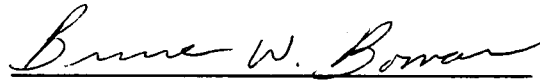


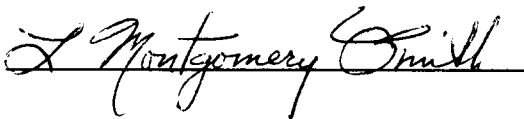
To the Graduate Council:

I am submitting herewith a thesis written by Joseph Steven Carter entitled "The Development of a Controller for Differential Pressure Calibrations." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.


B.W. Bomar, Major Professor

We have read this thesis
and recommend its acceptance:





Accepted for the Council


Associate Vice Chancellor
and Dean of The Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at the University of Tennessee, Knoxville, I agree that the library shall make it available to borrowers under the rules of the library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor in his absence, by head of the Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my permission.

Signature Joseph Steven Carter
Date 4/25/94

THE DEVELOPMENT OF
A CONTROLLER FOR DIFFERENTIAL
PRESSURE CALIBRATIONS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Joseph Steven Carter
May 1994

ACKNOWLEDGMENTS

The author would like to express thanks to several people who helped in the preparation of this thesis. Thanks are extended to Dr. Bruce Bomar, Dr. Roy Joseph and Dr. Montgomery Smith for their assistance and council in preparation for this thesis.

A sincere thanks is extended to Mr. Ralph E. West and to Mr. Joe T. Bettis without whose help this work would not have been possible.

The author would like to thank Calspan Corporation and the United States Air Force for the opportunity to attend the University of Tennessee Space Institute.

Finally, the author would like to thank his wife Sharon for her support and encouragement during the writing of this thesis.

References to named commercial products in this thesis are not to be considered in any sense as endorsements of the product by the United States Air Force or the Government.

The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research was done by personnel of Calspan Corporation, AEDC Division, operating contractor for the aerospace flight dynamics testing facilities at the AEDC. Further reproduction is authorized to satisfy the needs of the United States Government.

ABSTRACT

Pressure transducers are used to provide flight performance and tunnel conditions information during wind tunnel testing. All pressure transducers used during testing must have calibrations traceable to the National Institute of Standards and Technology (NIST); therefore, calibration is required on a scheduled basis for every pressure transducer used in the process of testing flight vehicles at Arnold Engineering Development Center (AEDC). To meet stringent data accuracy requirements, most transducers are calibrated on a daily basis: a time consuming process for the three thousand pressure transducers in use at the facility. These transducers are usually differential devices because they are easier to calibrate than absolute pressure transducers.

Initially, pressure calibration devices were very accurate portable air dead weight testers that had to be transported to the transducers under test. To eliminate this time consuming requirement, transducers were connected pneumatically to a differential pressure controller over lengthy pressure lines. Unfortunately, the pressure controller required over twenty minutes to set a stable output pressure due to the large volume of the pressure lines. The development of a differential pressure controller which substantially reduces the time needed to set calibration pressures, but maintains high accuracy and stability, is presented in this thesis.

The pressure controller accepts pressure commands in the range of ± 15 pounds per square inch differential (PSID). A flapper-nozzle pressure servovalve provides stability to approximately ± 0.0015 PSID and can charge a 20 cubic inch volume to 12 ± 0.01 PSID in approximately five seconds. The output pressure is controlled to better than ± 0.002 PSID by using a differential pressure working standard to provide the calibration manifold feedback pressure. The pressure controller uses a proportional plus integral

control algorithm that is satisfactory for volumes from five cubic inches to six thousand cubic inches.

The device has features and display options that are activated by a single switch making operation relatively simple. Routines to display the leak rate, zero the feedback transducer and calibrate the feedback transducer are included in the embedded program residing in memory on a STD BUS CPU card. All calculated control and display constants are stored in battery-backed memory. The controller is composed of two chassis connected by a multi-conductor cable. Separation of the electrical control chassis and the pneumatic control chassis allow the pressure source to be located near the pressure calibration manifold while the commands are issued by an operator in the wind tunnel control room. The pressure controller was evaluated in a laboratory setting, but it has been used on a daily basis in a transonic wind tunnel for over a year without failure.

TABLE OF CONTENTS

CHAPTER	PAGE
1. INTRODUCTION	1
Statement of the problem	1
Pressure calibration description	3
Pressure system pneumatic description	7
Pressure controller requirements	8
Thesis description and organization	11
2. PRESSURE CONTROLLER FUNCTIONS	12
Introduction	12
Electrical control chassis functions	12
Pneumatic control chassis functions	18
Control feedback devices	21
Remote interface functions	23
Input/Output structure	25
3. HARDWARE DESCRIPTION	29
Introduction	29
Processor card	29
Input/Output cards	30
Pressure transducers	31
Keypad decoder and A/D converter card	35
Pressure control valve	44
Valve control and D/A converter card	44
Solenoid valve control card	50
Power Requirements	51

CHAPTER	PAGE
4. CONTROL METHODOLOGY AND TIMING . . .	53
Introduction	53
Control valve characteristics	53
Voltage to current converter	60
Feedback transducer data acquisition	65
Control algorithm selection	67
5. SYSTEM SOFTWARE	76
Introduction	76
Main program functions	76
Assembly code subroutines	77
Memory requirements	79
6. PRESSURE CONTROLLER CHECKOUT	81
Introduction	81
Initial Setup	81
Pressure controller benchmarks	83
7. SUMMARY	90
REFERENCES	93
APPENDICES	96
APPENDIX A	97
APPENDIX B	105
VITA	109

LIST OF FIGURES

FIGURE	PAGE
1.1. Differential pressure transducer calibration	4
1.2. Absolute pressure transducer calibration	6
1.3. Pressure controller functional diagram	10
2.1. Electrical control chassis front panel layout	13
2.2. Electrical control chassis rear panel layout	14
2.3. Pneumatic control chassis rear panel layout	19
2.4. Pneumatic control chassis tubing	20
2.5. Feedback control selection diagram	22
2.6. Remote interface control word format	24
2.7. Pressure controller input/output block diagram	26
3.1. Working standard operation and output	34
3.2. Keypad decoder schematic	36
3.3. Analog transducer input circuitry	38
3.4. Second order Butterworth filter	40
3.5. A/D converter schematic	43
3.6. D/A converter schematic	46
3.7. Units, feedback and valve select schematic	47
3.8. Valve and relay power schematic	49
4.1. Schematic of flapper-nozzle pressure servovalve	54
4.2. Weight flow versus pressure ratio	57
4.3. Weight flow versus control pressure	58
4.4. Pressure servovalve coil resistance versus control current	60
4.5. Voltage to current converter schematic	62

LIST OF FIGURES

FIGURE	PAGE
4.6. Analog transducer timing	66
4.7. Pressure servovalve output pressure	69
4.8. Control algorithm program structure	74
6.1. Positive step pressure response	86
6.2. Negative step pressure response	86
6.3. Positive control pressure output	88
6.4. Negative control pressure output	89

CHAPTER 1

INTRODUCTION

Statement of the Problem

Pressure transducers use a variety of sensing elements to measure the force caused by a gas or liquid on a known area. Transducers are usually connected by a short tube to the area where the measurement is required. Different sensing elements are used to measure the applied pressure. Pressure transducers use flexible metal elements, manometers, strain gages bonded to a diaphragm and other electrical pickups to sense pressure. Pressure transducers employing bonded strain gages are the most commonly used at Arnold Engineering Development Center (AEDC). These transducers are durable and their accuracy is not significantly affected by temperature or vibration conditions encountered in transonic wind tunnels. The analog voltage signal output is amplified by circuitry inside the transducer housing or by an external amplifier. This signal is normally input to a multi-channel data system.

Pressure transducers are used to provide static or dynamic flight performance and test conditions information during wind tunnel testing. Measurements made at pressure orifices in the wind tunnel are used to calculate mach number or determine tunnel flow quality. Measurements made on a test article are used to calculate lift, drag and other flight vehicle performance data. The output characteristics of each pressure transducer used in the process of testing flight vehicles at AEDC must be measured. This is accomplished by applying known pressures to each transducer with a differential pressure controller and recording its output. This data is then reduced to obtain calibration coefficients for a first or second order curve fit for pressures over the expected input range. Due to stringent accuracy requirements, calibrations are performed on a daily basis

for every pressure transducer used in the facility. Much of the time required preparing for a test in a wind tunnel is spent performing pressure transducer calibrations and ensuring the integrity of pressure calibration, reference and other pneumatic tubing.

All test article and facility pressure transducers are pneumatically connected to a single calibration source. This simplifies the process of calibrations because the process can be performed from a single location. Unfortunately, it is difficult to set a precise pressure on a long pressure line. Also, many pressure transducers share the same calibration line to reduce the number of calibrations to be performed. This increases the volume that the pressure source must charge or evacuate.

The original pressure source was a manufacturer supplied differential controller that required over twenty minutes to set -12 PSID with a volume of six thousand cubic inches. The time required to perform all required calibrations with this device was approximately two hours. All pressure controllers having acceptable accuracy available from manufacturers would set the pressures no faster. They were designed to be portable or to be set up in a laboratory environment. In such installations supply rates are not extremely important because pressure lines are usually short. Features and instrument interfaces are stressed in their design. Also, these instruments must be periodically removed from service for calibration and additional units would have to be purchased as spares. The need for high flow rates was the determining factor in the decision to fabricate a pressure controller on site.

To reduce this calibration time a differential pressure controller was designed using a high flow rate pressure servovalve. This pressure calibration device is traceable to the National Institute of Standards and Technology (NIST). Its deviation about the setpoint is ± 0.0015 PSID or better and its accuracy is ± 0.002 PSID at full scale output. It provides manual as well as computer interfaces and its operation is straightforward. The

pressure controller can evacuate a volume of six thousand cubic inches to a stable pressure of -12 PSID in approximately seven minutes and the total calibration time has been reduced from two hours to less than forty five minutes.

Pressure Calibration Description

Most pressure transducers used during testing are differential devices that can be calibrated in place. In transonic wind tunnels the pressures encountered by test articles are usually in the range from 2 pounds per square inch absolute (PSIA) to 25 PSIA. Transducers having a usable input range of ± 15 pounds per square inch differential (PSID) are used most frequently because when referenced to atmosphere, locally 14.2 PSIA on average, the device covers the entire input pressure range. At times, transducers are referenced to a standard tunnel pressure such as tunnel static pressure or tunnel total pressure. Typical pressure ranges for these transducers are ± 5 PSID and ± 2.5 PSID. Since accuracy is normally expressed as a percent of full scale pressure, smaller range transducers measure low pressures most accurately.

The calibration procedure for all differential pressure transducers is the same. This process is presented in Figure 1.1. The transducer pressure port is maintained at atmospheric pressure while the reference is evacuated to a pressure at the upper limit of its expected range. The supply is then shut off by closing a valve. The leak rate is monitored by the operator. If a leak greater than specified in the calibration instruction is present, the line is pressurized for troubleshooting purposes and leak check spray is applied to all pressure joints and couplings. After all detectable leaks are repaired, the reference line is evacuated using the pressure controller. A positive pressure is then indicated because the reference is at a lower pressure than the pressure orifice. Data is obtained from the transducer under test for the positive pressure. The pressure controller is then used to

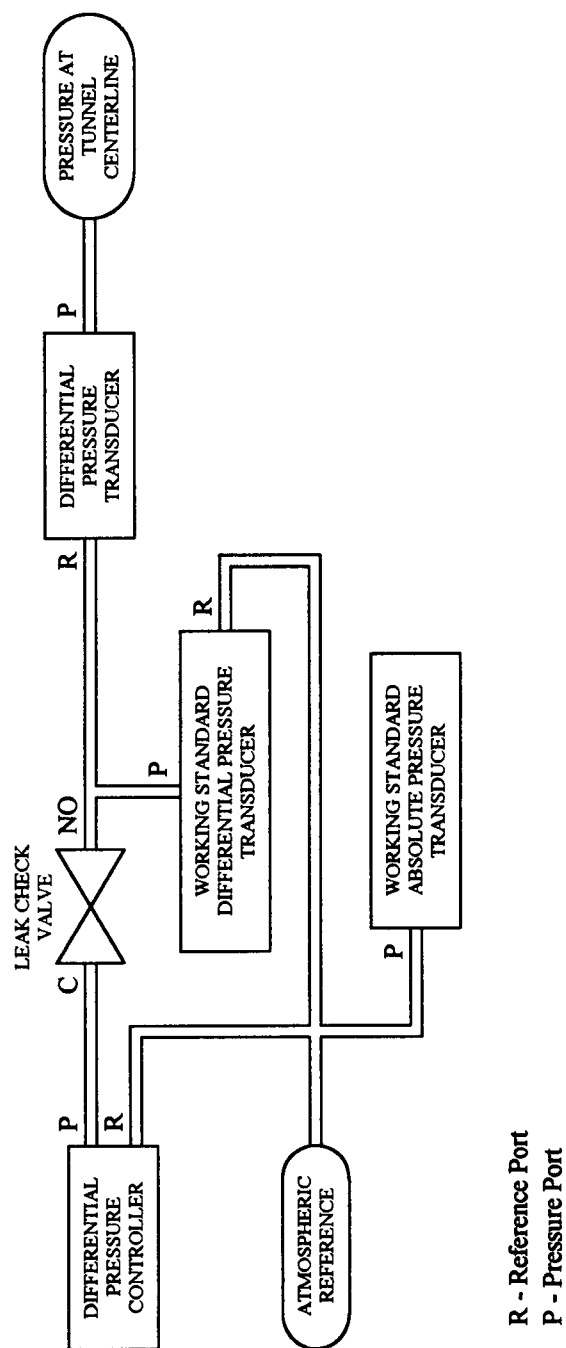


Figure 1.1. Differential Pressure Transducer Calibration

output several more pressures over the expected pressure range of the transducer in order to represent the calibration using a polynomial least squares curve fit.

All pressure media are elevation sensitive. Correction is not required when the working standard and the transducer under test are at the same altitude. In a wind tunnel environment the working standard, the test peculiar transducers and the facility transducers cannot be easily installed at the tunnel centerline altitude; therefore, the calibration pressure must be arithmetically corrected to the tunnel centerline pressure [1]. The reference pressure must also be maintained at or corrected to tunnel centerline pressure during calibrations. These corrections are most easily made in the tunnel data system; therefore, the differential pressure controller does not have provisions for elevation correction.

A typical installation could have hundreds of differential transducers mounted in a test article. The reference port of each transducer would be connected to the test article calibration manifold. The pressure port of each transducer would be connected to a pressure tap located on the model. During tunnel non-operational periods, the pressure taps would be at the tunnel centerline atmospheric pressure and a calibration pressure would be applied to the calibration manifold. The working standard transducer data would then be corrected to the tunnel centerline altitude when performing the calibration curve fit. The working standard pressure transducer has a range of +/- 17.5 PSID and has calibrations traceable to NIST.

The calibration process is similar for calibrating absolute pressure transducers and is shown in Figure 1.2. The main difference between the two processes is that the input pressure port must be switched from measuring the pressure of interest to measuring the calibration source, so one additional valve is required for each transducer.

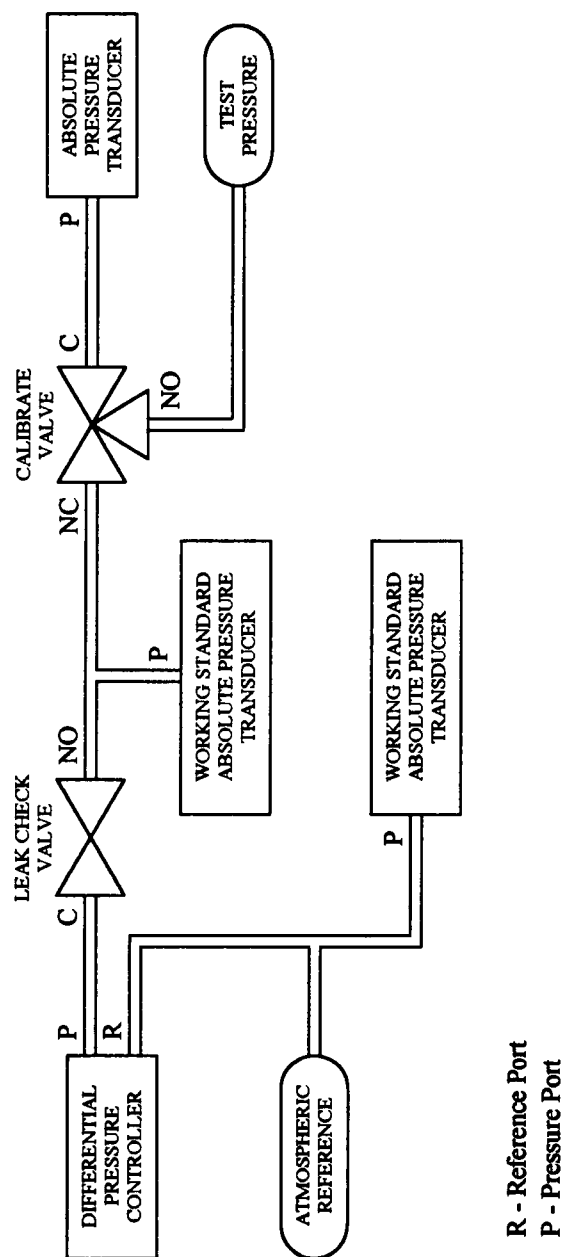


Figure 1.2. Absolute Pressure Transducer Calibration

Pressure System Pneumatic Description

Pressure transducers are located over a very large area in most wind tunnels at AEDC. Physical constraints force the wind tunnel compressors to be a substantial distance from the test section. Since it requires less time to perform the daily calibrations from a central location, a calibration manifold was installed several years ago. This calibration manifold connects all facility transducers and the test article transducers to the calibration console.

The pressure lines that connect these devices to the main calibration manifold are 3/4" diameter tubing. By using a large diameter, one can be more certain that the pressure at each end of the tube is the same. It takes less time for the gas to equalize in a large diameter tube than a small tube because pressure lag time is inversely proportional to the diameter of the tube [2].

The pressure lines that connect the compressor inlet pressure transducer and the compressor exit pressure transducer to the calibration manifold can be several hundred feet in length. These transducers are located close to the orifice at the compressor to maintain the frequency response. Each transducer is connected to the calibration manifold by a separate pressure line so each line can be isolated for troubleshooting.

Seven facility monitoring pressure transducers are connected to the main calibration manifold with 3/4" tubing. The total volume for the seven transducers is estimated at 6000 cubic inches. It required over twenty minutes to evacuate this volume to a stable pressure of -12 PSID using the previous pressure controller. Up to two hours might be needed to complete daily calibrations and checks depending on the complexity of test peculiar pressure measuring requirements. Further investigations showed that newer model pressure controllers could not supply adequate amounts of gas to reduce the time for calibrations. Typical supply rates of two liters per minute would require over 90

minutes to fill the volume of the pressure lines and several more minutes for the pressure to stabilize to within the required 0.002 PSI.

Pressure Controller Requirements

A differential pressure controller was needed to alleviate the problems associated with the performance of pressure calibrations from a central location in a large transonic wind tunnel. This thesis describes the design of a differential pressure controller that performs calibrations on a variety of transducers and has high gas supply rates together with excellent stability and accuracy. These qualities were designed in the pressure controller as well as many features beneficial to the calibration process.

The pressure controller consists of two parts. The electrical control chassis accepts operator inputs and generates control signals. The pneumatic control chassis outputs the commanded pressure. Separation of the two chassis is required so that the pneumatic control chassis can be located near the main calibration manifold and the electrical control chassis can be conveniently placed in a control room. The operation of the pressure controller is not affected if the two chassis are placed several hundred feet apart. A single multi-conductor cable is the only connection between the two chassis. All valve control lines from the electrical control chassis are electrically isolated from the pneumatic control chassis to prevent the occurrence of ground loops and noise. The pressure controller accepts commands from -15 PSID to +15 PSID. Since the output pressure cannot exceed the range of the servovalve, the normal output range is -13 PSID to +15 PSID when atmospheric pressure is the selected reference pressure.

A required output range of 1 PSIA to 30 PSIA to calibrate the pressure transducers used during testing was needed. Pressures below atmosphere are set using a vacuum pump connected to the pressure servovalve. Similarly, pressures above

atmosphere are set using a regulated pressure source connected to the pressure servovalve. Also, the pressure source was required to have high gas supply rates as well as fine resolution. A flapper-nozzle pressure servovalve controlled with a constant current closed loop feedback system is used to meet these requirements. The pressure servovalve supplies up to 85 standard cubic feet of gas per hour and has a pressure output resolution of approximately 0.0002 PSID. The pressure servovalve is located in the pneumatic control chassis shown in Figure 1.3.

The digital output of a working standard having a usable input range of ± 17.5 PSID was connected to the electrical control chassis. This interface to a working standard differential pressure transducer was needed to meet the accuracy requirements. This device is used as the feedback transducer when performing calibrations, but a high quality analog transducer was also installed in the pneumatic control chassis for times when the working standard is not connected. The analog transducer was not classified as a working standard since this would require the pressure controller to be removed from service periodically for certification.

The ability to control pressures using an additional analog feedback source is included as a feature of the pressure controller. A second analog transducer and pressure servovalve are located near the test article. They are used to set calibration pressures on electrically scanned pressure modules, ESPs, located inside the test article. These modules contain 32 to 64 differential pressure transducers in a package eight cubic inches or smaller. Data from each transducer on a module are multiplexed over one signal line connected to the ESP data system. Up to 64 ESPs may be located inside a test article.

This feature enables the ESPs to be calibrated quickly since the test article ESP calibration manifold has short fill and settle times. ESPs are calibrated while the facility is in operation; therefore, the savings of several hours during the course of a test saves many

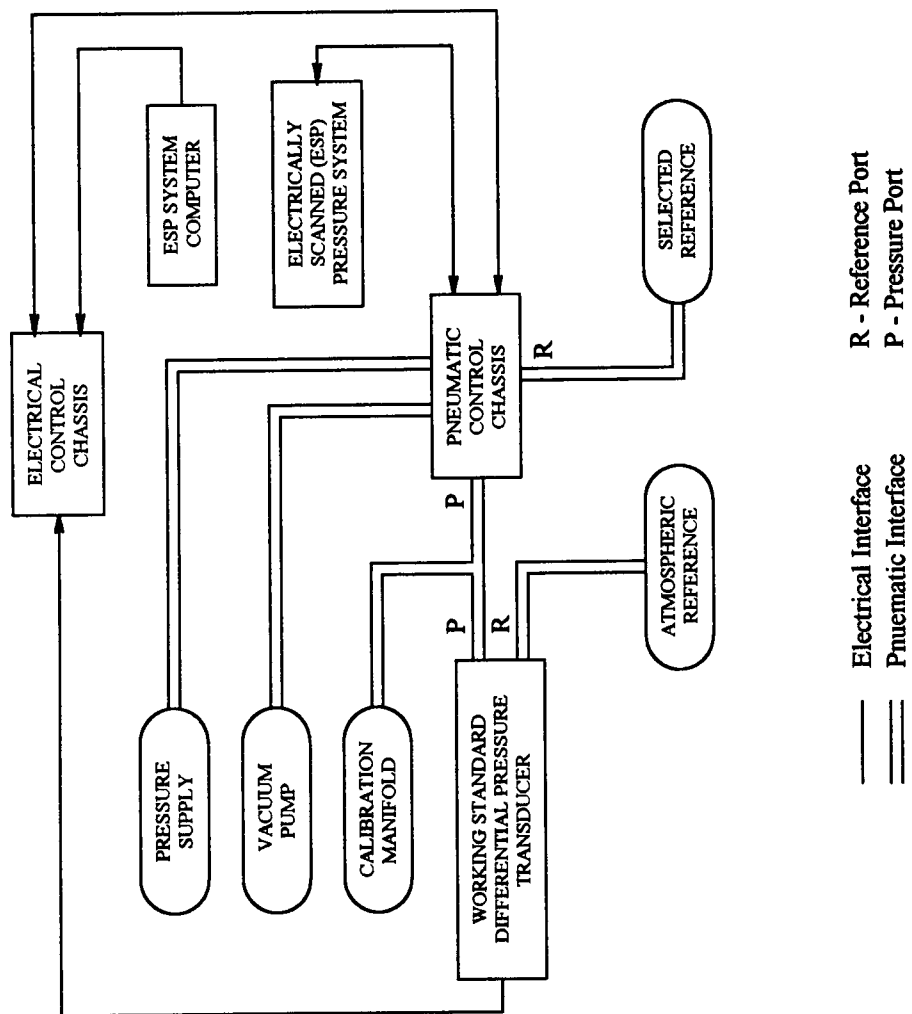


Figure 1.3. Pressure Controller Functional Diagram

thousands of dollars in energy costs alone. This feature minimizes the time required to perform on-line ESP calibrations. The pressure controller provides a means of remote control from a computer controlling the ESPs seen in Figure 1.3.

Thesis Description and Organization

This thesis will describe the design, development and checkout of the differential pressure controller used for calibrations and daily checks in the transonic wind tunnels at the AEDC. The development of the pressure controller is discussed in the following chapters. The device features along with its input and output structure is presented in Chapter 2. Chapter 3 discusses the system design and the methods employed to provide hardware that meets the objectives of the project. Chapter 4 discusses the operation and characteristics of the pressure control valve. Chapter 5 gives an overview of the embedded control program and flowcharts detailing control processes. Chapter 6 describes the system checkout and its operation following installation. Chapter 7 gives a summary of the final product and presents recommendations for future improvements.

CHAPTER 2

PRESSURE CONTROLLER FUNCTIONS

Introduction

The pressure controller was designed using STD BUS design practices for all input and output. Two special function STD BUS cards were designed and they were fabricated using low cost utility decoded input/output cards. These cards were wire wrapped for the initial unit, but will be fabricated from printed circuit cards for future production pressure controllers. A development system was available for generating 8085 CPU [3] executable code. This processor has been available for many years and has proven to be very reliable and is powerful enough to implement all necessary instrument functions.

