAR)'
      READ(5,110) XLBL
      READ(5,110) YLBL
110   FORMAT(20A1)
C
      TYPE*,'ENTER NUMBER OF X AXIS TIC MARKS, Y AXIS TIC MARKS'
      ACCEPT*,NXTIC,NYTIC
```

```
C
C                   CALCULATE SECONDARY MINIMUM AND MAXIMUM Y VALUES
C
        ISTART=IEND+1
        DO 120 I=ISTART,ICOUNT
        IF(Y(I).GT.YMAX(2)) YMAX(2)=Y(I)
 120    CONTINUE
        YMIN(2)=YMAX(2)
        DO 130 I=ISTART,ICOUNT
          IF(Y(I).LT.YMIN(2)) YMIN(2)=Y(2)
 130    CONTINUE
C
C                   SCALE AND SHIFT DATA OF SECOND PLOT
C
 140    SCALE=(YMAX(1)-YMIN(1))/(YMAX(2)-YMIN(2))
        NPSTRT=NPTS/2+1
        DO 150 J=NPSTRT,NPTS
          Y(J)=(Y(J)-YMIN(2))*SCALE+YMIN(1)
 150    CONTINUE
        CALL HIPLOT(TIME,Y,ICOUNT/2,2,XLBL,YLBL,0.,TMAX,YMIN(1),
     1  YMAX(1),NXTIC,NYTIC)
C
        STOP
        END
```

```
C        *********************************************************
C        *                                                       *
C        *                -SUBROUTINE TRAJECT-                   *
C        *                                                       *
C        *   THIS SUBROUTINE CALCULATES A SETPOINT TRAJECTORY.   *
C        *   THE SETPOINT RAMPS TO A BASE PRESSURE FROM ZERO     *
C        *   WHERE 3 CYCLES OF A SINUSOIDAL CURVE ARE TRACED.    *
C        *   AFTER RETURNING TO THE BASE PRESSURE, THE SETPOINT  *
C        *   DECAYS TO ZERO.                                     *
C        *                                                       *
C        *********************************************************
C
         SUBROUTINE TRAJEC(COUNT)
         COMMON DWELL,SK,SETPNT,PTAB,PSIN,SLOPE,PBASE,AMP,PERIOD
         IF (COUNT.GE.PTAB+40.) GO TO 10
         IF (COUNT.GE.PTAB) RETURN
         SETPNT=COUNT*DWELL*SLOPE
         GO TO 30
10       PTIME=3.*PERIOD/DWELL+PTAB+40.
         IF (COUNT.GE.PTIME) GO TO 20
         PSIN=PSIN+1.
         SETPNT=PBASE+AMP*SIN(6.2832*PSIN*DWELL/PERIOD)
         GO TO 30
20       IF (COUNT.LT.PTIME+40.) RETURN
         SK=SK+1.
         SETPNT=SETPNT*PUD
         IF (SETPNT.LT.0.) SETPNT=0.
30       RETURN
         END
```