The pressure controller was designed to be compatible with existing systems in the AEDC wind tunnels. Also, it was designed to be easy to operate with little possibility of damaging any pressure transducer being calibrated. Several useful operating modes were included in this design to aid in pressure transducer calibrations. Finally, the pressure controller was designed to set pressures quickly and accurately.

Electrical Control Chassis Functions

The front panel and rear panel layout of the electrical control chassis are shown in Figure 2.1 and Figure 2.2. There are two numeric displays on the front panel (pressure request and function display) updated approximately 3 times per second. Each display is composed of five seven segment LED display modules and one +/- LED display module. The resolution of each display is 0.001 PSID or 0.1 PSFD depending on the selected units.

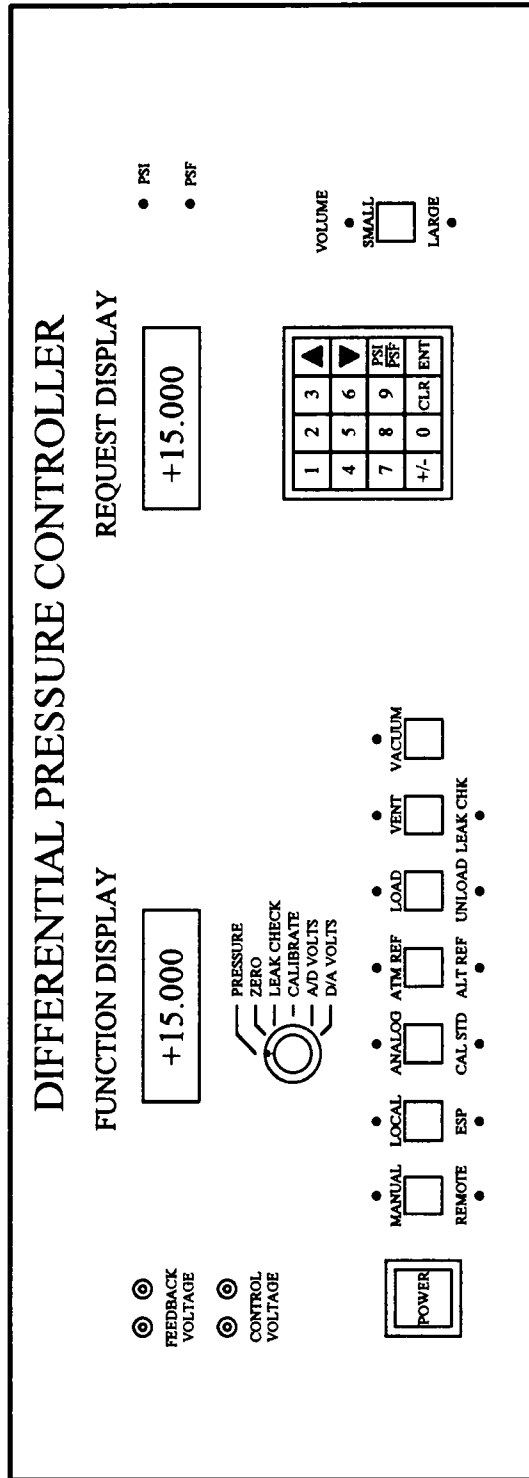


Figure 2.1. Electrical Control Chassis Front Panel Layout

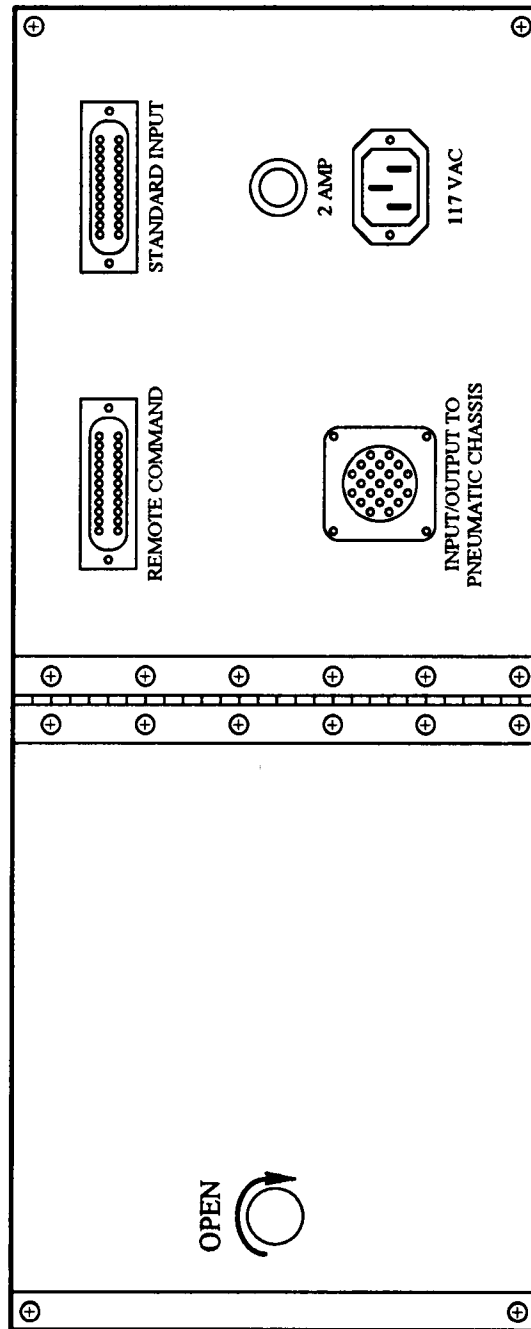


Figure 2.2. Electrical Control Chassis Rear Panel Layout

The pressure request display is used primarily to display the desired calibration pressure and is controlled by the sixteen button keypad on the front panel.

The 16 button keypad is used to input pressure or voltage requests when operating in the manual mode. The keypad is a 4 X 4 matrix switch from which eight signal lines are output to a decoder located on a utility decoded input/output card. When a button is pressed, a binary code representing the button position is available to the CPU. Approximately six inputs can be read per second. In addition to the numbers 0 through 9, the following buttons are located on the keypad:

Toggle Sign changes the sign of the requested pressure display between positive (+) and negative (-).

Clear Display resets the pressure request display to zero. The units and sign are not affected.

Enter Command initiates the setting of the current pressure request value. The enter button is also pressed to initiate the analog transducer zero and the analog transducer calibrate functions.

Toggle Units changes the units of pressure between PSID and PSFD. An LED indicates the units selected and the decimal point changes accordingly.

Increment Pressure Positive increments the value on the pressure request display. The displayed pressure is automatically requested after the button is pressed.

Increment Pressure Negative decrements the value on the pressure request display.

If a pressure of +10.000 PSID were required, the sign and units would be set then the buttons 1_0_0_0_ENT would be pressed. This sequence displays and requests a pressure of +10.000 PSID. Pressing numeric buttons does not affect the least significant

digit. The instrument was programmed in this manner because calibration pressures are normally set at regular intervals. However, if a pressure of 9.995 PSID were required, the increment pressure negative button could be pressed 5 times after +10.000 PSID was set. Since a new pressure is requested every time an increment button is pushed, the pressure controller would set a pressure of +9.995 PSID with no further commands. The pressure controller would eventually reach the full scale negative pressure if the increment negative button were pushed repeatedly because the increment buttons support the arithmetic carry feature. The increment pressure buttons are useful in setting precise pressures when monitoring a working standard that is not electrically connected to the pressure controller

Although the function display will continue to display pressure until the A/D is saturated (approximately -15.300 PSID or +15.300 PSID) the maximum pressure that can be requested is +/- 15.100 PSI or +/- 2175.0 PSF. If a pressure greater than either of these numbers is requested, the pressure request display automatically limits the display to avoid unrealistic commands. The software also limits the most significant digit to 1 or 2 (depending on the selected units) as an added feature.

The CLR button can be pressed to blank the display before entering a new pressure, but it is not necessary to do this since the instrument automatically shifts the digits on the display to the left as new numbers are input. It should also be noted that the least significant digit returns to zero when any digit on the keypad (0 through 9) is pressed and the new entry is shown on the second digit.

The function display is used primarily to display the actual pressure. Six different function displays were designed into the pressure controller. They are:

Pressure displays the current pressure reading of the selected feedback transducer in PSID or PSFD.

Feedback transducer leak rate calculates and displays the leak rate of the calibration line once every ten seconds. The selected feedback transducer is used to determine the displayed leak rate.

Analog transducer zero displays the current reading of the selected analog transducer. The operator can press the enter button if the offset is unacceptable. The offset voltage read after the button was pushed is used to correct the pressure display for subsequent calculations. The zero offset for each analog transducer is retained when power is lost. This function should be completed before performing the analog transducer calibrate function.

Analog transducer calibration performs a calibration of the selected analog feedback transducer and stores the new calibration constants. The calibration is performed as recommended by the manufacturer at 80% of full scale (+12 PSID and -12 PSID). The working standard is used to calculate the correction constant that is used in adjusting the scale factors. If the analog transducer disagrees with the standard by more than 0.75 PSID the calibration process is terminated and no new scale factors are calculated.

Analog transducer voltage displays the uncorrected reading of the selected analog transducer with a resolution of one millivolt (1 mV).

Control voltage displays the control voltage with a resolution of 1 mV on the pressure request display. This voltage is input to a voltage to current converter and directed to the pneumatic control chassis. The pressure generated by the control current to the pressure control valve is read by the feedback transducer and shown on the function display. The value of the control voltage is entered using the 16 button keypad.

Pneumatic Control Chassis Functions

The rear panel layout of the pneumatic control chassis is shown in Figure 2.3. The front panel of the pneumatic control chassis contains only a pressure gauge and an output fitting. The pneumatic layout of the pressure controller is shown in Figure 2.4. There are five large orifice solenoid valves installed in the pneumatic control chassis in addition to a pressure gauge, an analog feedback transducer and a pressure control valve. All valves used in the pneumatic control chassis are large orifice valves to maximize the speed at which pressures can be set. The pressure gauge is not intended for calibrations; it is only used to provide a local readout if the electrical control chassis is not nearby.

Four toggle switches on the electrical control chassis actuate the solenoid valves in the pneumatic control chassis. These switches are active only when the manual/remote toggle switch is in the manual position. The valve selection is input to an optically isolated solenoid drive circuit on a utility decoded input/output card. The switches are inactive when the remote mode of operation is selected because the information for the valve position is then input from the remote input control word. The state of the valves does not change when the remote mode is selected. The position of the valves is maintained until a new valve control word is transmitted to the remote parallel input. The five valves in the pneumatic control chassis are:

Load Pressure / Unload Pressure loads the calibration manifold with the requested pressure or blocks the output. This valve connects the pressure manifold to the atmospheric manifold when power is off. It is used to vent pressure from the calibration manifold in the event of unsafe conditions.

Analog transducer vent applies the reference manifold pressure to both ports on the local analog transducer and to the calibration manifold. When the vent valve is energized, the leak-check valve is also energized to

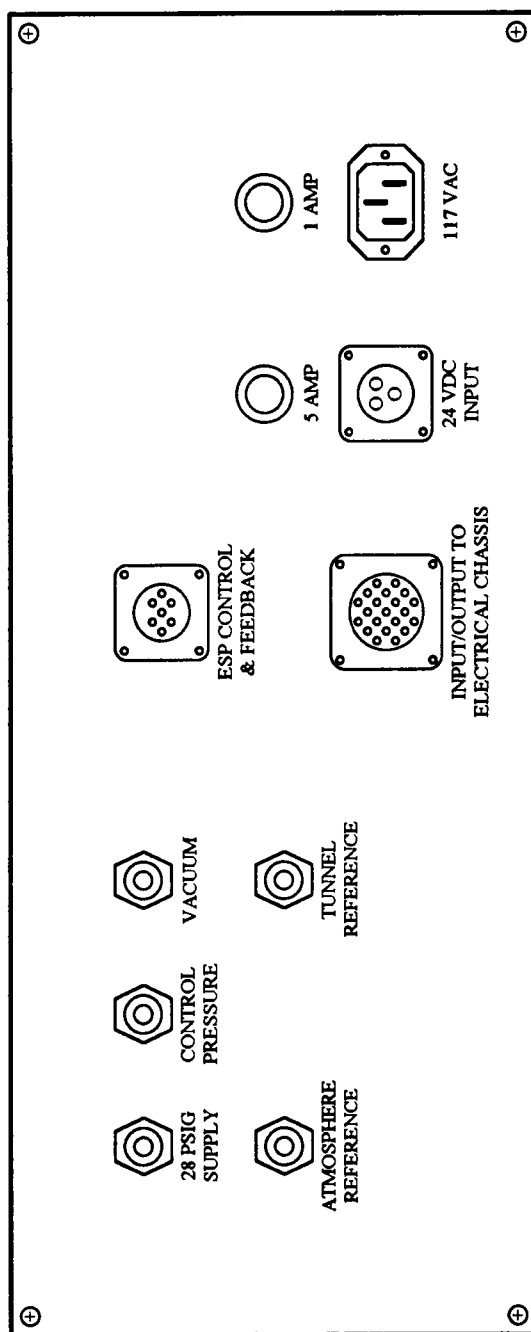


Figure 2.3. Pneumatic Control Chassis Rear Panel Layout

prevent gas from entering the calibration line through the pressure control valve. The calibration manifold is vented to obtain a zero reading in calibrations.

Vacuum energizes the vacuum load valve. Setting pressures very close to 0 PSIA cannot be done with a pressure control valve due to leakage in the pressure control valve. When the vacuum valve is energized, the leak check valve is also energized to prevent gas from entering the calibration manifold through the pressure control valve.

Reference Select connects either the atmospheric reference pressure or an alternate pressure reference for the local analog transducer. The pressure controller always maintains a constant pressure above or below the selected reference pressure.

Leak Check is placed in the off position to load a pressure. When the leak-check valve is energized, any transducer on the calibration manifold may be monitored for leaks. The calibration manifold is leak checked prior to performing any transducer calibrations.

Control Feedback Devices

The arrangement and selection of the control feedback devices is illustrated in Figure 2.5. This figure shows the selection between analog transducer and working standard transducer feedback control. Also, it shows the selection between the analog transducer located in the pneumatic control chassis and the analog transducer located in the ESP calibration system. The feedback control mode is selected by switches on the electrical control chassis. These switches not only direct the input voltage to the electrical control chassis, but they direct the control current output to the pressure control valves. A stable system can be more easily obtained by placing the feedback transducer in close proximity to the pressure control valve because pressure lag effects are reduced.

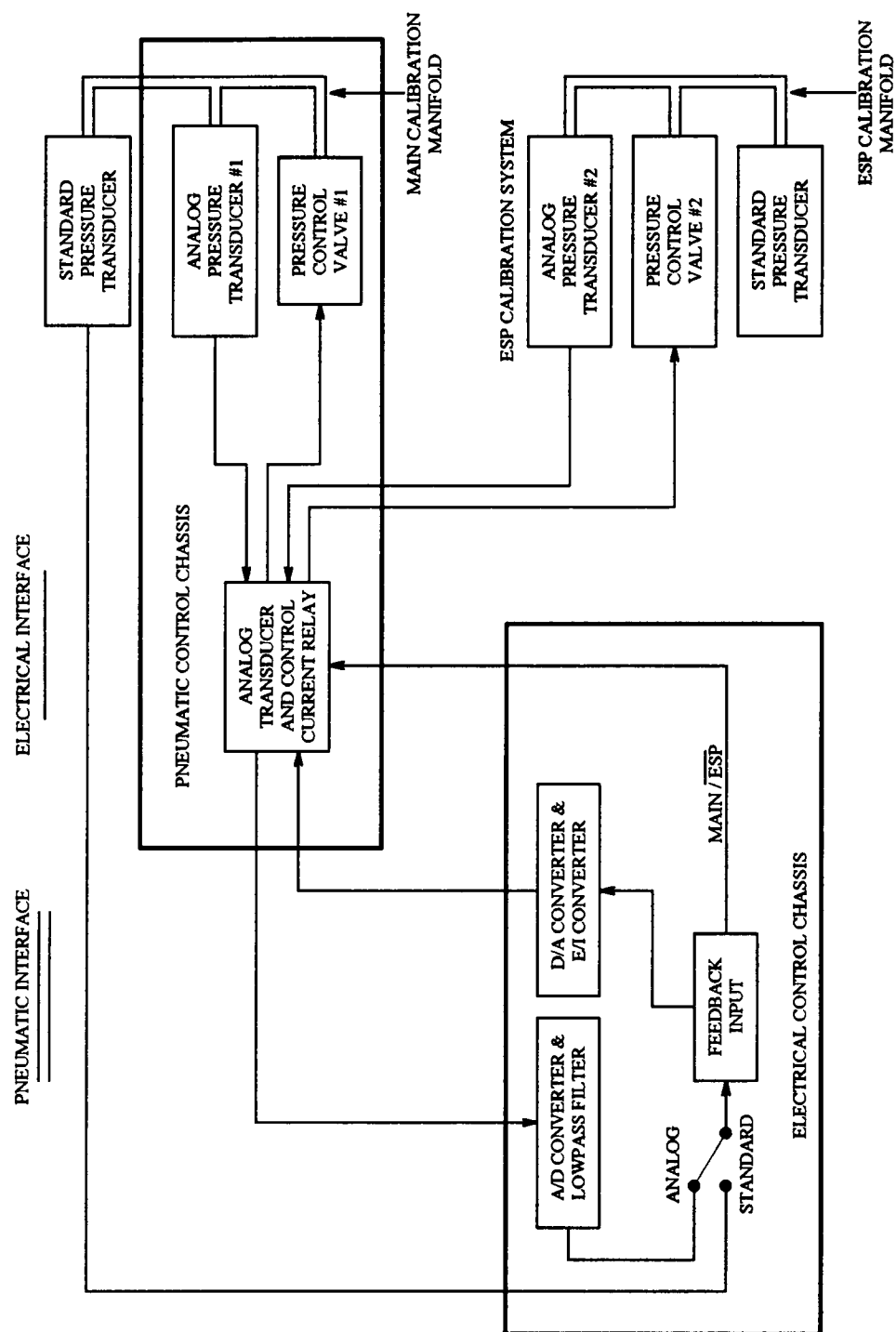


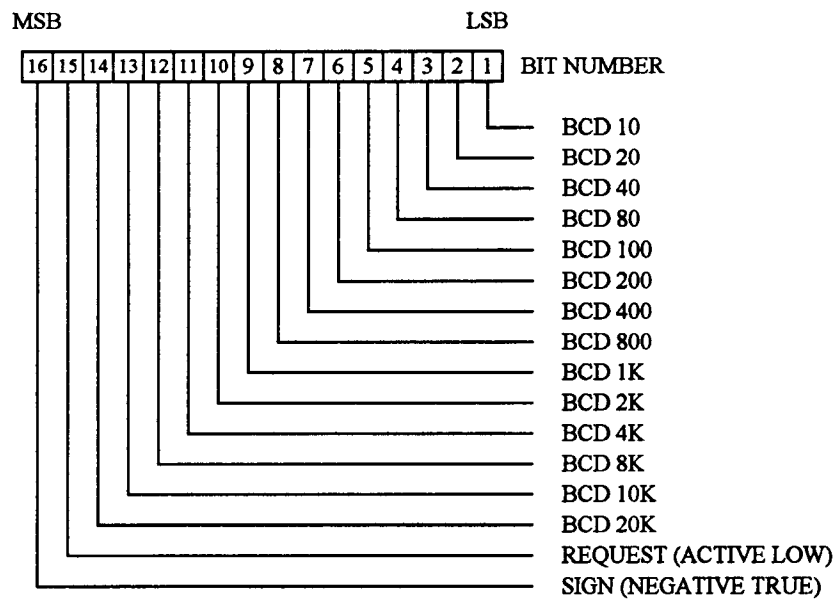
Figure 2.5. Feedback Control Selection Diagram

The ESP system pressure control valve and analog feedback transducer are not usually located in the same area as the pneumatic control chassis. They are located together near the test article to minimize the time required for the calibration pressures to settle. The ESP system and the pneumatic control chassis are connected by a six conductor cable having three shielded, twisted pairs of wires. The transducer power, the feedback signal and the control current setpoint enter the pneumatic control chassis through a seven pin connector on the rear panel. Operation of the solenoid valves will have no effect on the controlled pressure when the ESP analog transducer is used for feedback. The ESP system incorporates all the necessary valves to vent, leak check, change references, load and unload the ESP calibration manifold; therefore, it was not necessary to implement these functions in the pressure controller.

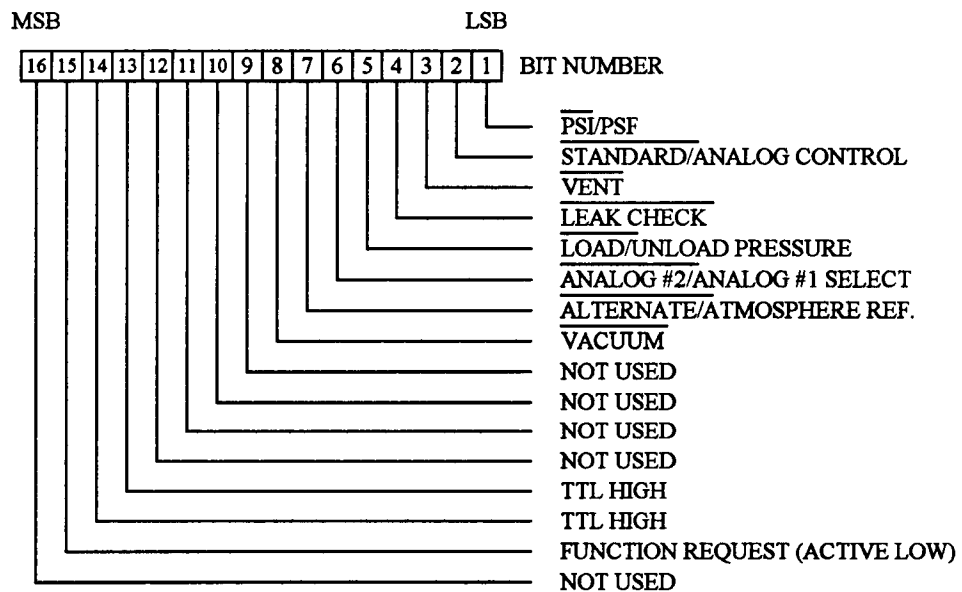
Remote Interface Functions

The remote interface is a 16 bit TTL compatible parallel input that can be used to control the output pressure from an external device such as a programmed I/O interface card or a bank of switches. Any front panel command may be requested over the parallel interface except increment pressure positive or increment pressure negative. Since the least significant digit is not available on the parallel interface, it is set to zero following any pressure request made using the remote interface. A pressure request or a control status request can be made from an external device only if the manual/remote switch is set to remote. The format for pressure request is shown in Figure 2.6a.

The pressure request signal is a TTL active low bit from the host computer or remote control panel. This bit must be held low for a minimum of 200 milliseconds (mS) to ensure that the pressure request is read by the CPU because the loop time of the



(a) Pressure Request



(b) Control Status

Figure 2.6. Remote Interface Control Word Format

instrument is approximately 160 mS. The host computer system contains an I/O card that has been programmed to hold the pressure request bit to a TTL low level for 500 mS.

The format for the control status input is also shown in Figure 2.6b. All the valves can be actuated, the feedback devices can be selected and the units can be selected using the remote interface. The difference between pressure and control status request is that bits thirteen and fourteen are set to a TTL high for a status request. Although both bits are used for pressure requests, a pressure exceeding 30 PSID or 3000 PSFD would be requested if both signals were high. These pressures are out of the control range of the instrument. When both bits are high, a simple routine that controls the LEDS, valves, units and feedback device is processed immediately.

The length of time the pressure request signal must be held low could easily be reduced by connecting it to one of the available interrupts. If this were done the CPU would be instructed to control pressure to a different setpoint or change the control status executing the same subroutine that is currently used. After performing the necessary instructions, the instrument would return to its normal operating mode. Currently, all interrupts to the CPU are disabled, but provisions have been made to connect the request signal to an interrupt if future systems require the change.

Input/Output Structure

All of the input and output (I/O) to the 8085 processor is made using the STD BUS protocol. Up to 256 input ports and 256 output ports can be configured in a STD BUS system. Data are input to the main processor by addressing an input port during the execution of a simple assembly language program. Data are output to peripheral devices by addressing one of the available output ports during the execution of an assembly coded program. A block diagram showing all inputs and outputs is shown in Figure 2.7.

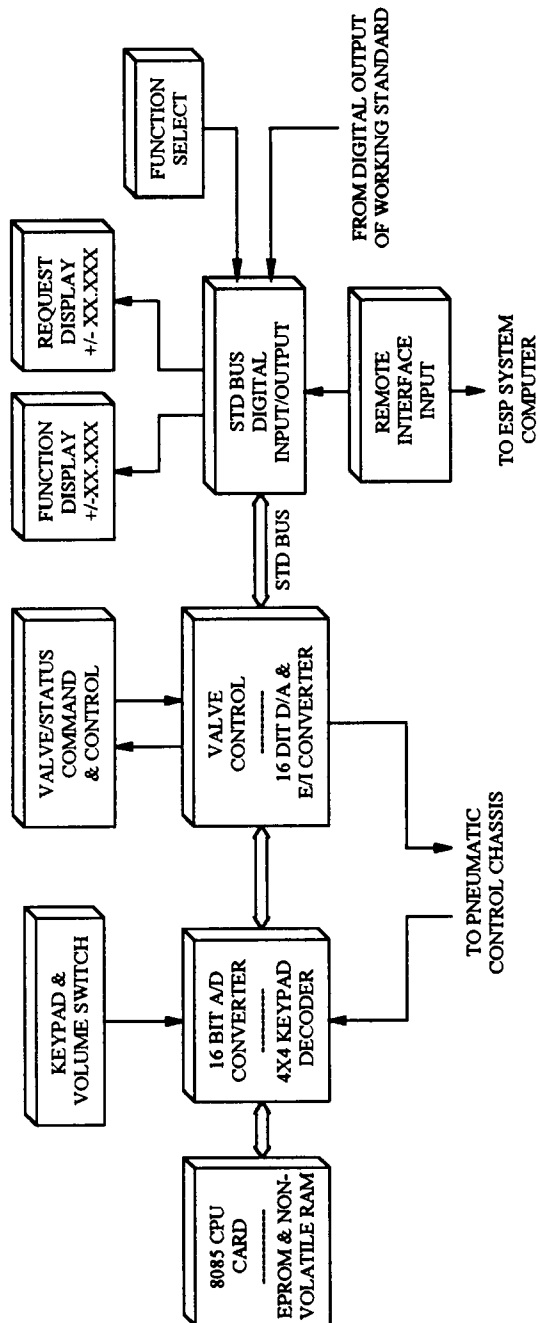


Figure 2.7. Pressure Controller Input/Output Block Diagram

The signals from the analog feedback transducers are multiplexed and input to a 16 bit analog to digital converter (A/D converter). The A/D output is input to the processor in a two's complement format consisting of two eight bit bytes. Each byte occupies an input port. The signal from the differential working standard is a five and one half digit binary coded decimal (BCD) number with sign. A total of twenty one bits are required to read the pressure to the full resolution of the instrument with an additional bit for the sign. The differential working standard requires a total of three input ports.

Commands from the host computer are input to the local processor in a sixteen bit format requiring two input ports. The display mode select switch requires only six bits; therefore, two unused bits are present on its input port. The signals from the vacuum, reference select, analog transducer select, load/unload, leak check, vent, analog/working standard control feedback and manual/remote control switches require eight bits and are connected to one input port. The status bit from the A/D converter and the five input bits from the keypad decoder are connected to another input port. A signal from a switch on the front panel of the electrical control chassis is also input on this port to indicate the expected volume.

The pressure control word is output in a sixteen bit offset binary format which occupies two output ports. This data is input to a sixteen bit digital to analog (D/A) converter. The resulting voltage is converted to a constant current and switched to the selected pressure control valve using a relay. Seven of the eight bits that are input as the status and valve position indicators are output to drive the light emitting diodes (LED's) on the front panel of the electrical control chassis and the valves and relay in the pneumatic control chassis. The PSI/PSF bit replaces the manual/remote signal to make a total of eight bits used on the output port. Five of these signals are sent to the pneumatic control chassis to actuate the solenoid valves.

The pressure request and the mode select display are both five digit plus sign BCD LED displays. The decimal position changes as the requested units of pressure change. The resolution of the each display is 0.001 PSID or 0.1 PSFD. A total of eighteen bits are required to display the full range of the instrument (+/- 2175.0 PSFD or +/- 15.100 PSID). Three additional bits are needed to indicate the sign and decimal position.

CHAPTER 3

HARDWARE DESCRIPTION

Introduction

In order for the pressure controller to provide all necessary features, the instrument was designed as a microprocessor-based system. Since the frequency response of pressure systems is relatively low, an eight bit microprocessor is sufficient for all operations. The STD BUS interface was chosen because of the availability, reliability and variety of controller and input/output boards.

Processor Card

The processor card that was chosen has an 8085A CPU operating at a frequency of 6.25 MHz. The 8085A CPU is an industry standard 8-bit microprocessor. The CPU has five interrupt inputs. The three maskable interrupts are accessed by a connector on the front edge of the card. The non-maskable interrupt, PBRESET, and the low priority INTR each have a designated pin on the STD BUS connector. A second connector on the card edge allows for user access to the serial input and output ports of the 8085A.

The 8085A can access 64K bytes of system memory. The purchased CPU contains sockets for 32K byte storage capability. The on-board memory devices installed in the four 28 pin sockets on the card may be 8K by 8 bit random access memory, RAM, or read only memory, ROM, devices. On-board jumpers are used to determine what type of memory device occupies each socket. The memory can be either in the lower 32K byte or the upper 32K byte region that can be addressed by the 8085A CPU. Also, the 8085A CPU can output data to any of 256 eight bit output ports and access data from up to 256

eight bit input ports. The card needs only 5 VDC power for operation and automatically executes the embedded control program upon power up. This card has two layers and conforms to all STD BUS specifications in size and construction [4].

Input/Output Cards

Input/output cards are needed to read operator inputs, remote command and feedback pressure. They are also needed to output data to the local displays, control solenoid valves and to operate the pressure control valves. Four I/O cards perform the instrument functions. Two of the cards have four 8-bit input ports and four 8-bit output ports. These ports occupy four consecutive I/O addresses and can be remapped in increments of four over the full I/O address range. The other two are utility I/O cards having over 17 square inches of wire wrapping area. The utility I/O cards have input and output port strobe logic as well as all the necessary STD BUS buffering and decoding logic. These cards have I/O capability that occupies eight consecutive I/O addresses and can be remapped in increments of eight.

Each input/output card reads four 8-bit TTL buffered inputs. The input port is read by a non-inverting, tri-state octal buffer. Each bit is conditioned by a Schmitt trigger that provides 200 mV of hysteresis in order to reduce noise. Also, each input bit is connected to a 4.7K Ohm pull-up resistor. The pull-up resistor ensures that the input goes to a valid TTL level when the input line is open and reduces noise as well.

Each card also has four 8-bit latched outputs. The output bits are non-inverting and can drive 20 LSTTL loads or 5 TTL loads [5]. Upon power up or PBRESET, the output bits are simultaneously set to the TTL low (logic 0) state. This sets all valves to their power-off state and sets a 0 mA control current.

Pressure Transducers

Three pressure transducers are available for use as the feedback device. One switch selects between two analog feedback transducers. A second switch enables the user to select the working standard as the feedback device instead of an analog transducer. The analog transducer located in the pneumatic control chassis is referred as the local transducer. The second analog transducer is referred to as the ESP transducer.

The analog transducers use a variable capacitor to detect changes in pressure. This sensor is fabricated in the shape of a ceramic capsule. The capsule deforms proportionally to the pressure difference applied between the reference port and the reference pressure is directed inside the capsule and the feedback pressure surrounds the capsule. As the input pressure increases, gold electrodes inside the sensor move closer together changing the capacitance. This change in capacitance is converted to a linear voltage by a charge-balance signal conditioning circuit. The principles used during construction give negligible common mode pressure effects up to 200 PSIG line pressure.

The transducers are compatible with all non-corrosive gases used for pressure calibrations and can be subject to pressures of 45 PSID without significant changes in the calibrated output. The frequency response of the transducer is approximately 20 Hz. The combined hysteresis, non-linearity and repeatability errors are less than 0.1% of full scale output and the output noise is less than 0.5 mV. The accuracy of the analog transducer is specified as $\pm 0.05\%$ of full scale pressure [6]. The transducer can be maintained to this accuracy by trimming the zero and the span potentiometer located behind access holes in the transducer housing. The construction of the sensor together with the quality of internal components allow the transducer to reach these accuracy specifications upon power up while providing excellent long term stability. These transducers are rugged enough to

withstand the temperature and vibration found inside transonic wind tunnels with little degradation of the output signal.

Both analog transducers require 22 to 30 VDC excitation and provide a high level, -5 VDC to +5 VDC differential output for a -15 PSID to +15 PSID input pressure. The low side of the excitation is usually grounded. The signal range normally varies from 2 VDC to 12 VDC above the low side of the power supply. Variance in the output voltage on some transducers can range as high as 5 VDC to 15 VDC above ground. Voltages in this range would require the receiving electronics to have higher common mode voltage rejection capabilities, but if the signal low line is grounded and the power supply is allowed to float, the output signal will remain in the range of -5 VDC to +5 VDC referenced to ground.

The transducers are equivalent to four-terminal devices; therefore, both analog transducers cannot be excited by the same power supply when the signal low side of each is grounded. Errors in the signal output are avoided by grounding only one of the signal low connections at a time. A four-pole double throw relay in the pneumatic control chassis multiplexes the analog feedback signal to the A/D input circuitry. When the relay is energized, the ESP feedback transducer is selected.

The third feedback transducer is the working standard differential pressure transducer. Working standard feedback is enabled by selecting a switch on the electrical control chassis. This transducer is normally used to determine calibration coefficients of test peculiar transducers and to confirm the accuracy of other working standard pressure transducers located throughout the facility.

The working standard differential pressure transducer uses a stable fused quartz bourdon tube to sense the input pressure [7]. Some of the properties of a fused quartz bourdon tube include stability, high elasticity, low hysteresis and strength. The helix

shaped bourdon tube is surrounded by the reference pressure as shown in Figure 3.1. In order to measure differential pressures accurately, the reference pressure should be maintained at a pressure less than the input pressure. The reference and the input pressure must be externally switched with automatic switching solenoid valves to measure input pressures lower than the normal reference pressure.

The bourdon tube unwinds while expanding as the input pressure increases. A curved mirror welded to the end of the bourdon tube reflects the output from a high power LED to a pair of photodiodes mounted side by side. A change in pressure deflects the mirror causing the reflected light source to move. The photodiode signal conditioning circuit outputs an error signal when the system is not balanced. The error is used to alter the DC current through two force balancing coils. These coils are positioned in a field of permanent magnets that are anchored to bourdon tube. The force generated by these coils creates a radial force to counteract the mirror deflection. The system is in equilibrium when the torque generated by the force balance coils is equal to the force generated by the input pressure.

The current that maintains the system in a null position is passed through a precision resistor. The resulting analog voltage is input to a digital voltmeter. The input range of this signal varies from 0 volts at 0 PSID to 10.0000 volts at full scale pressure. The digital voltmeter employs a integrating A/D converter to provide a voltage indication approximately two and one half times a second.

This working standard differential pressure transducer has a parallel BCD output that is input to a STD BUS TTL compatible I/O card. This digital output is then used without adding any additional error since the digital output is not subject to zero shifts or other problems associated with analog feedback signals. The pressure data requires three input bytes as shown in Figure 3.1. The output of the working standard differential

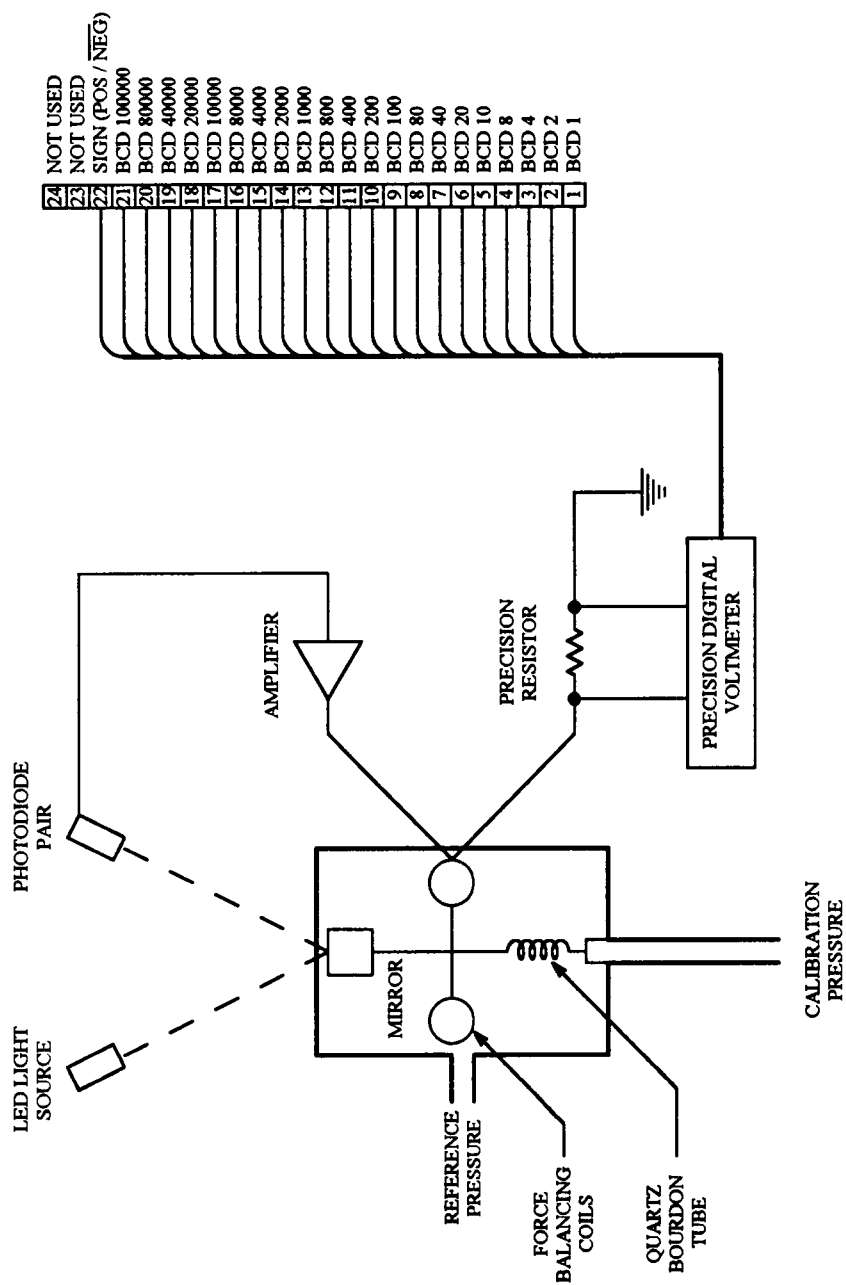


Figure 3.1. Working Standard Operation and Output

pressure transducer is scaled from 0 to 100% of full scale (FS). The full scale pressure is 2500 PSFD (100,000 counts); therefore, the resolution of the digital voltmeter is 0.025 PSFD/count (0.000174 PSID/count). The accuracy of the differential pressure working standard is quoted as $\pm(0.004\% \text{ FS} + 0.008\% \text{ RDG})$. This is the working standard by which most facility and test article transducers are calibrated.

Keypad Decoder and A/D Converter Card

When in the manual mode of operation, all pressure requests are made using a sixteen button keypad. The keypad functions as an array of single pole single throw switches in a 4 x 4 arrangement. A special function component designed specifically for these keypads is used to decode the active button and is located on a wire-wrapped STD BUS utility I/O card with the A/D converter. The schematic of the keypad and decode circuit is shown in Figure 3.2.

The device interfaced to the keypad is a MM74C922 key encoder [8]. The encoder circuit on the chip contains pull-up resistors and can be used with switches exhibiting as much as 50,000 Ohms (50K Ω) resistance. Two external capacitors are needed to enable the device to perform as required. A 2.2 micro farad (μF) electrolytic capacitor is used to debounce the keypad. The keypad has less than 4 mS bounce when pushed and less than 10 mS bounce when released. A 0.01 μF ceramic capacitor was used to set the rate of 5 KHz at which inputs from the keypad are scanned.

The MM74C922 has five outputs. Four tri-state outputs, A, B, C and D, are needed to indicate which button has been pressed. Their output is continuously active by setting the output enable (OE) pin to a low logic level. The output for the button pushed is the binary equivalent of the button number. An additional output is required to indicate when a button is being held down. This output is known as the data available (DAV) bit

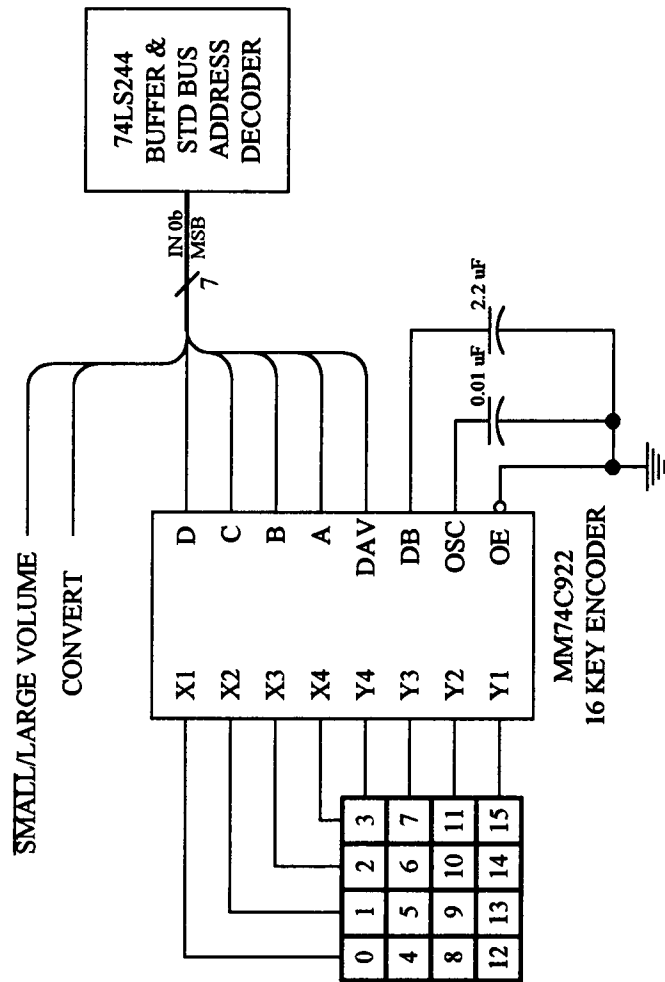


Figure 3.2. Keypad Decoder Schematic

and goes to a TTL high level when an entry is made. The DAV output returns to a low level when the button is released. If a second key was pressed before the first was released, the DAV signal will return to the high level after the normal debounce period. This enables a feature known as two key roll over to be utilized by the control program.

Data from either analog feedback transducer is electromechanically switched and input to the signal conditioning circuit on the front end of the A/D converter. The circuit consisting of an instrument amplifier, a low pass filter and a sixteen bit A/D converter is shown in Figure 3.3. This circuit is adjusted to accept input voltages from -5.100 VDC to 5.100 VDC without saturation.

The A/D converter is input to the STD BUS by connecting the lower eight bits to one octal tri-state buffer and the upper 8 bits to a second buffer. These signals are input to the CPU by connecting the outputs of each buffer to a buffer supplied on the utility I/O card and are read sequentially as inputs 8 and 9. The A/D converter is activated by reading input 10 (0A hexadecimal). This causes the CPU to read to generate an A/D start pulse via an address decoder chip supplied on the utility I/O card. This start signal (input 0A) is inverted before it is input to the A/D converter in order to set it to the normally off state. Each read pulse is approximately 390 nanoseconds (nS). This time exceeds of the minimum of 100 nS required to start the A/D converter. The A/D converter busy signal is input to the CPU together with the keypad signals by reading input 11. The A/D converter requires approximately 35 microseconds (μ S) to complete one conversion; therefore, data acquisition rates in excess of 28 KHz are possible with this device.

The instrument amplifier used is an AD524C [9]. It is used to condition the signal from the selected analog feedback transducer. The signal low input is connected to power supply ground in order to set the normal input range to -5.0 VDC to 5.0 VDC. This device is configured as a unity gain buffer and has a DC accuracy specification of 0.02%

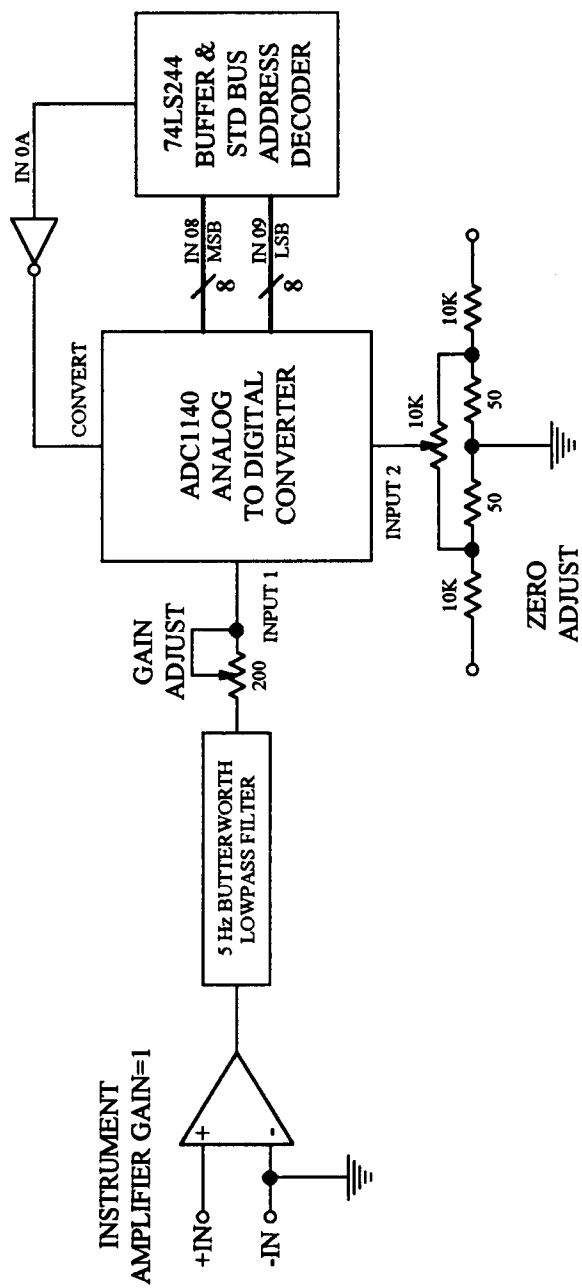


Figure 3.3. Analog Transducer Input Circuitry

or better. The effects of temperature will add no distinguishable errors to the signal and the offset voltage is less than 50 μV . The power supply used by this device and all other analog semiconductor devices is $\pm 15 \text{ VDC}$.

The second stage of the input voltage circuit shown in Figure 3.4 is a second-order lowpass Butterworth filter. This filter has a maximally flat amplitude response with a fairly steep rolloff to the stop band. It reduces conversion errors by limiting the rate of change of the signal to the A/D converter. It is a two-stage active filter using passive components and two operational amplifiers (op-amps). The ADOP27EN op-amp [9] was chosen due to its very low noise and low offset characteristics at a gain of one. Any offset errors generated in this stage are nulled at the input to the A/D converter. The corner frequency of this filter was set to 5 Hz. The resistor and capacitors were determined [10] is as follows.

$$\omega^2 = \frac{1}{R1 \cdot R2 \cdot C1 \cdot C2} \quad (3.1)$$

$$\text{where } \omega = 2 \pi f \quad (3.2)$$

The capacitance of C1 and C2 was chosen to be 0.47 μF . The damping factor, ξ , for a Butterworth response is 0.707.

$$0.707 = \frac{1}{2} \sqrt{\frac{R2}{R1}} \quad (3.3)$$

Substituting back into equation 3.3 yields a value for R1 of 47.889 $\text{K}\Omega$. The closest available metal film resistor is 47.5 $\text{K}\Omega$. R2 was chosen as a 95.3 $\text{K}\Omega$. Using these values, the frequency response is calculated to be 5.033 Hz nominally. Offset voltage caused by bias current drift through R1 and R2 add negligible errors over the operating temperature range.

By setting the frequency response of the input signal to the A/D converter to 5 Hz one can attain high accuracy without a sample and hold circuit. Very accurate sample and

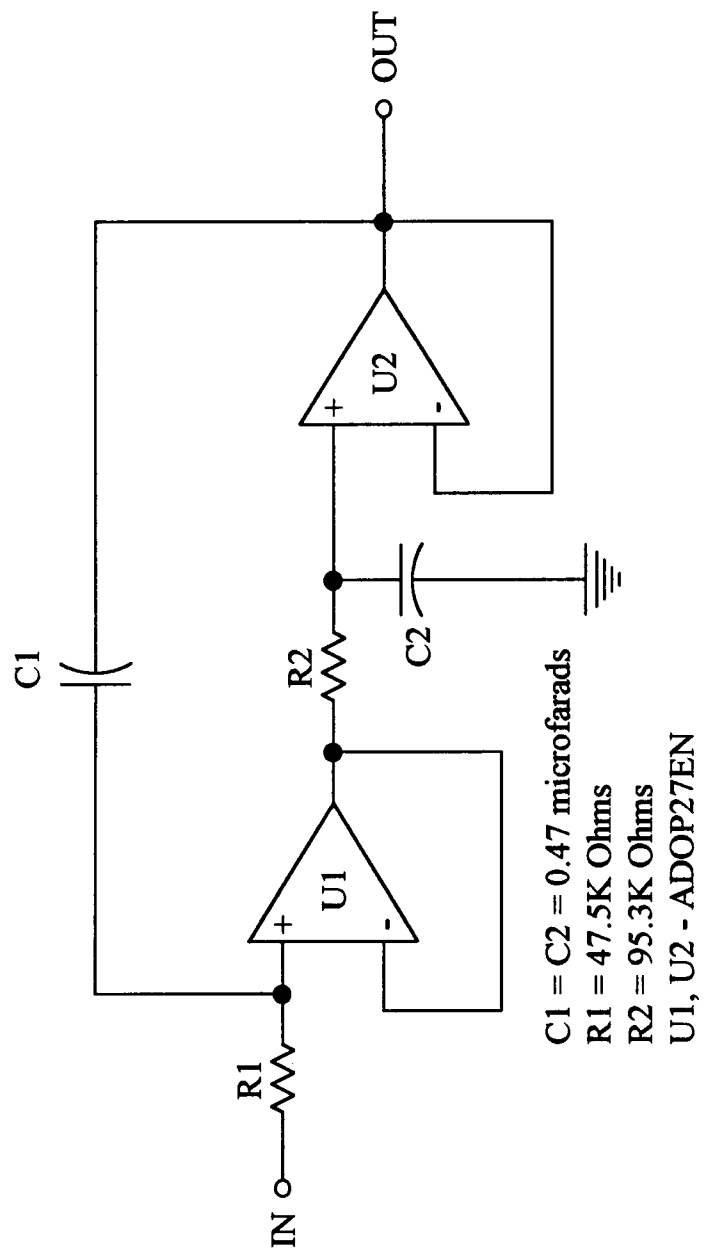


Figure 3.4. Second Order Butterworth Filter

hold devices cost a considerable amount and will add some error to the voltage conversion, but the filtering approach is not without its shortcomings. The main deficiency is that the A/D converter will not begin to approach its full capability of resolving dynamic signals, but the response of a pressure line is usually well under 1 Hz. The only other problem is that there may be a voltage change during the conversion process. The worst case error caused by fluctuations in the input signal can be easily calculated using the following relationships [11]. A sinusoidal signal is given by:

$$V = A \sin(\omega t) \quad (3.4)$$

The maximum value of $\frac{dV}{dt}$ occurs at $t = 0$ and is given by

$$\frac{dV}{dt}(\max) = \omega A \cos(\omega t)|_{t=0} = \omega A \quad (3.5)$$

Equation 3.5 gives an approximation of the maximum rate of change for the signal at the output of the filter. The result of equation 3.5 is 157.4 volts per second when using a 5 Hz filter. An amplitude change of 5 volts corresponds to a full scale pressure change. In this case the input signal would change only 5.5 mV during the 35 μ S needed by the A/D converter to complete a conversion. A more likely maximum error would be lowered significantly due to the frequency response of the feedback transducer. If an instantaneous pressure change of 15 PSID were present at the feedback transducer, a 5 volts change would be seen at the input of the filter circuit in approximately 200 mS because the time constant for a full scale pressure step change is estimated at 50 ms. In either case, the resulting error would mean little because the A/D would be able to read the pressure with a high enough accuracy for the pressure control algorithm to control the pressure to a stable value.

The analog pressure transducer can have several millivolts of zero offset error and the output voltage at full scale pressure can vary as well. It was determined that the voltage conversion system must be capable of higher adjustments than normally provided by the A/D converter. The A/D converter is configured in the bipolar mode with the input range from -5V to +5V. The gain potentiometer (Figure 3.3) attenuates the input signal as resistance is increased because the circuitry internal to the ADC1140 [12] A/D converter acts as an adder (Figure 3.5). The A/D converter can be set to saturate at input levels from 5V to 5.2V with a 200 Ω potentiometer. The potentiometer is set at its midpoint, 100 Ω , and the A/D converter saturates at ± 5.1 V, approximately ± 15.3 PSID. The data from the A/D converter is adjusted to account for this attenuation in the control program. This allows for some variation in the analog transducer output to be easily accommodated while using most of the resolution of the A/D converter.

The on-chip reference voltage supplied by the A/D converter is connected externally to REF IN. This voltage is used as the internal reference for the successive approximation circuitry in the A/D converter. The on-chip reference voltage is externally connected to Input 3 as well. Since the supplied zero offset input is not used, it is grounded. Input 2, which for an input from -5V to +5V is normally grounded, serves as the input for the zero offset circuit. The voltage injected at this point has one-half the effect of the signal voltage at Input 1. Since the voltage range presented by the resistive divider shown in Figure 3.3 is ± 75 mV, the zero adjustment range of the A/D converter is approximately ± 37 mV when accounting for the source resistance of the zero circuit. The inputs of the A/D converter can be used in several ways; therefore, the device is very versatile and can be tailored for many special applications.

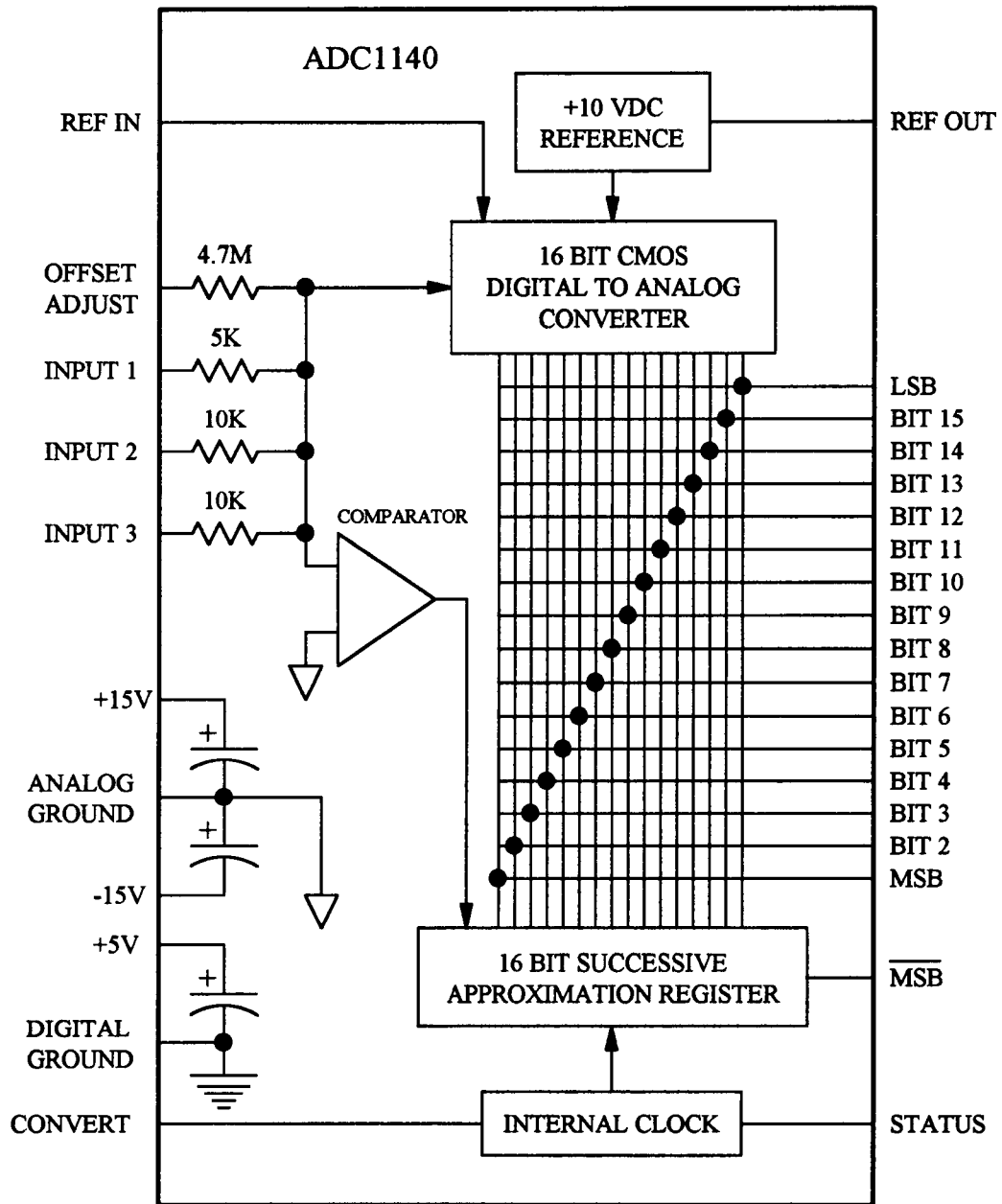


Figure 3.5. A/D Converter Schematic

Pressure Control Valve

Two types of pressure control valves were examined during the design process. The flapper-nozzle servo pressure controller (pressure servovalve) was chosen over the on/off solenoid operated pressure control valve. The on/off solenoid operated pressure control valve requires complex pulse width modulation to meter a precise volume of gas into the calibration manifold, but the pressure servovalve requires only simple proportional control (DC current). Additionally, the pressure servovalve continuously supplies gas to the calibration manifold. This constantly corrects for changes in volume or temperature. One shortcoming of the pressure servovalve is the requirement of a continuous supply of gas. This is not a problem when the control range is relatively low (pressures less than 30 PSIA) and a continuous supply of filtered house air is easily obtained. Pressure servovalves have been used in the AEDC wind tunnel facilities for over ten years without a failure. This was the deciding factor in the selection process. Details of the pressure servovalve will be discussed in Chapter 4.

Valve Control and D/A Converter Card

All the necessary components for digital to analog conversion, voltage to current conversion, valve and status indicator control were incorporated on one STD BUS utility I/O card. The voltage to current (E/I) converter is required to set the position of the flapper in the pressure servovalve. The control voltage is calculated by the pressure control routine in the main control program. Since the instrument was required to set and maintain pressures to very stable set points, a sixteen bit digital to analog (D/A) converter was used to provide a signal with high resolution to the E/I converter.

A D/A converter with an output voltage range from -10 volts to +10 volts was needed to control the E/I converter. User adjustment for offset and gain errors was also necessary on the device. The overall accuracy needed was 0.05% of reading or better with a settling time of 10 μ S or less. An Analog Devices ADDAC71-COB-V [12] was chosen to interface to the microprocessor and met the analog requirements. The pressure control word is calculated in the main program and is in a 16 bit two's complement format. The control word is converted to a complementary offset binary format and output to the D/A converter by writing to outputs 9 (LSB) and 10 (MSB). The bytes are held at this level by the octal latches until a new control word is output. All output ports are loaded with zeros if power is lost or the CPU is reset. This adds some degree of safety to the system since this will set 0 volts on the output of the D/A converter and the resulting pressure will be less than 5 PSID.

The output of the D/A converter is input to the E/I converter shown in Figure 3.6. The circuit is designed to provide a constant current through the pressure servovalve coil and the pressure servovalve will maintain a very stable pressure if the control current does not change. Design considerations of this circuit are presented in Chapter 4. Constant current operation is important because large input currents will cause the temperature and resistance of the coil to increase. It may take several minutes for the temperature of the coil to stabilize following a large change in commanded current.

Seven of the toggle switches located on the electrical control chassis are connected to the same STD BUS utility I/O card containing the D/A converter. Two of the switches control the selected feedback transducer and the final switch selects the manual or remote mode of operation. The switch selection is input to a circuit (Figure 3.7) which selects either the information from the switches or from the STD BUS output. The signals from the switches are disabled when the remote mode of operation is selected because the

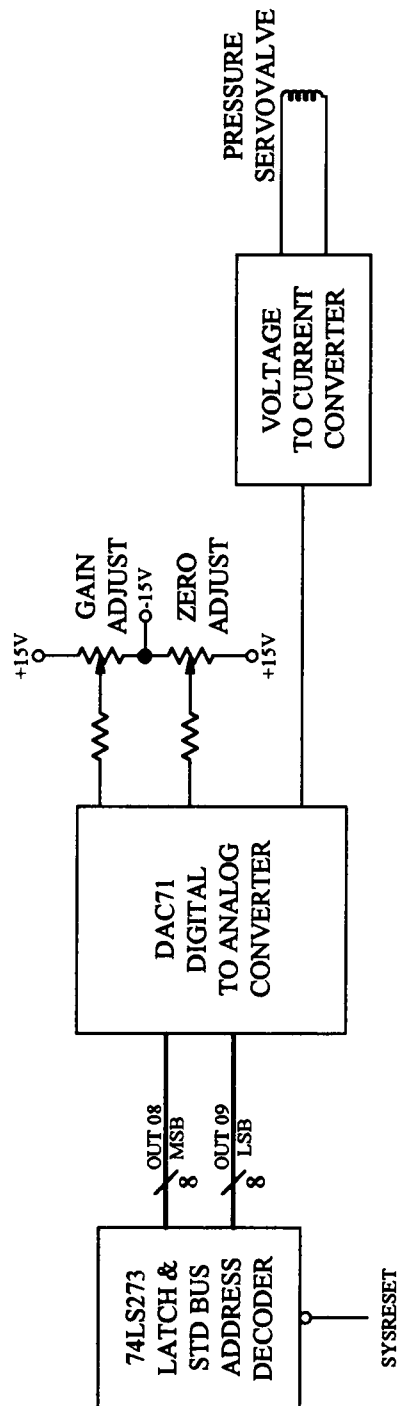


Figure 3.6. D/A Converter Schematic

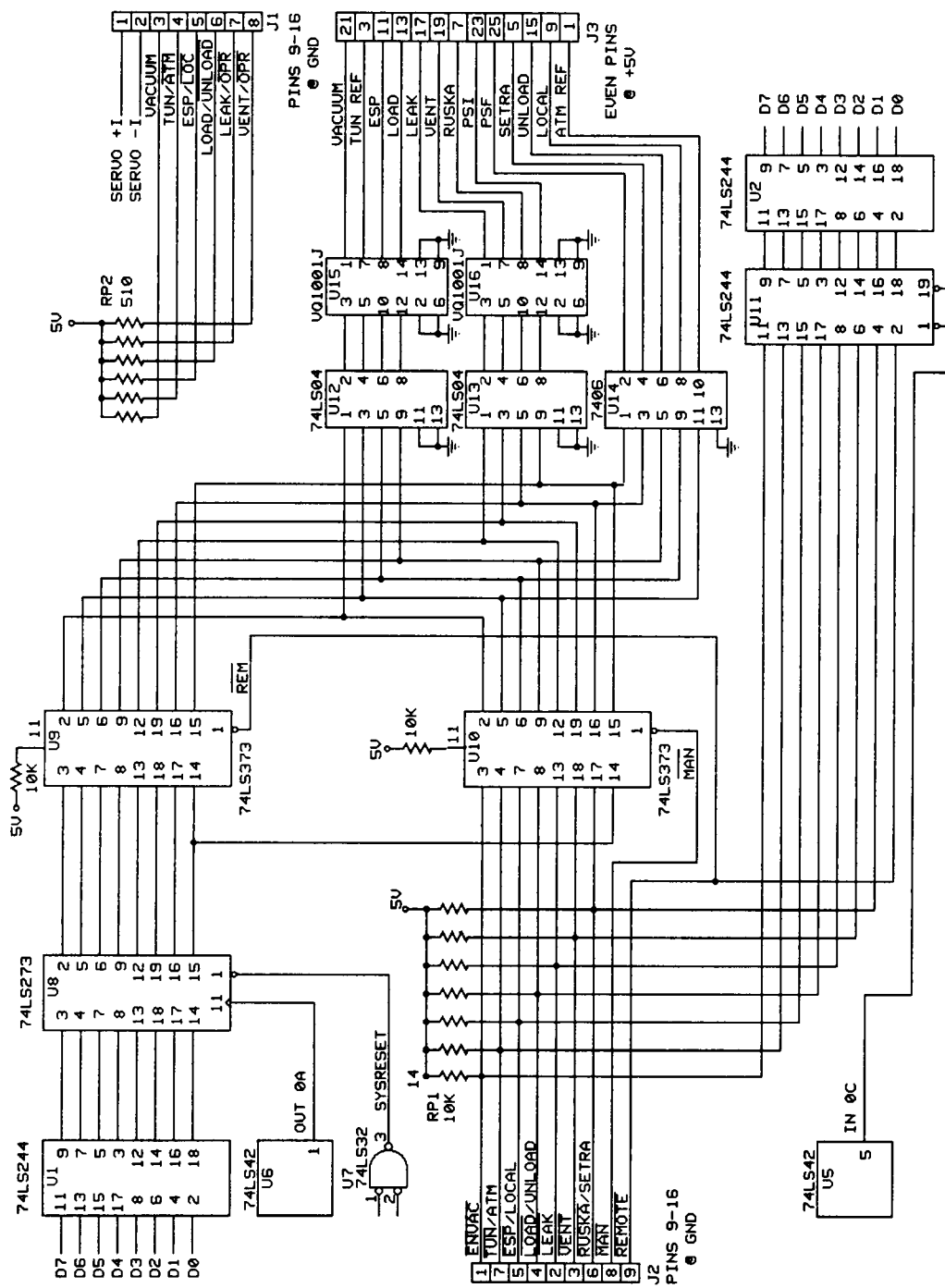


Figure 3.7. Units, Feedback and Valve Select Schematic

information for the valve position is input from the remote parallel input. Only the PSI/PSF bit is obtained from the STD BUS interface in either case. This is because the displayed units are program determined after a button is pressed on the keypad.

The output of the multiplexing circuit controls a device that is used to energize a solenoid coil by connecting it to ground as shown in Figure 3.8. The function is performed using a VQ1001 [13], n-channel enhancement mode metal oxide semiconductor field effect transistor, MOSFET. This device can be considered to be TTL compatible in this circuit configuration because the device will pass a drain current, I_D , no higher than 10 μ A when the gate to source voltage, V_{GS} , is 1.2 volts or less and the drain to source voltage, V_{DS} , is 5 volts. If V_{GS} exceeded the TTL high level threshold voltage of 2.4 volts, the allowable drain current would exceed 75 mA. This is substantially more than enough to sink the current necessary to operate the display LEDs.

The thirteen light emitting diodes on the front panel of the electrical control chassis that can be controlled from the remote interface are switched to ground using two VQ1001 chips and a 7406 open-collector hex inverter [5]. The Hewlett-Packard HLMP-3600 LEDs [14] are used because they have integral resistors that limit current to 12 mA when used with 5 volt power supplies. A 510 Ω resistor is connected in parallel to a display LED in order to supply the current to an optocoupler located in the pneumatic control chassis. Since the LED and the resistor are connected in parallel, both devices must use the same power supply. A total of six resistors are used in this manner to drive the optocouplers used to actuate the five solenoid valves and the feedback relay. The additional current load is less than 7 mA and is easily handled by the MOSFET.

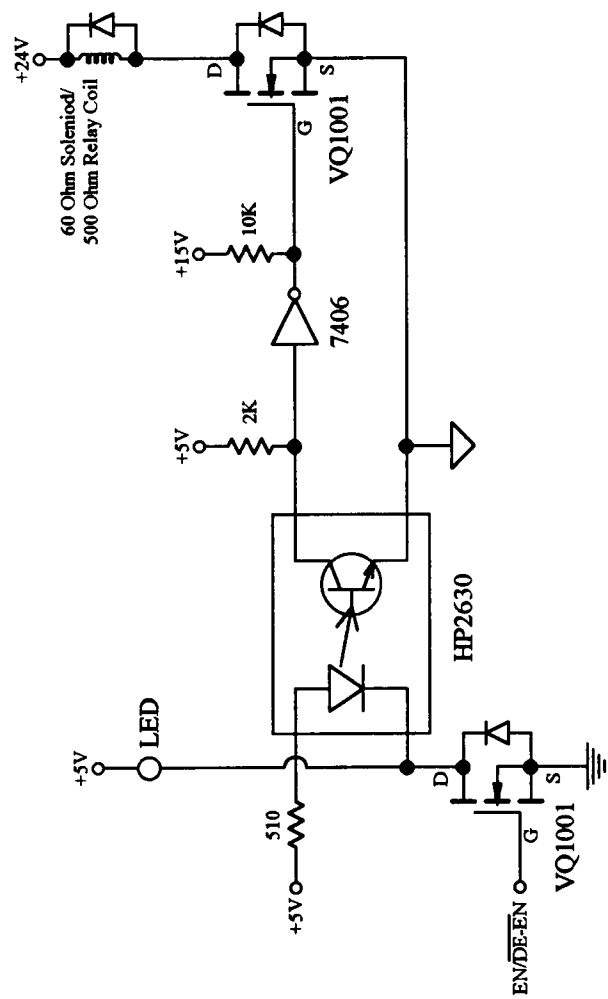


Figure 3.8. Valve and Relay Power Schematic

Solenoid Valve Control Card

Each valve and the analog feedback transducer relay is actuated by an optically isolated circuit located in the pneumatic control chassis as shown in Figure 3.8. Each circuit uses an n-channel MOSFET on a VQ1001 to switch the load to ground. All valves return to the normally closed (safe) position when power is lost in either chassis or if the cable is disconnected.

The optocoupler is a Hewlett Packard HP2630 [14] two channel device that provides electrical isolation between the electrical control chassis and the pneumatic control chassis. It can operate at speeds up to 10 MHz and is TTL compatible. Long cables can be used to connect the two chassis because the maximum resistance, R_{MAX} , of the cable is calculated to be 170Ω when used with a 5 volt power supply, V_S .

The optocoupler operates in a negative true logic mode. The output of the optocoupler is in the off state until the input current is provided to the optocoupler LED. The output signal is pulled to a TTL high level and is inverted with a TTL compatible open collector inverter to give a positive true logic. The output collector is connected to a $10\text{ K}\Omega$ pullup resistor which is connected to a 15 volt power supply. By placing 15 volts at the input MOSFET, the resistance from the drain to source, R_{DS} , is set very near its lowest attainable value. Since the pneumatic control chassis might be located in a low pressure environment, it is important that the power dissipation be low because the convection cooling would be substantially reduced.

The solenoid valves have a 60Ω coil designed for operation with a 24 VDC power supply; therefore, it requires about 400 mA to actuate the valve. The power dissipation of each circuit is approximately 136 mW at these conditions. The feedback select relay requires only 48 mA since its coil has a typical resistance of 500Ω . Up to 30 VDC at a continuous drain current of 830 mA may be used to actuate the valves or relay without

reaching the minimum breakdown voltage of the VQ1001. Although the device is rated for 1.3 watts per circuit, the overall power dissipation of the chip should be limited to 2 watts. All parameters are well within operating specifications, but only two MOSFETs are used per chip in case low pressure or high temperature environments are encountered.

Power Requirements

A single output +5 volt power supply and two dual output +/-15 volt power supplies are installed in the electrical control chassis. The +5 volt supply is an open frame linear power supply. It has an output that can be adjusted between 4.75 and 5.25 volts which is set to +5 volts for TTL logic operation. The overall RMS noise level on the supply is less than 25 mV. The current that can be supplied is 6.0 amps, but the maximum required is less than 4.3 amps. The average operating current was measured as 3.1 amps during checkout. The majority of the current is needed to drive the LED displays on the front panel and to supply the five STD BUS cards. All installed components were either TTL compatible CMOS devices or LSTTL devices to minimize the required current.

The power required by the analog circuit components and the pressure servovalve will vary with input voltage and pressure setpoint, but neither the +15 VDC or the -15 VDC line on the power supply should exceed 150 mA. A modular 200 mA linear power supply was installed to meet this requirement. This power supply has 0.02% or better line and load regulation with excellent long term stability. The overall maximum ripple and noise is specified as 0.5 mV RMS. The actual output current was measured between 80 and 120 mA. A 100 mA power supply with the same characteristics as above is installed in the electrical control chassis to excite the two analog pressure transducers. This power supply is allowed to float as a single ended +30 volt supply since the signal low output is grounded. Less than 25 mA is needed to power the two analog transducers .

A single triple output power supply with outputs of +5, +15 and -15 volts is installed in the pneumatic control chassis. The opto-coupler output and valve switching circuits require very little operating current since the power supply for the solenoid valves is located externally. The maximum amperage required of the 24 VDC power supply is approximately 2.05 amps. Values less than 1 amp will be required because it is unusual to energize more than two solenoid valves simultaneously.

CHAPTER 4

CONTROL METHODOLOGY AND TIMING

Introduction

The characteristics of the pressure servovalve and a description of the hardware and methods used to operate the device are presented in this chapter. The pressure servovalve works in a manner such that general nozzle equations accurately predict its overall behavior. The design of a constant current power supply used to achieve the required stability and the data acquisition methods using instrumentation interfaced to the STD BUS are presented. Also, the methods used by the digital control algorithm to set the requested pressure quickly and accurately with various pressure systems is presented.

Control Valve Characteristics

The flapper-nozzle pressure servovalve is used to provide the pressure output needed to calibrate test article and test facility pressure transducers. Figure 4.1 shows the construction of the pressure servovalve [15]. The supply pressure is input to the metering area and a vacuum evacuates the area. The metering area is lengthened or shortened by the movement of the flapper. The flapper is a rigid metal beam that is the opposing end of the armature. The pivot point of the beam is located above the metering area and below the permanent magnet and coil structure. The armature/flapper is attached to a heavy torsion spring under which a compressible O-ring is seated. The O-ring prevents gas from entering the magnet and coil area. Although very limited angular deflection is possible at the pivot point, the flapper can be positioned through its full range of travel with a +/- 25 mA power supply.

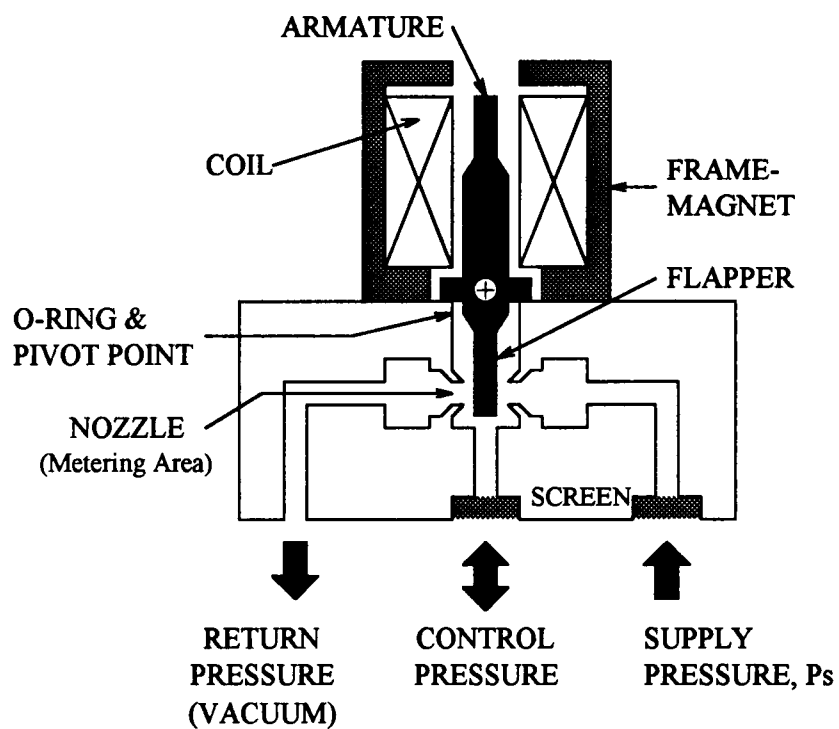


Figure 4.1. Schematic of Flapper-Nozzle Pressure Servovalve

The calibration gas is supplied at a constant pressure to the pressure servovalve by a pressure regulator with an attached moisture and oil filter assembly. This gas passes through the nozzle that is a cylindrically shaped variable flow restriction. The gas is evacuated by the vacuum pump connected to the nozzle exit. The flapper is positioned by changing the control current to the coil. The pressure servovalve will maintain a very stable pressure if the control current, supply pressure and return pressure are all stable. As the control current changes, the flapper is positioned to allow more or less of the supply gas into the calibration (control pressure) line.

Pressures equaling the supply level or vacuum level cannot be reached with a flapper-nozzle pressure servovalve because there is pneumatic leakage in these devices. The pressure servovalve will usually output pressures to within three percent of the supply pressure. Since the required pressure output range is from 1 PSIA to approximately 30 PSIA, the leakage presents no problems. A supply pressure of approximately 42 PSIA is used; therefore, an output pressure of about 40 PSIA can be reached. The maximum output pressure of 40 PSIA corresponds to a differential pressure of about 25 PSID. This pressure is safe for most pressure transducers since they can be subjected to an 300% over pressure with no permanent damage. In fact, with large volumes to be filled it is desirable to maximize the output pressure. Commanding a full scale pressure allows the vacuum pump to evacuate little gas from the metering area; therefore, more gas is directed to the calibration line. When the pressure in the calibration line has reached the desired level, the flapper would be moved to the calculated position for the desired control pressure.

The flow capabilities of the pressure servovalve can be estimated by the general nozzle equations if the geometry of the metering area is known. It is important to know the flow capabilities of the device in order to determine an appropriate pressure control algorithm. Other factors that affect the total weight flow rate are the temperature of the

gas, the upstream pressure and the downstream pressure. The standard conditions of sea level pressure, 14.7 PSIA, at 59 degrees Fahrenheit, 518.67 degrees Rankine, will be used as the flow reference. The general equation for weight flow, W , is expressed as [16]

$$W = \frac{K \cdot P_s \cdot A \cdot N \cdot C_d}{\sqrt{T}} \quad (4.1)$$

The units of weight flow are pounds per second. The values from which this term is calculated are expressed in dimensions of pressure in pounds per square inch, area in square inches and temperature in degrees Rankine. The factor K is dependent on the gas constants for the media used in calibrations. For air, the value K equals $0.5318 \sqrt{^\circ R} / \text{sec}$. The supply pressure, P_s , is set at 28 PSIG with a hand operated pressure regulator. This pressure can be estimated to be 42.7 PSIA when the value of 14.7 PSIA is used for the standard atmospheric pressure. The nozzle discharge coefficient, C_d , is dimensionless and is a correction factor that must be applied to all nozzles. The annular metering area is best described as a square edged orifice and C_d has been verified by the manufacturer to be approximately 0.85 at several test conditions.

The nozzle can best be described as the outer portion of a tin can with the ends removed. The area in square inches is then

$$A = \pi \cdot d \cdot l \quad (4.2)$$

The diameter of the nozzle is 0.11 inches and the metering area in 0.006 inches in length. The surface area of the nozzle in the fully open position is 0.0021 square inches.

The term N is determined from the pressure ratio of the nozzle upstream pressure, P_s (or the supply pressure), to the nozzle discharge pressure (or the control pressure). N is used to correct the weight flow calculation and is equal to one until the ratio of the supply pressure to the control pressure is 0.5283 or greater when air is used. The values of N used to adjust the normalized weight flow at a pressure ratio is shown in Figure 4.2.

The value 0.5283 is known as the critical pressure ratio for air. When the nozzle discharge is at a vacuum, the pressure ratio approaches zero and the gas can travel through the nozzle faster than the speed of sound. In this instance the nozzle is said to be choked and the weight flow is constant when the nozzle is choked because the pressure of the gas decreases with increased speeds encountered at lower ratios. The velocity will be the speed of sound or greater until the critical ratio is encountered. At the critical ratio the velocity will be no greater than the local speed of sound. The curve begins moving downward at the critical ratio as the discharge pressure increases. During these conditions, the nozzle is said to be unchoked. The velocity of the gas through the nozzle continuously decreases until the pressure ratio equals one. At a ratio of one, there will be no flow because the discharge pressure equals the upstream pressure.

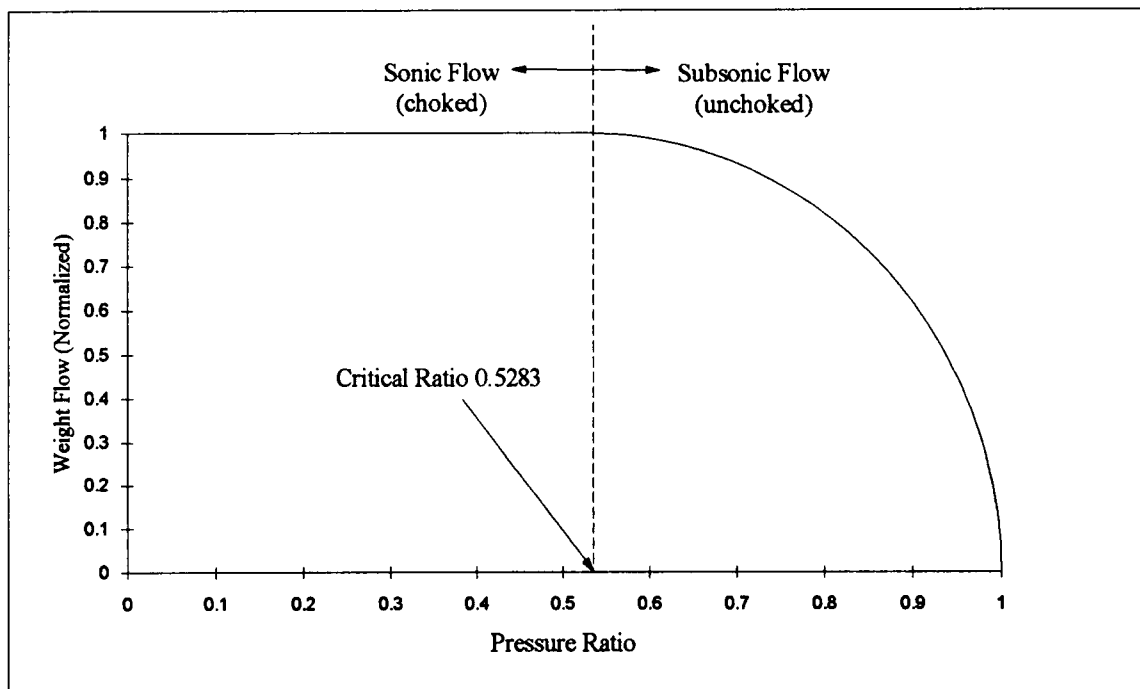


Figure 4.2. Weight Flow Versus Pressure Ratio

The critical pressure for the pressure servovalve at standard pressure and temperature is approximately 22.6 PSIA or 7.9 PSID. The weight flow can be assumed to be constant if the nozzle is fully open and the control pressure is less than 7.9 PSID. At this pressure the flow begins decreasing slightly until the weight flow is reduced by about six percent at a control pressure of 15 PSID (ratio of 0.7). This reduction is so small that the weight flow may be assumed constant for pressure increases over the entire operating range. The nozzle should be fully open until the setpoint is reached when large volumes to be charged are present and the new control pressure is an increase over the previous pressure. The weight flow characteristics for charging a volume are seen in Figure 4.3.

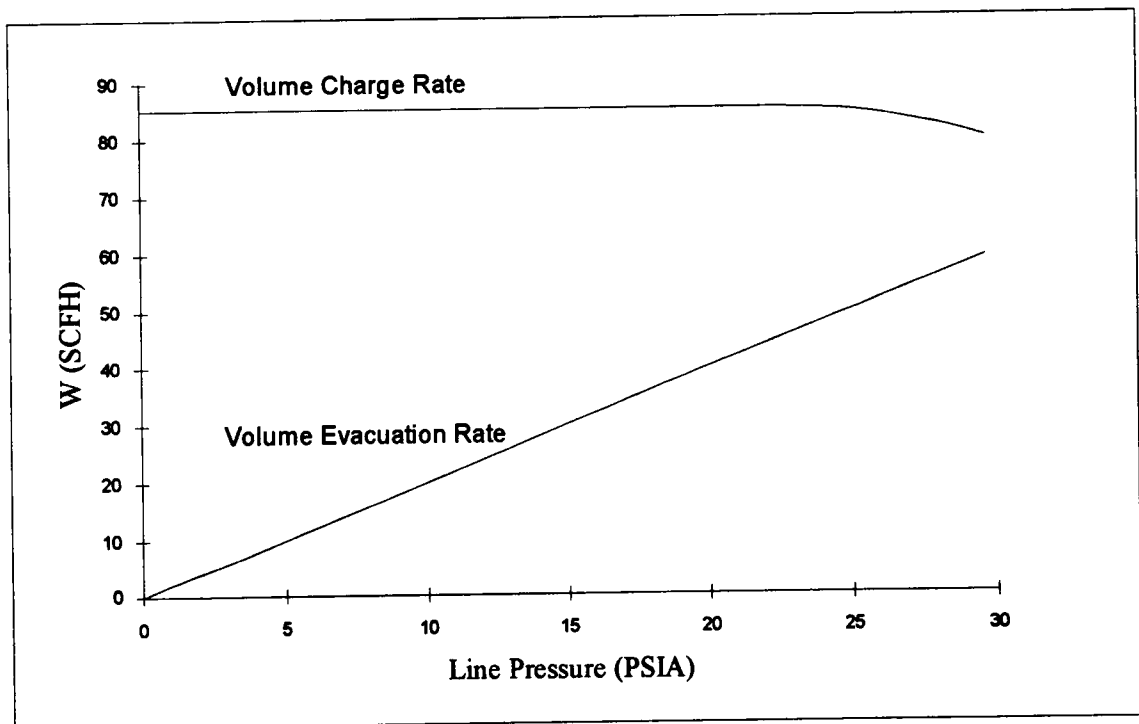


Figure 4.3. Weight Flow Versus Control Pressure

Figure 4.2 is also used to estimate weight flow for decreases in pressure, but the control pressure becomes the supply pressure and the vacuum pressure becomes the discharge pressure in the weight flow and ratio calculations. The typically used vacuum pump can evacuate 500 to 1,000 cubic feet per hour, CFH, and is insensitive to the line pressure; therefore, the vacuum line is always at a low pressure. The nozzle is assumed to be choked continuously because the pressure ratio will be low. The weight flow will be reduced, however, since the upstream pressure is continually decreasing. For example, if a pressure request of -12 PSID is made from an initial 0 PSID setting, the initial upstream pressure on the nozzle is atmospheric pressure. At this time the weight flow will be approximately two-thirds less than that of a positive increase in pressure because the supply pressure is reduced from 42.7 PSIA to 14.7 PSIA.

The weight flow for discharging a volume is about one third that of charging a volume as shown in Figure 4.3 at a pressure of 14.7 PSIA. Since gas is proportionally less dense at low pressures when the temperature is held constant, setting pressure at the low end of the control range does not require an excessive amount of time. The upstream pressure will continually decrease as the control pressure approaches the setpoint and the weight flow will be proportional to the control pressure. In fact, since the line pressure decreases at the same rate as the nozzle upstream pressure, the volume displacement is nearly the same at any control pressure.

From equation 4.1 the maximum weight flow is calculated to be $1.757 \cdot 10^{-3}$ lb/s or 6.326 lb/hr at standard conditions. At standard conditions air weighs $7.418 \cdot 10^{-2}$ lb/ft³; therefore, the maximum rate the pressure servovalve can charge a large volume at standard conditions is $2.37 \cdot 10^{-2}$ ft³/s or 40.93 in³/s. Similarly, the nominal evacuation rate is 14.1 in³/s if the supply pressure is assumed to be at atmospheric pressure. The manufacturer specifies the pressure servovalve to have a flow rate of 82 standard cubic

feet per hour, SCFH, for positive flow. This compares favorably to the calculated output of 85.3 SCFH using the theoretical equations. Calculations using local atmospheric pressure and temperature instead of standard conditions can easily be made, but the difference in flow rates will usually be negligible.

Voltage to Current Converter

The constant current supply needs to meet several important requirements. The E/I converter must supply the control current needed to position the flapper through its full range of travel. Also, the E/I converter must provide an output that will drive a long cable without oscillating. Finally, the E/I converter must provide a stable output current and be insensitive to load changes. Heating effects cause the resistance of the coil to drift as shown in Figure 4.4; therefore, constant current control is used.

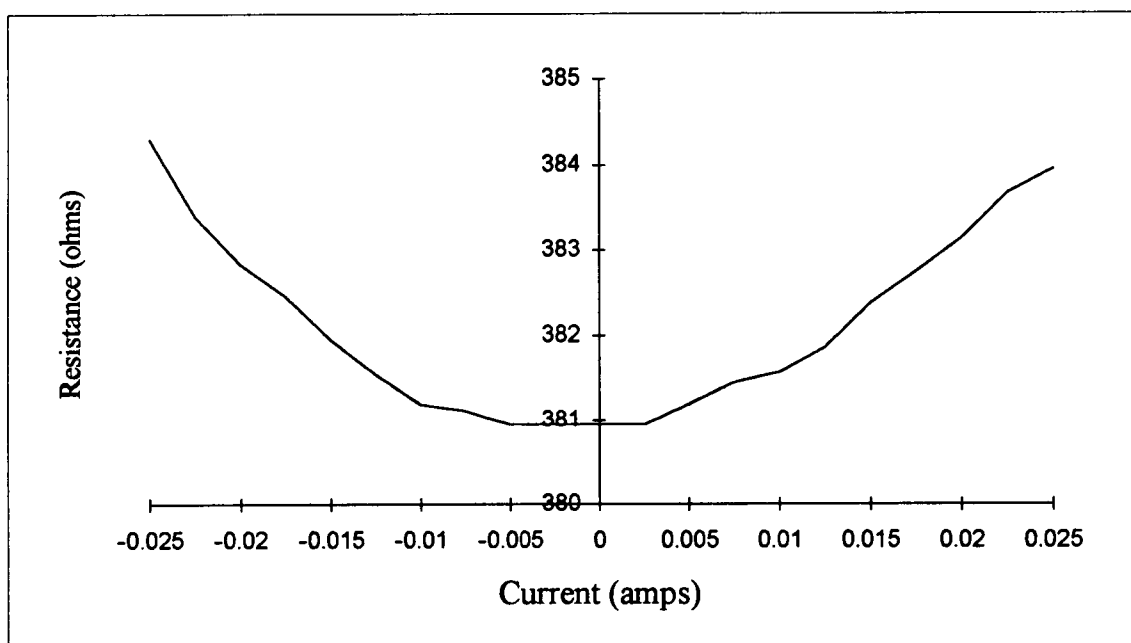


Figure 4.4. Pressure Servovalve Coil Resistance Versus Control Current

The pressure servovalve is rated for input current ranging from -25 mA to 25 mA. The circuit that performs this function is shown in Figure 4.5. The constant current supply was designed to convert an input voltage of 1 volt to 2.5 mA because the D/A converter supplies a control voltage ranging from -10 volts to +10 volts. The transadmittance is determined by the gain of the instrument amplifier and the value of the current sense resistor, R_s . Since resistor conversion is the basis for voltage to current conversion, the stability of the circuit is primarily affected by the temperature stability of R_s . Also, the stability of the voltage from the D/A converter affects conversion accuracy. Since the accuracy requirements of the pressure controller is stringent, great care was taken in designing the E/I converter to be insensitive to load changes.

It is important to use a resistor that will not heat significantly when shunting the control current. A relatively low voltage is developed by the current through R_s when a low valued resistor is used. This enables the use of a small precision resistor having a low power rating. Also, using a small valued resistor will not significantly reduce the voltage compliance of the circuit. Assuming a typical full scale output supplied by the buffer chip, U3, of +/-12 volts, the maximum resistance that the circuit can operate with is 480 Ω . Since the coil resistance of the pressure servovalve is nominally 385 Ω and R_s is 40 Ω , the maximum cable resistance is 55 Ω . This is approximately equal to a 1500 foot cable having #22 AWG conductors. Since the power used by R_s at full scale current is only 25 milliwatts, mW, a low power shunt resistor may be used.

The outer feedback loop of the circuit returns the output voltage of the instrument amp, U4, to the inverting input on U1. The voltage, V_{OUT} , seen at the output of U4 is

$$V_{OUT} = 10 \cdot R_s \cdot I_s \quad (4.3)$$

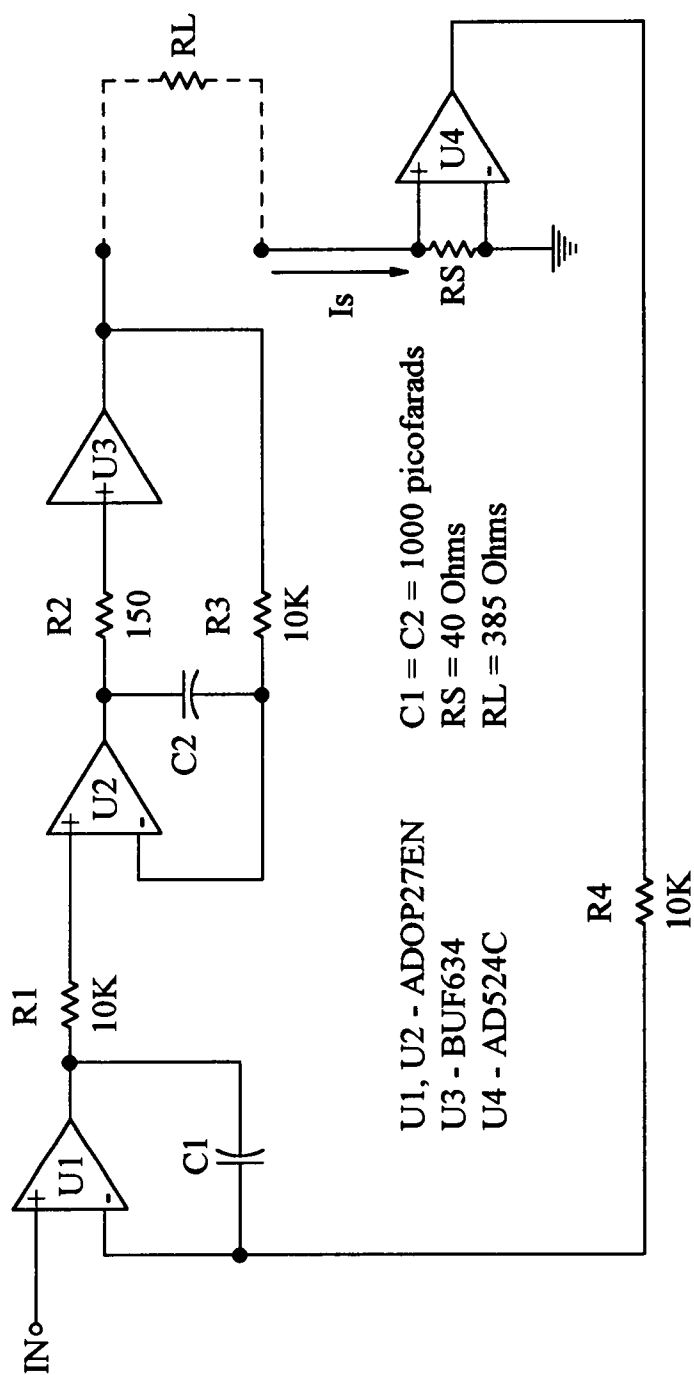


Figure 4.5. Voltage to Current Converter Schematic

Feedback forces the voltage difference between the two inputs of op-amp, U1, to be approximately zero volts while accommodating all load voltages that will normally be encountered. If a 1 volt control voltage from the D/A converter were present at the non-inverting input on U1, a current of 2.5 mA through R_s would be generated because the output of the op-amp will change in order to place the two inputs at the same potential.

A Burr-Brown BUF634 [17] was chosen for the buffer chip because it has built-in short circuit protection and will supply ± 250 mA when used with a ± 15 volt power supply. This device has built-in short thermal shut-down and an internal current limiting circuit. It also has a frequency response of up to 180 megahertz, MHz; therefore, the chip is bypassed at the power pins with 10 μ F tantalum capacitors in parallel with 0.01 μ F ceramic capacitors to assure stable operation at high frequencies.

The buffer chip is connected to an internal feedback loop with the op-amp, U2, to provide a unity gain buffer circuit. By using an op-amp in this configuration, any offset or non-linearity of the buffer chip is virtually eliminated. The reduction of offset voltages by a factor equaling 125 dB is realized because any offset voltages would be effectively reduced by a factor equal to the open loop gain of the OP27.

The capacitor, C1, is necessary to insure the stability of the op-amp buffer circuit. Any oscillations occurring at this point can be eliminated by adding a small valued capacitor, 0.001 μ F or less. This capacitor adds a zero that cancels the pole introduced by the feedback resistor and the input capacitance of the op amp. A second compensation capacitor, C2, is used in the outer feedback loop to prevent oscillation at the output of U1. By properly selecting the compensation capacitors, stability can be ensured by placing the second pole very close the unity loop gain crossover. This circuit operates at frequencies much higher than the 200 Hz frequency response of the pressure servovalve. The response was measured and found to be flat to frequencies up to 1 KHz. The overall

frequency response of the circuit is dependent on the characteristics of the cabling connecting the two chassis, but the operation should exceed the response of the servovalve.

The capacitive load presented by typical twisted pair wire ranges from 30 picofarad per foot , pF/ft, to 50 pF/ft. A typical installation might require a length of 200 feet. If the capacitance were 50 pF/ft the total load capacitance, C_L , would be 0.01 μ F. In order to drive the cable it is important to limit the frequency response of the buffer chip to levels that will prevent excessive output currents. The maximum slew rate that the BUF634 can achieve with a particular load capacitance can be calculated from

$$I_L = C_L \frac{dV}{dt} \quad (4.4) [17]$$

It is desired to keep the output current less than 250 mA. If the load capacitance is 0.01 μ F the maximum safe slew rate is calculated to be 25 V/ μ s. The slew rate of the OP27 output is 2.8 V/ μ s when a 2 K Ω or greater feedback resistor is used; therefore, the BUF634 should remain in the safe region for driving dynamic loads. Low capacitance cable should be used when there is a long distance between the electrical control chassis and the pneumatic control chassis to insure proper operation. If desired, this circuit can be adapted for driving higher frequency signals by maintaining a small load capacitance and replacing U1 and U2 with high frequency, unity gain stable op amps.

This E/I converter has the benefit of providing isolation between the electrical control chassis and the pneumatic control chassis while providing the accuracy and stability needed to control the pressure servovalve. Precautions have been taken to insure stability at all setpoints and there is sufficient drive capability to insure voltage compliance in most installations. Also, this circuit can be adapted to meet many constant current requirements, including high frequency and high power applications.

Feedback Transducer Data Acquisition

Since flexibility was a main concern of the pressure controller design, all data parameters must be made available to the control logic. Also, the digital output from the working standard is required in order to obtain high accuracy. Both of these requirements are met by using a microprocessor for all data acquisition, calculations, control and display. It was determined that a fairly slow update rate would be acceptable because the response of the calibration line is usually several seconds or more; therefore, a fairly slow processor could be utilized without significantly increasing the calibration time.

After the pressure controller software was written and debugged, the program loop period was found to be either 145 or 160 mS depending on the selected feedback transducer. When the working standard is used for pressure control, the data loop period was longer due to the necessary BCD to binary conversion.

A predictable loop time would give more repeatable control. The program loop time when using analog feedback was lengthened in order to use the same control constants during both control modes. Since reading the analog feedback transducer requires less time, three readings were made and averaged during each loop. Averaging decreases the error of the feedback signal which improves the pressure stability. After the conversion is initiated on the A/D, the processor is placed in an idle mode for approximately 3 mS. During this time, no activity is present on the data or address lines on the bus. This lowers the background noise in the system and causes the loop time to be almost the same as when using working standard feedback. The timing diagram for the analog transducer data acquisition is shown in Figure 4.6.

Digital data acquisition does offer many advantages. There would be no automatic calibration or zero offset without a microprocessor. The output of the working standard can be used without adding any additional error since the digital output is not subject to

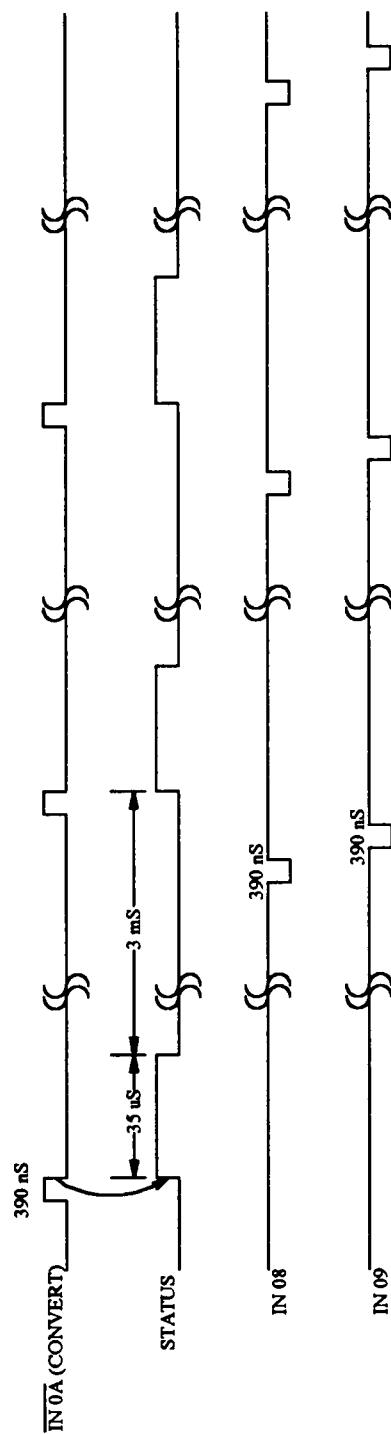


Figure 4.6. Analog Transducer Timing

zero shifts or other problems associated with analog feedback signals. The working standard can be monitored for safe input pressures and illegal BCD numbers. If an unsafe pressure is read the pressure controller automatically requests 0 PSID. If an illegal BCD number is read the last legal reading is used for calculations. Also, many display options are available with the addition of a microprocessor. Switch inputs can be read to change control modes or displays as required by the operator.

Control Algorithm Selection

The pressure control circuitry could be composed entirely of analog components when using an analog feedback transducer, but the digital output of the working standard is used to set most calibration pressures. Since the analog transducer can be trimmed to provide high accuracy, the A/D converter would not be needed for analog control. Also, the bandwidth of the pressure controller would be significantly increased and the pressure settling time could be possibly be decreased. However, some form of digital feedback and control would be best suited to control the output pressure in this design because flexibility and accuracy provided by using the output of the working standard outweigh added costs.

The addition of a microprocessor allows for complex control algorithms, but extensive calculations require more processor time. Since an 8 bit microprocessor was chosen, the control algorithm must be efficient if a fast loop time is to be implemented. It is possible to design a control algorithm for a fixed volume, but the calibration volumes connected to the pressure controller vary.

When the supply pressure is restricted by a control device and there are no flow restrictions in the line, the time necessary to set a pressure is nearly independent of the lag

time. If the temperature is held constant the time to charge a fixed volume from a known starting pressure to a different pressure can be estimated using the ideal gas laws.

$$P_1 V_1 = P_2 V_2 \quad (4.5)$$

The total internal volume, V_1 , of a 100 foot, 3/4 inch diameter tube connected to a 100 foot, 1/4 inch diameter tube is approximately 470 in³ using equation 4.5. The internal diameter of 3/4 inch pressure tubing is 0.68 inches and the internal diameter of 1/4 inch pressure tubing is 0.19 inches. When the 3/4 inch tube supplies the 1/4 inch tube, the lag time is less than 0.5 seconds for an input pressure to reach 26.99 PSIA from a starting pressure of 14.7 PSIA [2].

$$V_1 = \frac{l_1 \cdot \pi \cdot d_1^2}{4} \quad (4.6)$$

If 40.93 in³/s, M, gas were input to the line, a pressure of 26.7 PSIA, P_2 , would be reached in the time calculated using equation 4.6.

$$t = \frac{V_1(P_2 - P_1)}{M \cdot P_1} \quad (4.7)$$

The time necessary to increase the pressure in a 470 in³ volume by 12 PSI from an initial atmospheric pressure is approximately 9.4 seconds. This calculation was made assuming a constant flow rate of 82 SCFH. The time necessary to decrease the pressure in a 470 in³ volume by 12 PSI from an initial atmospheric pressure is approximately 27.2 seconds. This calculation was made assuming an initial flow rate of 29.4 SCFH.

The previous calculations indicate that the time required to set a pressure is a function of the volume of the tube and not the transmission characteristics of the calibration line and gas. These data supply the required information to implement a control algorithm. Using the full output available from the pressure servovalve was the approach used to set pressures. The output curve of the pressure servovalve is shown in Figure 4.7.

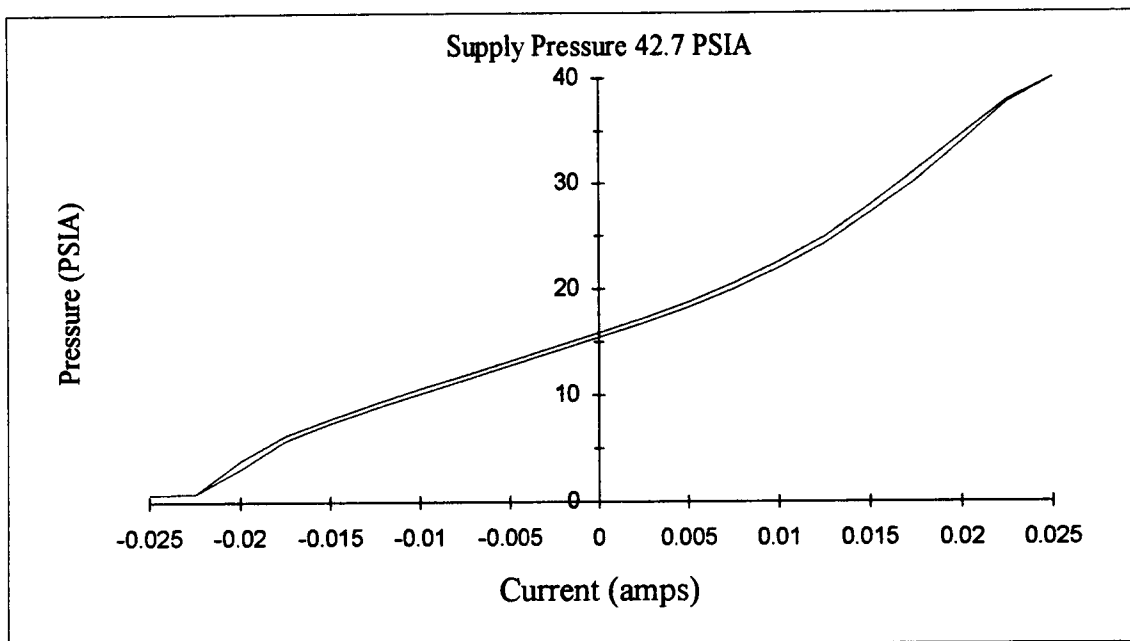


Figure 4.7. Pressure Servovalve Output Pressure

Although the pressure servovalve has a stable output if the supply pressure and the control current are fixed, the output is not repeatable because of the hysteresis of its coil. The pressure servovalve exhibits approximately 0.5 PSI deadband between ascending and descending pressures and an expression for the output characteristics was not derived. The data at each calibration point for both ascending and descending pressures were averaged and a single plot was obtained.

The data appears to be an odd function of current except for a constant offset; therefore, an odd order least squares polynomial fit should describe the data. Several order polynomials were evaluated and a third order fit was chosen. The largest residual occurring with this curve fit is approximately $100\mu\text{A}$. The main source of error in this data fit is induced by the hysteresis of the servovalve. The expression used to calculate the proportional term is shown below.

$$I_{OUT} = a_0 + a_1 \cdot P_{REQ} + a_2 (P_{REQ})^2 + a_3 (P_{REQ})^3 \quad (4.8)$$

$$a_0 = -5.6656 \cdot 10^{-3}$$

$$a_1 = 1.2572 \cdot 10^{-3}$$

$$a_2 = 1.8081 \cdot 10^{-6}$$

$$a_3 = -1.0887 \cdot 10^{-7}$$

P_{REQ} is the required pressure. The pressure units are expressed in PSID and the current is in amps.

This fit is calculated from data recorded during checkout. The result of the curve fit is multiplied by a term necessary to convert the calculated number to a two's complement 16 bit binary number. The resulting binary number is converted to the equivalent offset binary number and output to the D/A converter. The curve fit is typical of this particular model pressure servovalve, but may differ significantly between units. As expected, the second order term contributes little to the calculation of the control current because the shape of the curve indicated an odd function.

Automatic zero correction can be insured by using proportional plus integral control. Integral control adds a percentage of the error between the output pressure and the commanded pressure to the previously calculated integral term. The integral term is initialized to zero and the proportional term is recalculated after each new pressure request. The error will eventually be forced to zero because the integral term continually adjusts the control current until the pressure settles.

Since it may take some time for the pressure to reach the desired setpoint, the control current will likely reach the maximum allowable value before the setpoint is reached. This condition is known as reset wind-up and will usually cause excessive oscillations in the output pressure because the integral term must be adjusted from the maximum level. By the time the integral term returns to zero the pressure has gone well

beyond the setpoint. The integral term will then adjust to counter this offset. Eventually the pressure will stabilize, but the time required to set a pressure is excessive.

The problem of oscillations is greatly reduced by a simple process. When a new pressure is requested, the integral term is set to zero and only the proportional value is output. Subsequent loops are processed and a portion of the error is added to the integral term. The integral portion of the control current is large at this time because the error is large. When the output pressure reaches the requested pressure, the integral is reset to zero. The integral is then readjusted as necessary to maintain the setpoint. The integral portion of the control current is small at this time because the error is small. There is some overshoot at the source when setting pressure with this approach, but overshoot helps to pressurize the entire calibration line.

An optimized integral constant can be calculated for a particular pressure installation, but it is easier to find a usable expression by testing the device. During the checkout of the pressure controller, a switch was used together with test peculiar programming to vary the integral term. All of the daily calibrations and pressure checks were performed using different integral values. Values of the integral term ranging from 1 percent to 50 percent of the pressure error were studied on different calibration lines and it was found that no one value would give good pressure control for all situations.

There were two basic types of calibrations performed daily. The most common type of calibration is setting pressure on many transducers simultaneously. The volume is large in this case. The other type of calibration is setting pressure on one transducer which is pneumatically connected to the calibration manifold by a tube having no other connections. The volume in this case is considerably smaller. From the average calibration times of each type of calibration, an average constant for large volumes and an average

constant for small volume was determined. The switch used to vary the integral term was then used to indicate the presence of a small or large volume.

The value used for a small volume is 10 percent of the pressure error. This constant is multiplied by the first order constant from the pressure servovalve curve fit. The result is stored as data and multiplied by the pressure error. The current calculation is summed with the previous calculations to provide constant correction. This value will cause the control current to increase slightly during the execution of each program loop. After the pressure has been reached, the integral term is set to zero and fine tuning about the setpoint occurs. Very little fluctuations occur after the final pressure has been reached because the control current changes little as the error approaches a small value. Unless the supply pressure to the servovalve changes or there is an abrupt change in temperature or volume, the pressure will be maintained. If the volume switch indicates a small volume when there is actually a large volume present, the pressure will be reached more slowly and slowly changing oscillations will occur until the output pressure stabilizes.

The value used for a large volume is 25 percent of the pressure error. This value will cause the control current to increase more rapidly. The control current will quickly reach the maximum output and remain there until the pressure is reached. Conditional statements in the pressure control subroutine limit the integral portion of the control voltage to ± 10 volts minus the proportional value in volts. This is done to insure that the integral value will not reach unrealistic values. When the requested pressure has been reached, the integral value is set to zero. If the volume switch indicates a large volume when there is actually a small volume present, the pressure will be reached more quickly and the output pressure will usually exhibit small rapid fluctuations.

The ESP calibration manifold normally has a small volume. When pressure control using ESP system feedback is selected, the integral constant is the same as the constant

used for a small volume. The proportional term may be calculated with a different data fit because the output characteristics of the ESP system servovalve may differ. All other aspects of pressure control are identical.

It was discovered during testing that the term used for integral control should be different after the pressure has been reached. A large integral term is needed to speed the pressure setting, but a smaller value would make the fine tuning process free from oscillations. The method used to achieve rapid approach to the setpoint followed by a smooth ramp function from the peak overshoot value is as follows. After the setpoint has been reached and the integral portion of the output is set to zero, the integral constant is halved. Since the correction is made from an overshoot and the hysteresis of the servovalve takes some time to overcome, the integral term will normally be a non zero value. The control pressure is then reached with little or no overshoot because the calibration manifold pressure does not lag the feedback pressure by a large amount. The program structure for the control algorithm is shown in Figure 4.8.

The output pressure becomes more difficult to control at low pressures. The pressure changes much more rapidly with decreasing current at a pressure of 3.5 PSIA, -11 PSID, or lower. Since a small voltage change translates into a large pressure change at these setpoints, the output current must be adjusted slowly if the pressure is to be set without a significant overshoot. The integral constant must be lowered when pressures less than -11 PSID are requested. The program automatically sets the integral constant to 3 percent of the pressure error for any selected volume if a pressure less than -11 PSID is requested. This causes the setpoint to be reached more slowly, but oscillations are virtually eliminated.

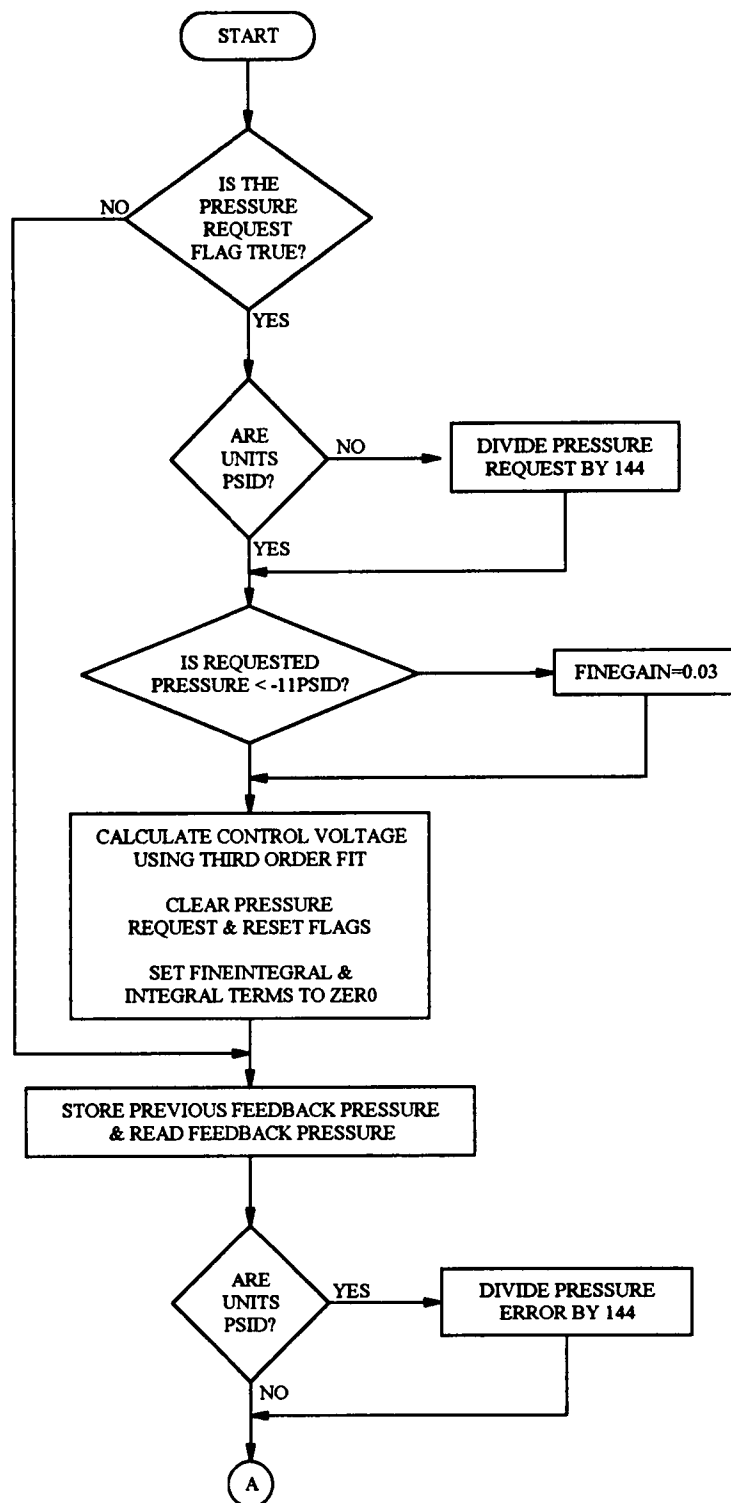


Figure 4.8. Control Algorithm Program Structure

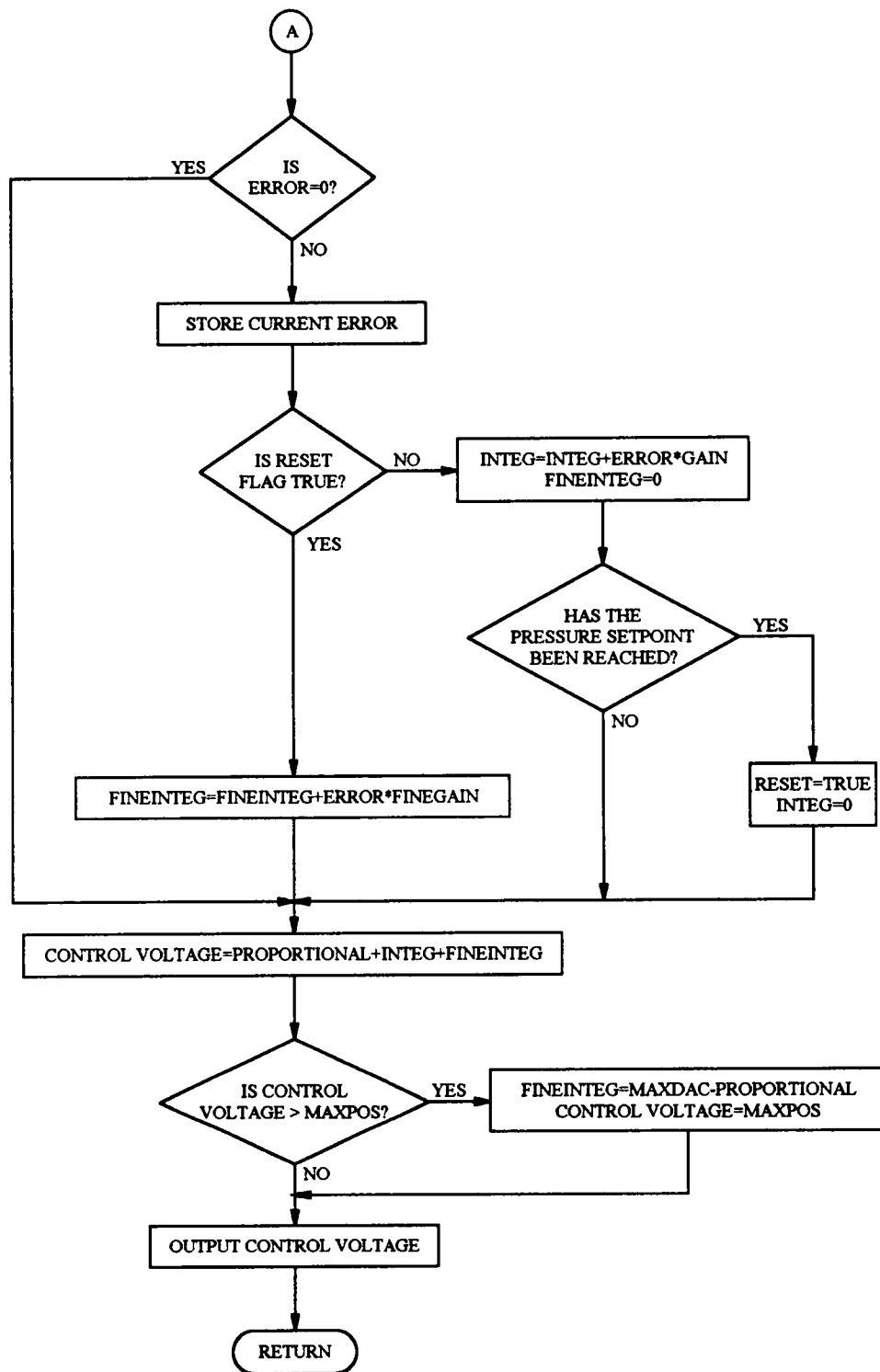


Figure 4.8. cont. Control Algorithm Program Structure

CHAPTER 5

SYSTEM SOFTWARE

Introduction

The operation of the pressure controller is directed from an operator or from a remote host. Many functions are contained within the program structure of the pressure controller. All input and output calls to devices interfaced with the STD BUS are made with subroutines written in 8085 assembly code. After the binary or BCD data is input to the processor, program statements written in Pascal manipulate the data. The format of the data is defined as double precision; therefore, no significant loss of accuracy occurs during processing. The results of the program are used to set the control current, drive the displays, control valves and change status bits. When necessary, these data are rounded to the nearest integer, converted to the required format and output to the display or control circuitry. All embedded programs reside in read only memory and the data and stack are stored in random access memory located on the CPU card.

Main program functions

Most features of the embedded program have been previously discussed. The main program was written using Pascal. This program is compiled, checked for errors, converted to 8085 assembly code and linked to the subroutines written in assembly code. The main program issues calls to subroutines written in assembly code for all input and output to the STD BUS. The program structure is shown in Appendix A.

The conditional branching capabilities of Pascal make the process of selecting the required tasks simple. Built-in safety features are incorporated within the program loop

and are executed immediately following detection. Pressures exceeding the input capabilities of the working standard are prevented from occurring and output pressures exceeding the input range of the A/D converter cannot be requested. The accuracy to which data is internally calculated enables stable pressure control. The capabilities of the program allow for complex control algorithms that increase the pressure setting speed. The many useful display functions are activated by a single rotary switch input to the program. Using a high level programming language simplified generating the assembly code necessary to operate the pressure controller.

Assembly code subroutines

Subroutines written in assembly code are used to input feedback pressure, switch positions, commands from a remote host and information from a keypad. These subroutines are also used to output data to the pressure servovalve control circuitry, actuate solenoid valves, display status information, output requested pressure and display feedback pressure. The following fifteen subroutines are called by the main program.

PSTART initializes the Pascal environment and directs the unmaskable interrupt to the first program statement. All other interrupts are disabled in this subroutine.

INISYS resets the pressure request display to zero. Zero PSID is requested and all display LEDs and valves are set to the default positions if the remote mode of operation is selected by the toggle switch. The default position of the valves are the power-off state. Analog transducer #1 is selected as the feedback device and the last used units are selected.

BINBCD converts a two's complement binary word to a five digit BCD number. This information is returned to the main program in two 16 bit words.

REQOUT outputs four BCD digits to the pressure request display. The sign and decimal point information are combined with the most significant digit and output as well.

FUNOUT outputs the feedback pressure or selected function display in the same manner as the pressure request is output.

GETVOL reads the volume switch and stores the data in memory.

PUSHSW reads the position of the valve and status control switches and stores the data in memory.

KEYPAD reads the keypad data. The data valid bit, DAV, is checked. If the DAV bit is not present, -1 is returned to the processor. This is stored in memory and used to compare with future readings. If DAV is present the last button position is read from memory and is compared with the current button. The subroutine determines if a new button has been pressed and the command is executed. This structure enables the program to read a button, process the command and ignore it on subsequent loops if it is pressed and held for an extended period. This structure also enables the reading of a different button on every loop.

LOADSW outputs the valve and status bits when the remote mode of operation is selected. The information requires eight bits and is used to actuate valves and to drive the front panel LEDs. The units bit is output with this subroutine for the manual as well as the remote mode of operation.

GETREM reads the commands from the remote host. The pressure requests are input in a BCD format requiring 16 bits. This information is stored in memory. If a status or valve change is requested the data is processed and LOADSW is executed.

RSETRA controls the data acquisition of the feedback transducer. The A/D converter is activated by reading input 10. The program delays for 3

mS and the data from the A/D converter is read by input ports 8 and 9 and stored in memory. The process is repeated two more times.

RRUSKA reads the working standard pressure transducer. The data is read as two 16 bits words and stored memory. The data is in BCD format and is converted to a real number by the main program.

ROTYSW reads the position of the rotary switch and stores the data in memory.

DACOUT outputs the calculated control voltage to the D/A converter. This data is converted from two's complement format to offset binary representation before it is output.

Memory requirements

The main program performs all high level decision making and mathematical operations, but all input and output activity is directed through the STD BUS backplane as directed by the subroutines written in assembly code. All programs are linked together and loaded into one Texas Instruments model TMS27C64-25 [18] 8K by 8 bit EPROM using a device programmer connected to a personal computer. The maximum EPROM access time of 250 nS allows the device to operate at faster speeds than the system clock and within the confines of the STD BUS protocol.

The main program is over 440 lines of code written in Pascal. This program is assembled and linked with approximately 350 lines of assembly code and the programs needed from the Pascal library of the development software to form an embedded program of approximately 7K bytes. Since the program is smaller than 8K byte, only one EPROM is required to store the embedded program.

All data and information loaded on the stack are stored in RAM. This data is stored in one Dallas Semiconductor DS1225AD-150 [19] non-volatile static RAM. The

device has a built-in voltage regulator that senses when the supply voltage falls below 3.0 volts and switches to standby power using a built-in lithium battery. The device functions properly with supply voltages from 4.25 to 5.5 volts, but when the supply voltage falls below 4.25 volts, data cannot be written to memory. During power-up, the internal battery is used for data retention until approximately 3.0 volts is reached. At this time the internal circuitry connects the external supply to the memory and disconnects the internal battery. Data is write protected until the supply voltage reaches 4.5 volts and normal operation resumes.

Memory retention of non-volatile static RAM is guaranteed for a minimum of ten years after initial use. This device functions in every way as a static RAM device with access times of 150 nS or less. This device is fully compatible with the STD BUS address timing and the system clock. Although 4K byte of area is available for data storage on the device, only 475 bytes are needed. The remaining 4K bytes of memory within the device is allocated to the program stack, but no more than fifteen bytes are ever used for this purpose.

Under half of the available on-card memory is needed to implement the capabilities of the pressure controller. Sufficient storage remains to further develop the firmware as required. The availability of the development software using Pascal allows the addition of any extra features to be made. Also, any other STD BUS hardware such as RS-485 or IEEE-488 communication cards could be added if needed. The open ended architecture of the pressure controller enables future revisions, including CPU upgrades, to be accommodated.

CHAPTER 6

PRESSURE CONTROLLER CHECKOUT

Introduction

The pressure controller was designed and fabricated in an instrumentation laboratory. Fabricated circuitry was calibrated and proper operation was verified. The circuits were found to function as expected. System software was then installed and the CPU was replaced with an 8085 emulator. The program was executed block by block and line by line as required. After some debugging, the pressure controller met all accuracy and stability requirements.

Initial Setup

All valves were actuated using the front panel switches. The keypad was operated and all functions were verified. The pressure controller was measured by a separate working standard and was found to output the requested pressure when any of the three available feedback transducers were selected. The remote interface was then connected to a switch bank and the pressure control function was requested. Operation was changed between manual and remote modes. The valves and status bits were selected individually to change their state using the remote interface. All front panel and remote commands performed as expected.

Calibration voltages were applied to the analog input test point and the A/D converter was adjusted to an accuracy of 1 mV using the A/D Volts option. The conversion accuracy of the A/D converter is shown in Table 1 in Appendix B. The D/A Volts option was selected and the D/A converter was adjusted to agree within 500 μ V of

a digital voltmeter connected to the control voltage test point. The pressure servovalve was connected to the circuit and the control current was read. The conversion accuracy of the D/A converter and the E/I converter is shown in Table 2 in Appendix B. The first column shows this control voltage to the E/I converter supplied from an external voltage standard. The second column shows the output current generated by the E/I converter. The last column shows the compliance voltage generated by the E/I converter with the pressure servovalve and a 60Ω series resistor in the circuit.

The pressure transducer in the pneumatic control chassis was set to zero by venting the calibration manifold followed by performing the Analog Transducer Zero option. Then, the transducer was calibrated against the working standard connected to the electrical control chassis. All zero and calibration constants were automatically stored in non-volatile RAM and were retained until future zero or calibration operations. The pressure controller was then able to display and control pressures within the specifications stated by the manufacturer.

The Feedback Transducer Leak Rate option was then verified by using a voltage source to simulate the analog transducer. The display is updated and data is acquired once every ten seconds when this option is selected. The leak rate calculation was verified by changing the input voltage after an update. The calculated leak rate would be displayed ten seconds later. Step voltage changes were applied and the expected leak rate pressure was calculated and found to be accurate within 0.25% for step changes of 1 V or more. The working standard leak rate calculation was accomplished using a switch bank to simulate a step pressure change.

The effect the Small/Large Volume switch has on the control voltage was measured using a digital storage oscilloscope. A voltage was input to the test point and a pressure was commanded. The initial control voltage output from the D/A converter was

found to equal the value generated by the pressure servovalve curve fit. The initial output voltage was measured. This voltage was found to be the proportional term of the control voltage output and the position of the volume switch was found to have no effect on this term, as required.

A pressure was commanded with the volume switch indicating a large volume. Since the input voltage was held constant by the voltage source, the error between the feedback and the setpoint was constant. The change in the control voltage following each program loop was recorded. Several program loops were executed before the control voltage saturated when the switch indicated a large volume. Each program loop produced the same increase in control voltage. A negative error was then simulated and several program loops were recorded. In each case the change between program loop updates was equal to the calculated integral value. A test was performed using identical initial conditions for a small volume. When the switch indicated a small volume, about twice as many loops were processed before the control voltage saturated. The control voltage was measured and the output was found to increase and decrease as expected.

Pressure Controller Benchmarks

After all features of the pressure controller program were found to function properly, the analog transducer was calibrated using the built-in features of the pressure controller. Following this calibration, the analog transducer was checked at various pressures versus the working standard. The results are shown in Table 3 in Appendix B. The accuracy of the analog transducer is within the specifications of the manufacturer, but more accurate and stable pressure control can be obtained using the working standard as the feedback transducer. Since no loss of accuracy occurs when using a digital output, the accuracy of the pressure controller is essentially the same as the working standard.

Stability checks were performed in the instrument laboratory and the pressure controller was found to output a stable pressure in any feedback mode. The instrument was then installed in the pressure calibration system. Significantly larger volumes were encountered in the wind tunnel installation and the integral constant in the pressure control subroutine was determined by the process described in Chapter 4.

Although the wind tunnel was a much different environment than the instrument laboratory, the stability of the pressure controller was not affected greatly. The deviation about the setpoint of the pressure controller in the field installation was measured as 0.0015 PSID when using the working standard as the feedback transducer. The deviation about the setpoint was measured as approximately 0.004 PSID when using the transducer in the pneumatic control chassis as the feedback transducer. The stability was nearly the same whether a large volume or a small volume was present on the calibration manifold, but the error recovery seen with a small volume was much faster.

The accuracy of the pressure controller is essentially the same as the accuracy of the selected feedback transducer. No loss of accuracy is added when using the digital output of the working standard and the A/D converter has better than twice the accuracy of the analog feedback transducer. The accuracy of the pressure controller when using the working standard is $\pm(0.0008 + 0.008\% \text{ Rdg.})$ PSID. The accuracy of the pressure controller when using analog feedback is ± 0.008 PSID.

The pneumatic control chassis was connected to a volume estimated to be 6000 cubic inches, the largest normally pressurized during daily calibrations and checks. All standard facility monitoring pressure transducers were pressurized to obtain this volume. A pressure of +10 PSID was commanded and the pressure was reached in approximately two minutes. The time required for the output pressure to stabilize within the measurement accuracy of the feedback transducer was approximately one minute. The

calculated time needed to fill the volume was approximately 104 seconds. A pressure of -10 PSID was commanded and the pressure was reached in approximately six minutes. The time required for the output pressure to stabilize was slightly more than two minutes. The calculated time needed to fill the volume was approximately 290 seconds.

The time required to reach the pressure was approximately 20 percent longer than the calculated time. No leaks were found in the pressure line, but the possibility of flow restrictions could not be eliminated. The additional time needed for the pressure controller to output a stable pressure was found to be directly related to the accuracy of the pressure servovalve curve fit at the control pressure. Other volumes ranging from 500 to 2000 cubic inches were checked with similar results.

A stripchart recorder was connected to the D/A voltage output and the A/D input voltage test points on the electrical control chassis. A fixed volume of 17 cubic inches was connected to the output pressure fitting on the pneumatic control chassis. The overall volume to be pressurized was estimated to be 20 cubic inches when accounting for the internal volume of the pneumatic control chassis. The control voltage that corresponded to a +15 PSID output pressure was commanded using the D/A Volts option. The output results are shown in Figure 6.1.

The time required to fill the volume was calculated to be about 0.67 seconds using an estimated nozzle length of 0.0045 inches. The pressure rate of 15 PSID per 0.67 seconds is 22.5 PSID per second. A line having this slope is shown on the figure to demonstrate how the measured pressure response compared to the calculated pressure response for a fixed volume.

Figure 6.2 shows the time required to fill the volume to a pressure of -13 PSID. It was calculated to be about 1.47 seconds with the nozzle set to the full scale negative

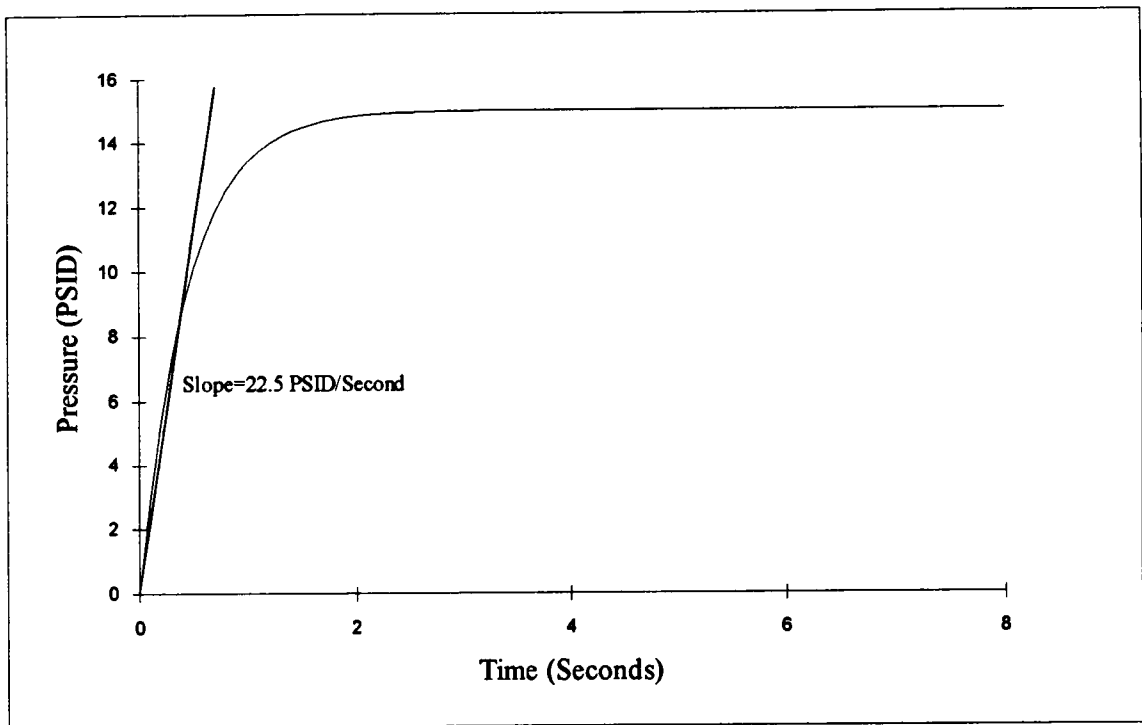


Figure 6.1. Positive Step Pressure Response

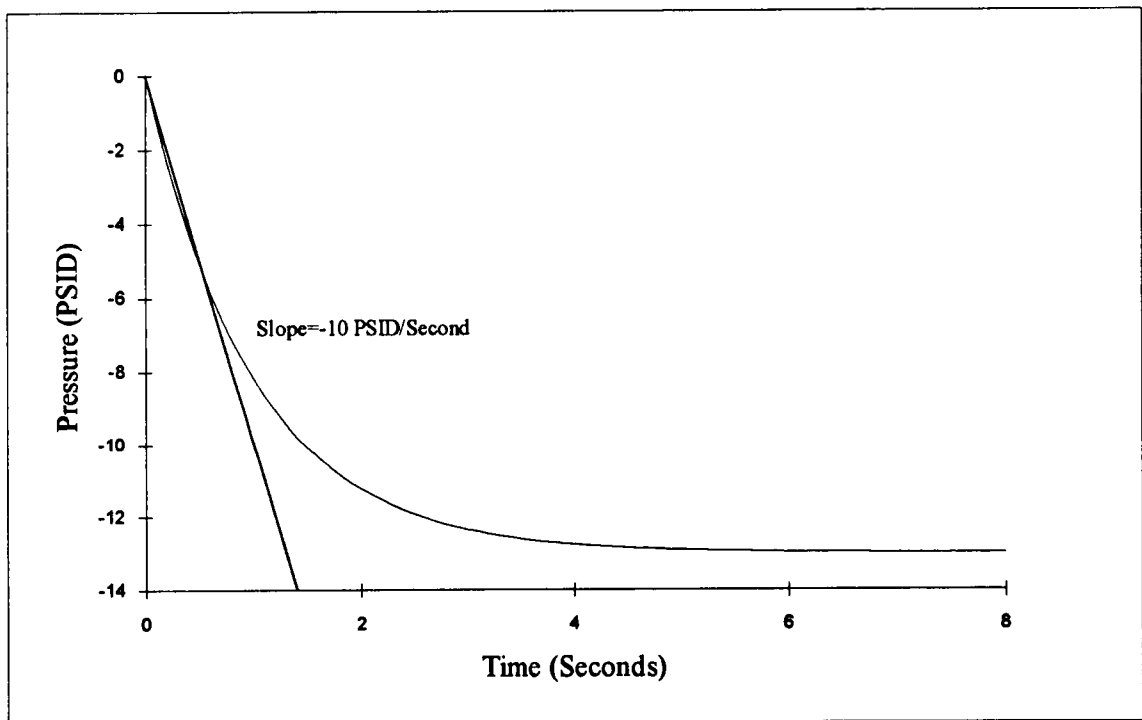


Figure 6.2. Negative Step Pressure Response

position. The pressure rate of 15 PSID per 1.47 seconds is close to 10 PSID per second. A line having this slope is shown on the figure to demonstrate how the measured pressure response compared to the calculated pressure response for a fixed volume. Some differences can be attributed to ambient temperature and local atmospheric pressure.

Figures 6.3 and 6.4 show the control voltage versus time with the feedback pressure versus time for a positive pressure setting of 12 PSID and a negative pressure setting of -12 PSID, respectively. Again, the volume in this test was twenty cubic inches. The initial control voltage is equal to the proportional term. The program calculates the integral value and several discrete steps can be seen before the setpoint is reached and the integral term is set to zero. After the setpoint is reached, the control voltage changes little because the error is small at this point and the integral constant is one half of the starting value. The time required to set the pressures could be shortened with a smaller integral constant.

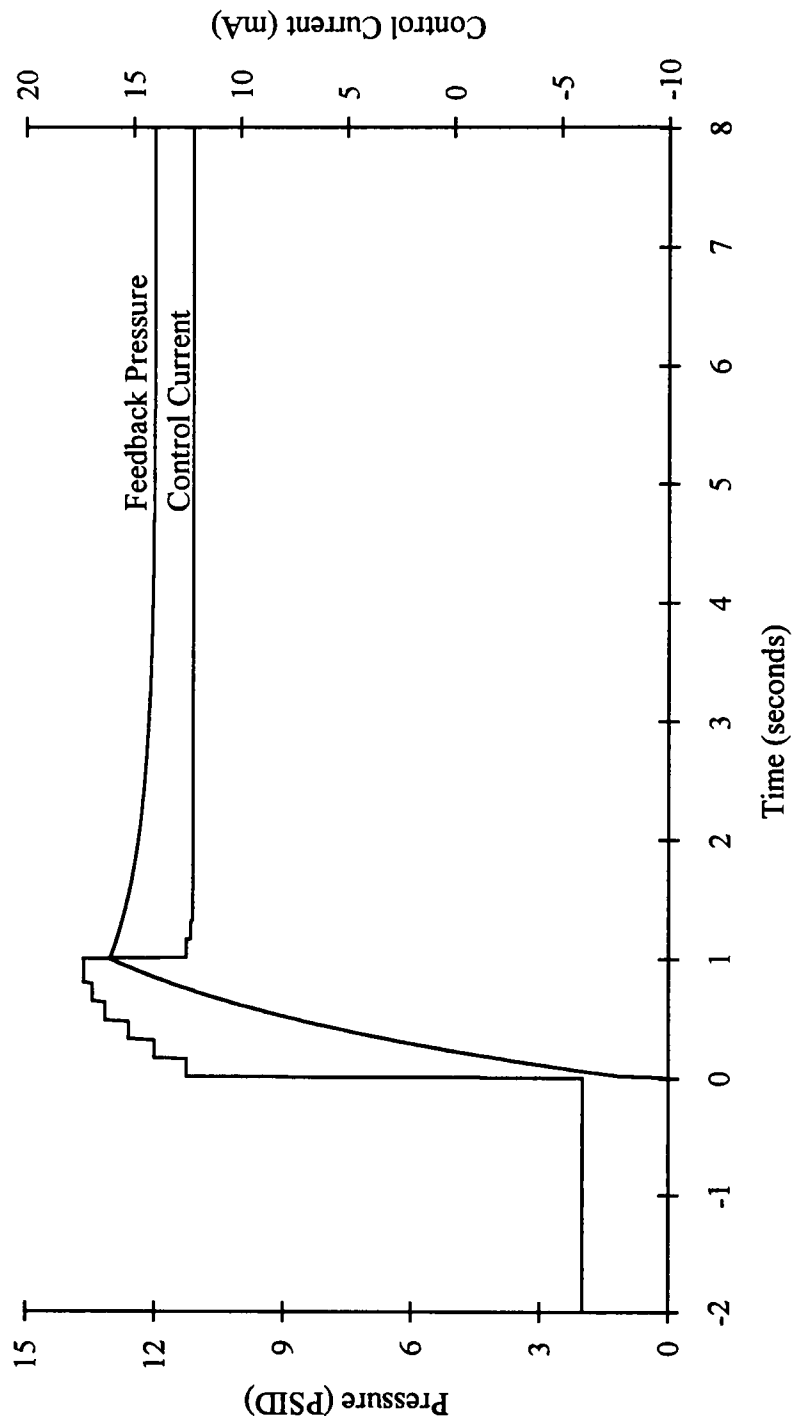


Figure 6.3. Positive Control Pressure Output

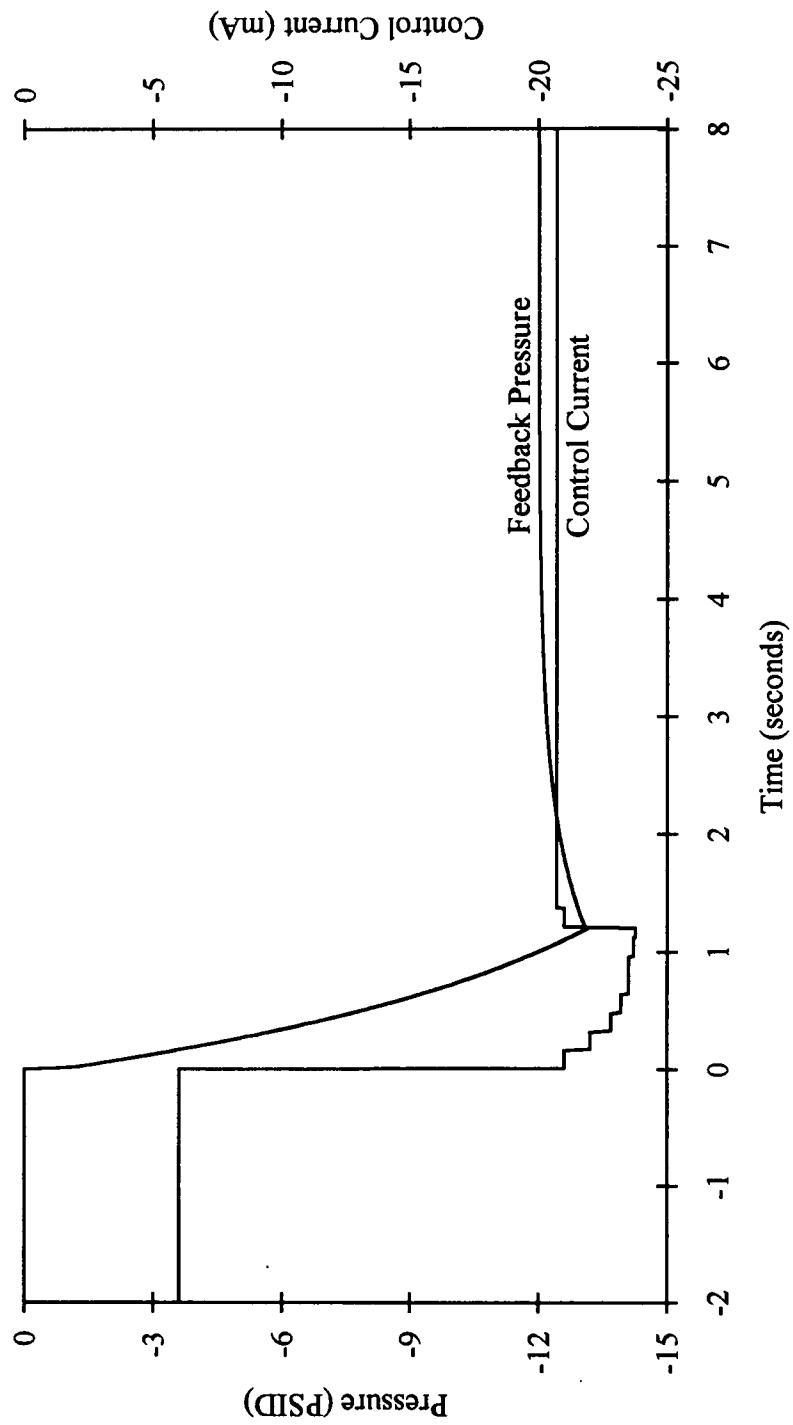


Figure 6.4. Negative Control Pressure Output

CHAPTER 7

SUMMARY

The pressure controller provides NIST traceable calibrations. Its accuracy and stability are within the uncertainty of the working standard. All calibration pressures can be commanded from a single location or from a host computer. The internal pressure control valve provides greater flow rates than typically available from manufacturers. Also, the pressure will always stabilize after the calibration line has filled to the desired pressure. The display options and the single function switches provide uncomplicated, but complete operational capabilities.

The software used in the instrument can be modified for additional capabilities or refined operation. The CPU used for program control could be upgraded to processors currently available for personal computers if required. The voltage to current converter has already seen extended use in the test facilities at the AEDC. The STD BUS is supported by a substantial number of manufacturers and special communications or input/output boards can be added since there are three empty slots in the card cage.

Although the pressure controller provides all necessary features required in testing at the AEDC, several modifications would improve the operation of the device. The addition of several counter/timer registers would provide the capability for fixed program loop times or the creation of special purpose routines such as generating sample periods for the leak check display. A more powerful CPU would allow more complex control algorithms and increase the bandwidth of the instrument. The pressure settling time could be noticeably shortened with a processor powerful enough to reduce the program loop time while performing complex calculations. For example, a program change to measure the pressure charge and discharge rates of the calibration manifold could be used to

automatically generate an optimum integral constant. Also, storage of the final control voltage on pressure settings could be used by the instrument to set future commands.

An option to curve fit the pressure servovalve would be especially useful. The proportional calculation would not be accurate if the curve fit of the servovalve were in error. In this case the fine tuning process would be unnecessarily lengthy. An option to provide zero overshoot is useful in applications when the hysteresis of the transducer under test is desired. An internal atmospheric transducer or an interface to an external atmospheric working standard would fix the curve fit of the pressure servovalve to a measured reference pressure. Currently, proportional error exists when the atmospheric pressure reference differs greatly from the atmospheric pressure at the time of the servovalve calibration. This additional transducer could also be used to read the alternate reference pressure for the same reasons. The addition of a pressure servovalve curve fit option and a reference transducer interface are planned improvements to the device.

Several options would make the pressure controller more appealing if many instruments of this type were produced. All hardware could easily be included in one chassis, but the capability to control a remote pressure would remain. The addition of standard communication interfaces such as IEEE-488 or RS-485 and more choices of pressure units and user-scalable units would be desirable as well. Also, the instrument could be less expensive to manufacture by reducing the number of printed circuit cards, machining a single piece solenoid valve block and replacing the front panel controls with a membrane switch panel and liquid crystal display.

In summary, the pressure controller has reduced the time required for calibrations in the transonic wind tunnels at the AEDC. Efficiency has been improved while improving the accuracy of setting and maintaining calibration pressures. The instrument also provides

many new and useful features and can be modified in future versions. The author knows of no other pressure controller that supplies the quantities of gas, contains the features and controls pressure to such accuracy as the device presented in this thesis.

REFERENCES

REFERENCES

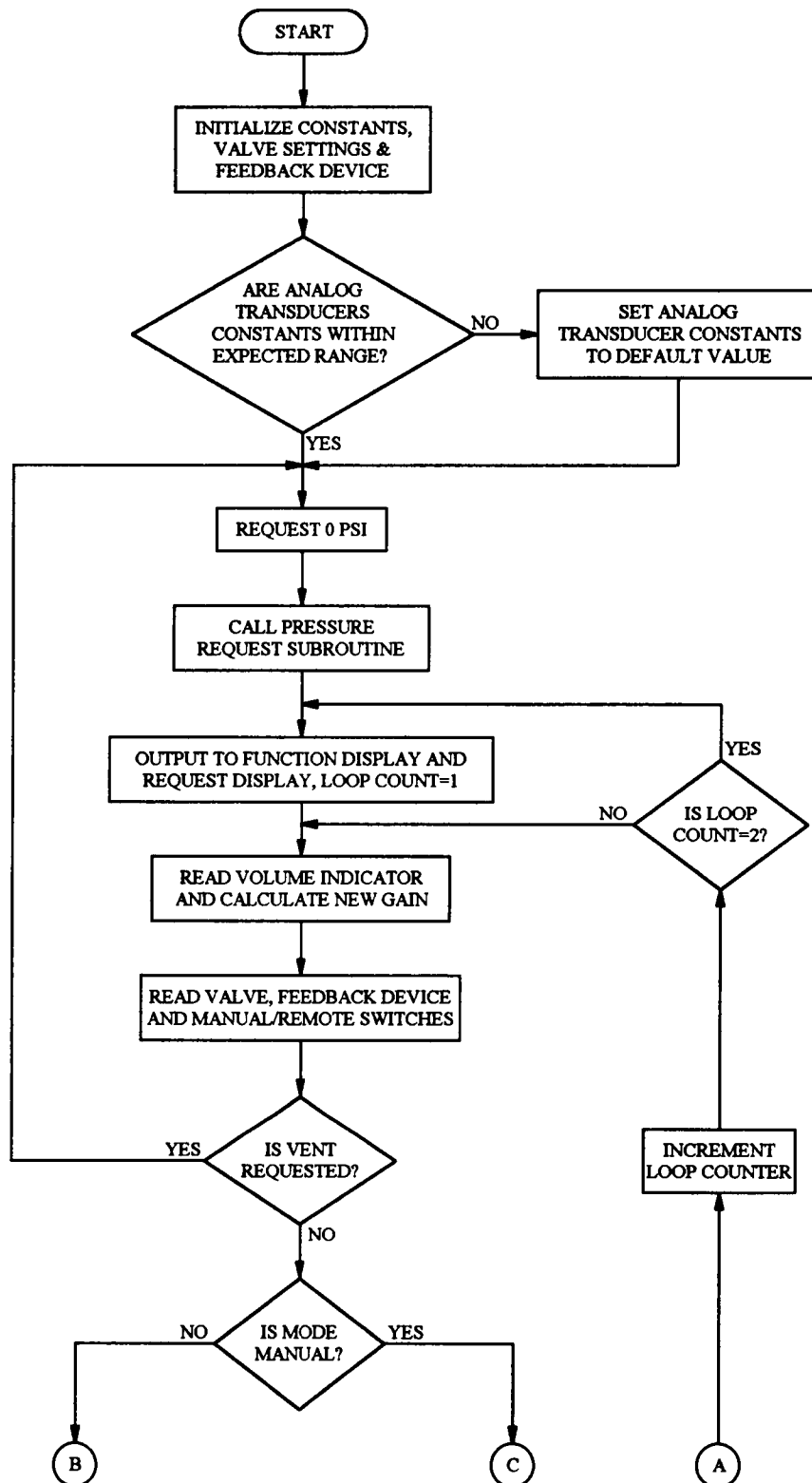
1. Mensor Corporation, Mensor Digital Pressure Gauge Model 11900 Operating Instructions, Manual Number 11840001 E, Houston, Texas, 1980.
2. Kinslow, Max, Lag Time in Pressure Measuring Systems, Thesis (M.S.) University of Tennessee, June 1959.
3. Intel Corporation, Microprocessors and Peripherals, Santa Clara, California 1993.
4. Pro-Log Corporation "Series 7000 STD BUS Technical Manual". Monterey, California.
5. Signetics Corporation, TTL Data Manual, Sunnyvale, California, 1986.
6. Setra Systems Inc, Model 270 High Output Pressure Transducer Data Sheet, Acton, Massachusetts, 1987.
7. Ruska Instrument Corporation, Series 6000 Digital Pressure Gage Data Sheet, Houston, Texas, 1985.
8. National Semiconductor Corporation, CMOS Logic Databook, Santa Clara, California, 1988.
9. Analog Devices Inc., Amplifier Reference Manual, Norwood, Massachusetts, 1992.
10. Wyatt, Michael, Active Filter Makes Component Selection Easier, EDN, January 20, 1992.
11. Comer, David J., Modern Electronic Circuit Design, pg 261, Addison-Wesley, Reading, Massachusetts, 1978.

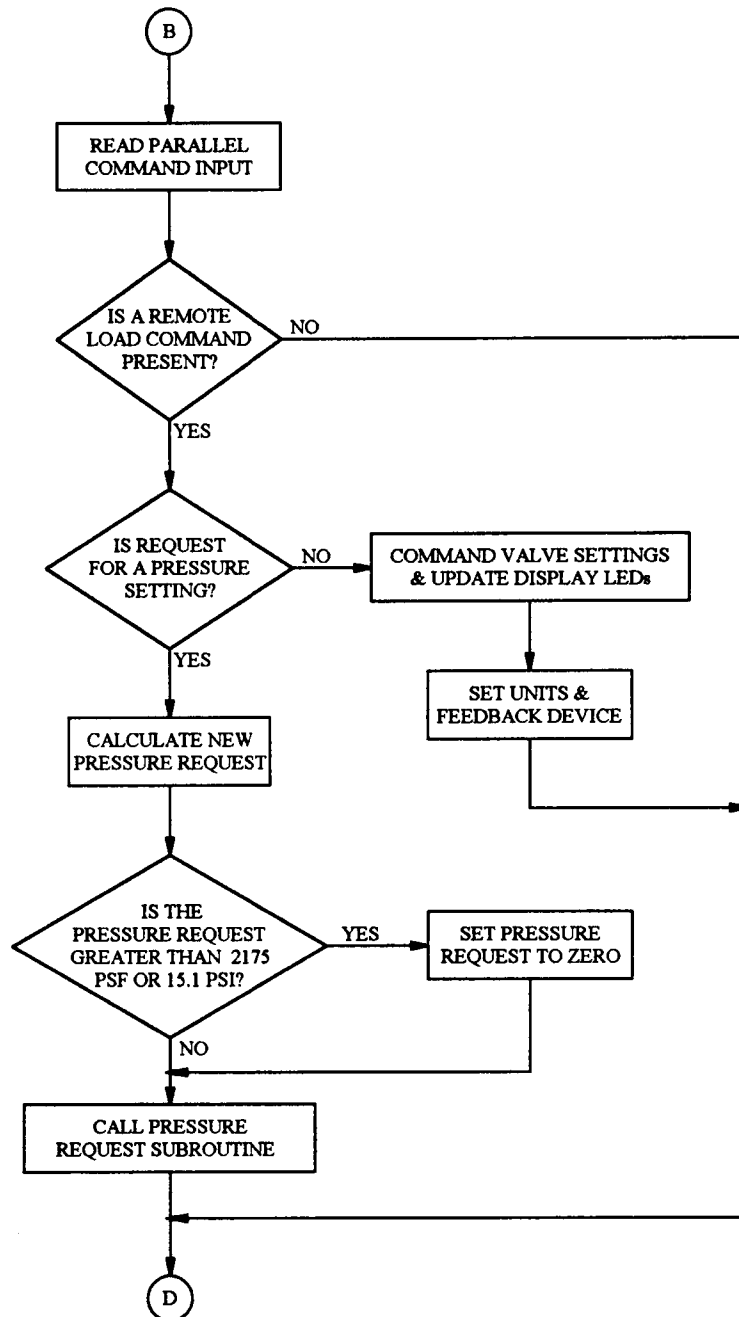
REFERENCES

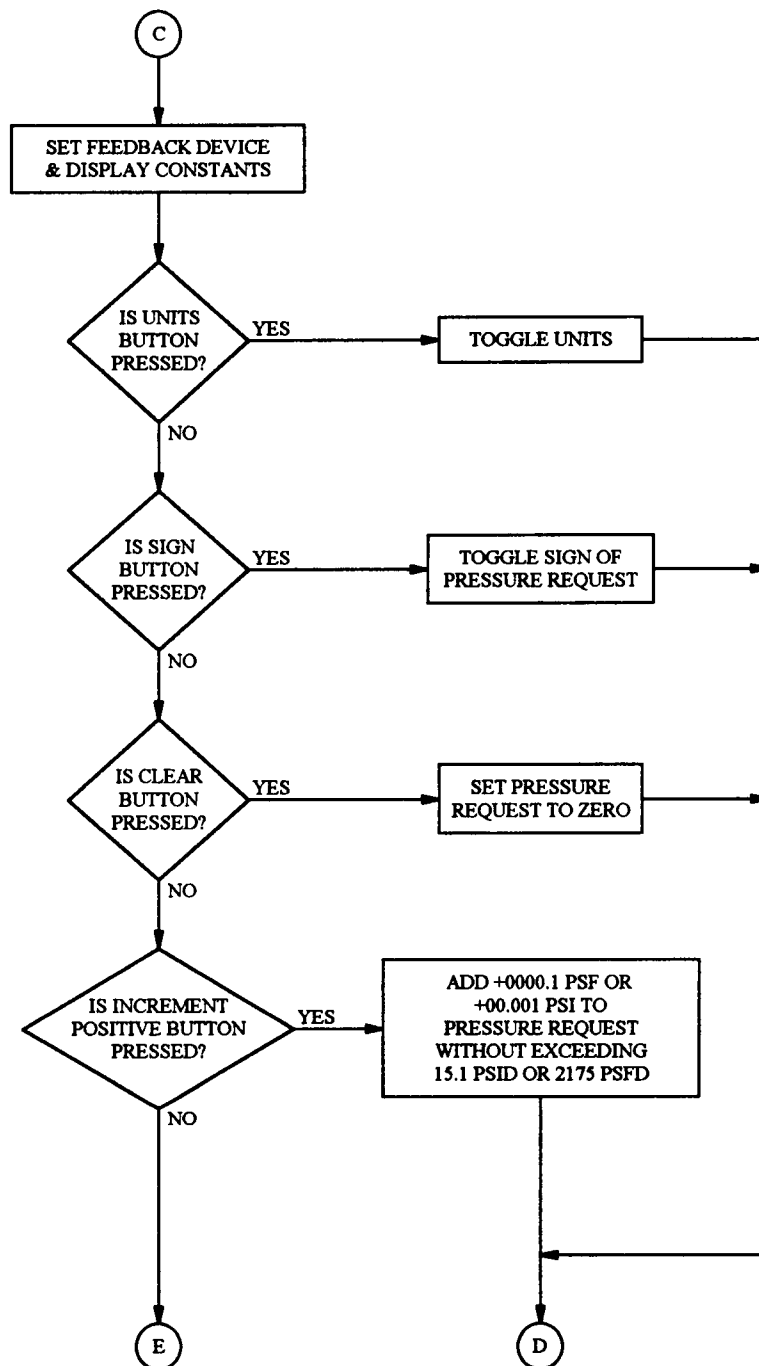
12. Analog Devices Inc., Data Conversion Products Databook, Norwood, Massachusetts, 1988.
13. Siliconix Inc., Low Power Discretes Data Book, Santa Clara, California, 1991.
14. Hewlett-Packard Company, Optoelectronics Designer's Catalog, Santa Clara, California, 1993.
15. Hydraulic Servocontrols Corporation, Precision Pressure Control Valve Model 58C Application Bulletin, Buffalo, New York, 1991.
16. Andersen, Blaine W., The Analysis and Design of Pneumatic Systems, John Wiley & Sons, New York, 1967.
17. Burr-Brown Corporation, BUF634 High-Speed Buffer Applications Bulletin, Tuscon, Arizona, 1993.
18. Texas Instruments Inc., MOS Memory Data Book, Dallas, Texas, 1988.
19. Dallas Semiconductor Corporation, Product Data Book, Dallas, Texas, 1992.

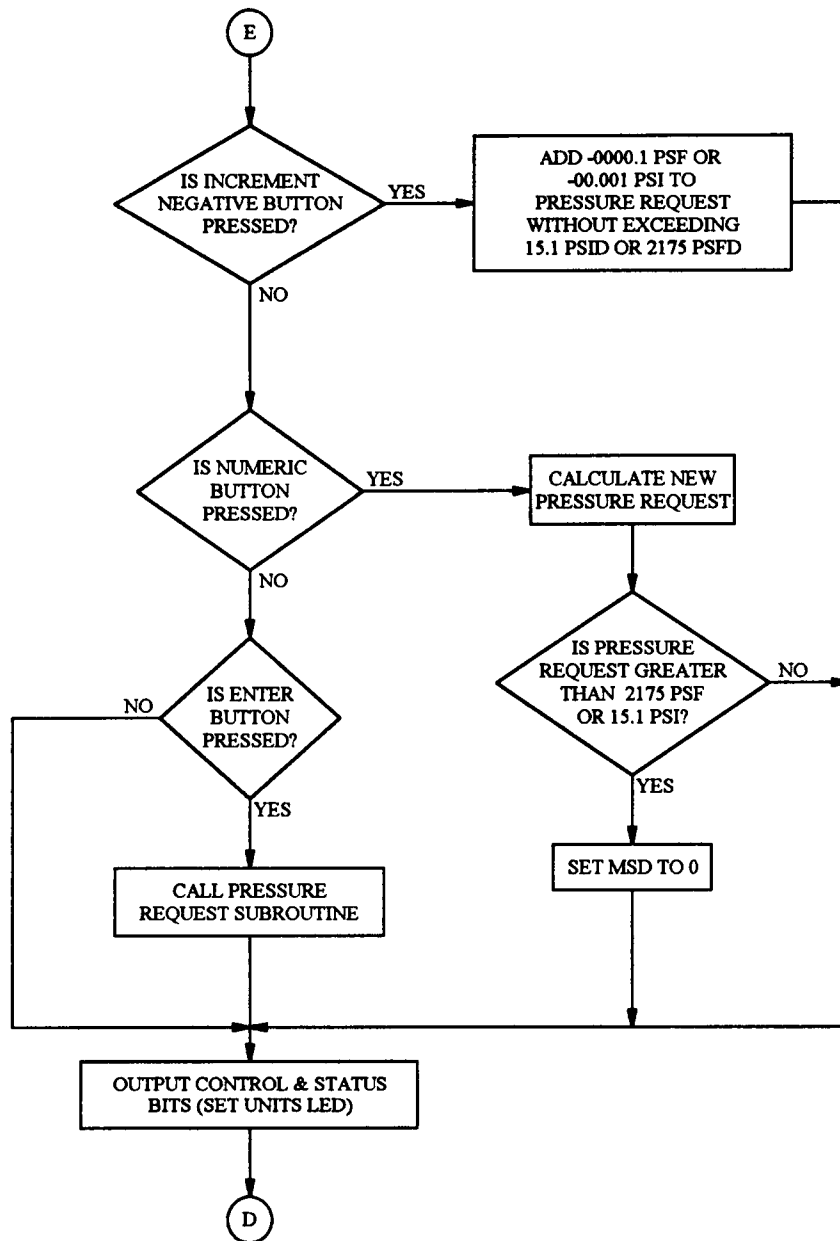
APPENDICES

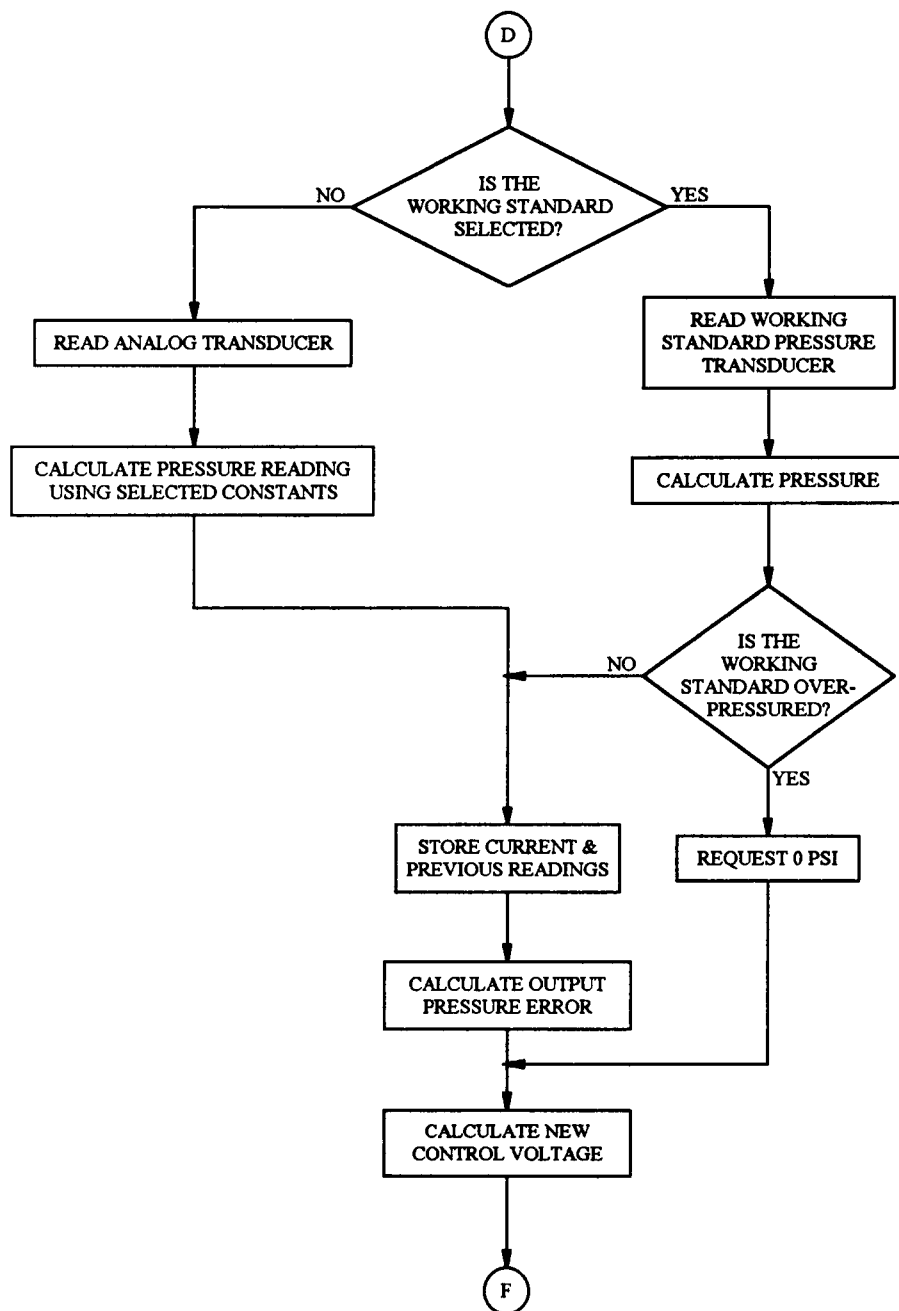
APPENDIX A

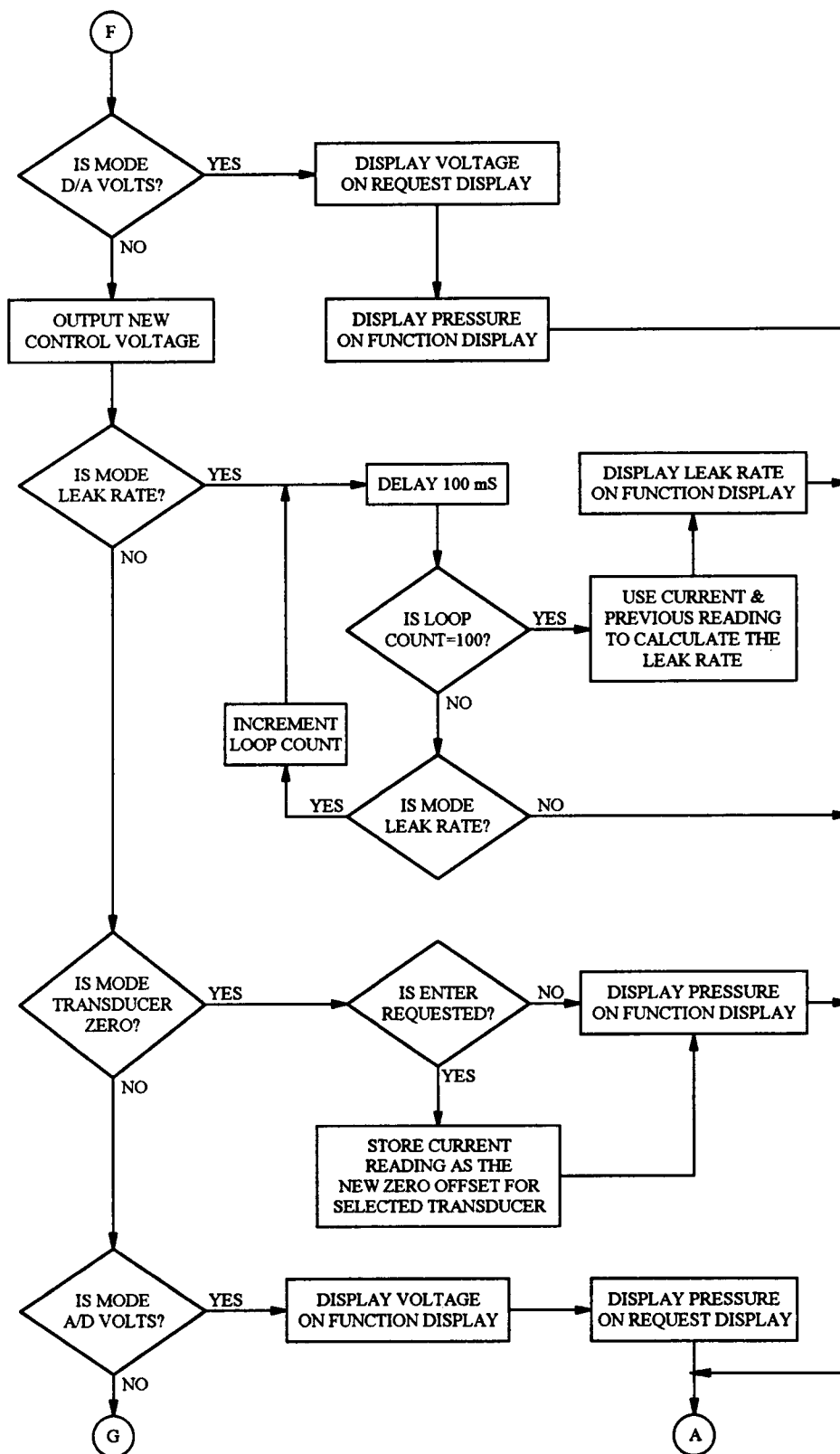


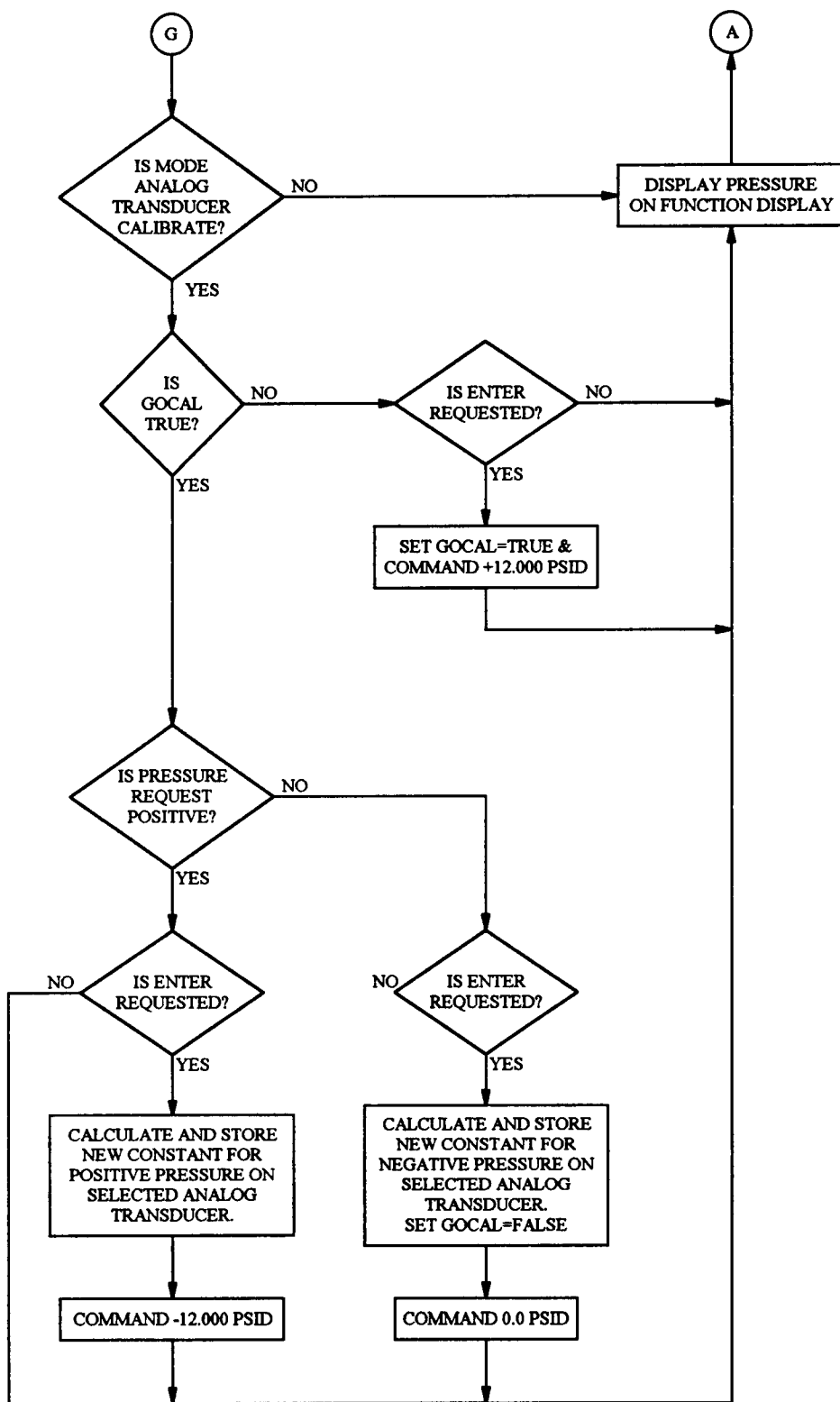












APPENDIX B

INPUT VOLTAGE	CONVERSION ACCURACY
-5.0	-5.000
-4.0	-4.000
-3.0	-3.000
-2.0	-2.000
-1.0	-1.000
0.0	0.000
1.0	1.000
2.0	2.000
3.0	3.000
4.0	3.999
5.0	4.999

Table 1. Analog to Digital Converter Accuracy

INPUT VOLTAGE	CONTROL CURRENT (mA)	COMPLIANCE VOLTAGE
-10.0	-24.998	-12.109
-9.0	-22.498	-10.878
-8.0	-19.998	-9.658
-7.0	-17.498	-8.444
-6.0	-14.998	-7.230
-5.0	-12.499	-6.020
-4.0	-10.000	-4.813
-3.0	-7.500	-3.609
-2.0	-5.000	-2.405
-1.0	-2.500	-1.203
0.0	0.000	0.001
1.0	2.500	1.203
2.0	5.000	2.406
3.0	7.500	3.611
4.0	10.000	4.816
5.0	12.498	6.024
6.0	14.998	7.236
7.0	17.498	8.449
8.0	19.998	9.664
9.0	22.498	10.884
10.0	24.998	12.100

Table 2. Voltage to Current Converter Accuracy

INPUT PRESSURE	INDICATED PRESSURE
-15.0	-15.007
-12.0	-12.001
-9.0	-8.997
-6.0	-5.996
-3.0	-2.998
0.0	0.000
3.0	3.000
6.0	6.002
9.0	9.004
12.0	12.002
15.0	14.994

Table 3. Analog Transducer Accuracy

VITA

Joseph Steven Carter was born in Lawrenceburg, Tennessee. He received his early education in Columbia, Tennessee and was graduated from Columbia Central High School in 1981. He entered Tennessee Technological University in the fall of 1981. He received a Bachelor of Science degree in Electrical Engineering in the spring of 1985.

After graduation, he accepted a position with Calspan, Inc., AEDC group, in June 1985, where he is currently employed as a lead systems engineer in the instrumentation operations department in the Von Karman Facility. His work involves the development of instrumentation for wind tunnel test facilities with emphasis on analog circuit design and microprocessor based instrumentation. The author entered The University of Tennessee Space Institute in the fall of 1986 and received his Master of Science degree in Electrical Engineering in May, 1994.

He is married to the former Sharon L. Neufeldt. They have two children, Kelly and Ryan.