To the Graduate Council:

I am submitting herewith a thesis written by Charles Dennis Rose entitled "A Minicomputer-Based System for the Calibration of Strain Gage Balances." 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.

E. C. Huebschmann

E. C. Huebschmann, Major Professor

We have read this thesis and recommend its acceptance:

James W. Cummings

Ray D Joseph

Accepted for the Council:

L Evans Roth

Vice Chancellor
Graduate Studies and Research

A

A MINICOMPUTER-BASED SYSTEM FOR THE CALIBRATION OF STRAIN GAGE BALANCES

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Charles Dennis Rose

June 1982

ACKNOWLEDGMENTS

The author wishes to express his appreciation to Dr. E. C. Huebschmann, Dr. R. D. Joseph, Mr. J. C. Blevins, and Mr. R. L. Ledford for their advice and assistance throughout this study. Appreciation is also expressed to the officials of Arvin Calspan, Inc., and the Air Force for the opportunity to attend The University of Tennessee Space Institute.

The study reported herein was supported by Headquarters, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee. Reproduction to satisfy the requirements of the United States Government is authorized.

ABSTRACT

Strain gage balances and angular position indicators are used to measure the aerodynamic loads acting on aircraft, missiles, and space vehicles during wind tunnel testing. A calibration of these balances and indicators furnishes data which represent the response of the devices to certain loads and angles. From these data, equations are derived which may be used to determine the load applied to a balance or the angle of a position indicator during a test. This study describes the development and design of a minicomputer-controlled system for the calibration of these devices.

During this investigation, all of the hardware required to calibrate balances and angular position indicators was developed, as well as the operating specifications for the software. This system uses an analog-to-digital converter to digitize all calibration data and uses analog instrumentation to condition and amplify strain gage signals. The minicomputer controls the entire balance calibration process including system setup and calibration. The previous calibration system, which was not computer-based, was used to determine effective methods for improving balance calibrations.

The new system provides a significant improvement in speed and accuracy. The analog-to-digital converter used in this system is far more accurate than the voltage-to-frequency conversion technique used previously. Unlike the old system, this system provides digital and analog filtering to improve the signal-to-noise ratio. The automation of system calibration and setup was the major factor

in reducing calibration time. The resulting system is quite flexible, allowing the operator to satisfy the specific calibration requirements of various balances and angular position indicators. Such things as full-scale signal input, bridge excitation, and filter cutoff frequency can be changed easily.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The aerospace industry of today has advanced to a highly technical state in which it is impossible to perform all the calculations necessary to design state-of-the-art aircraft. Massive safety factors can no longer be used to correct for errors in calculations, since every unit of weight has to be deployed efficiently. This climate has led to the evolution of experimental techniques using aircraft models in wind tunnels. Various wind tunnels used for these experimental evaluations of aircraft are now in operation at the Arnold Engineering Development Center (AEDC).

Two of the devices used to measure the aerodynamic loads acting on aircraft are strain gage balances and angular position indicators. For these two devices to be useful in wind tunnel testing, they must be calibrated by applying the loads and angles to the devices that are likely to be exerted on them during testing. Balances are calibrated by hanging deadweights on the balance and recording the millivolt output of the strain gage bridge. The data obtained are then used to derive the equations which permit the determination of the forces and moments applied to the balance during testing. Angular position indicators, which also use strain gage bridges, are calibrated by pitching the indicator to known angles and recording the output of the bridge. The pitch or roll angle of a model can then be determined by reading the millivolt output of the indicator and using the equations derived from the calibration data to calculate the angle.

The present work deals with the design and fabrication of a new system of hardware and software to record calibration data from strain gage balances and angular position indicators. The Force and Moment Readout System (FAMROS) will condition and measure the output of strain gage bridges as they are loaded. The FAMROS will also perform a least-square curve fit on the data to ensure that it will be usable in later wind tunnel testing. This curve fit is useful for revealing hysteresis and discontinuities of the balance output. These problems result from such things as defective gage bonding, gage lead wire fouling, or balance mechanical problems. In this study, emphasis will be placed on improvements in data accuracy and the reduction in time required to calibrate a device. This will be accomplished by using state-of-the-art computers and instruments to condition, amplify, and record the strain gage data. The computer will also be used to automate tasks, such as system calibration and setup performed during a calibration.

The end result of this project is an accurate, state-of-the-art system for the calibration of balances and angular position indicators. The system of hardware and software provides calibration data accurate to 0.01% of the full-scale load of the device. This system is in daily use in the Propulsion Wind Tunnel Facility (PWT) at AEDC, and has provided a significant improvement in the area of balance calibration.

CHAPTER II

DEFINITION OF THE PROBLEM

II.1. Description of Strain Gage Balances

A description of the devices to be calibrated is necessary for a complete understanding of the calibration process. The majority of the devices calibrated are strain gage balances. A strain gage balance is a device which uses an electrical signal to measure the forces and moments acting on a model while it is being tested in a wind tunnel. The balance is used to measure six components of force and moment that act on a model. These six components are: Normal force (F_N), side force (F_Y), axial force (F_A), rolling moment (M_ℓ), pitching moment (M_m), and yawing moment (M_n). The standard sign convention and three-dimensional orthogonal coordinate system of aircraft and missiles are shown in Fig. 1. The respective internal strain gage balance axes are parallel to the axes of the model.

Generally speaking, the balances to be calibrated are placed in one of three categories: Case I, Case II, or Case III [1].[1] These three types of balances are listed in Table 1, with the forces and moments measured by each of the balance's six components.

A typical direct-reading balance, shown in Fig. 2, is referred to as a Case I balance. This balance directly reads each

---

[1]Numbers in brackets refer to similarly numbered references in the Bibliography.

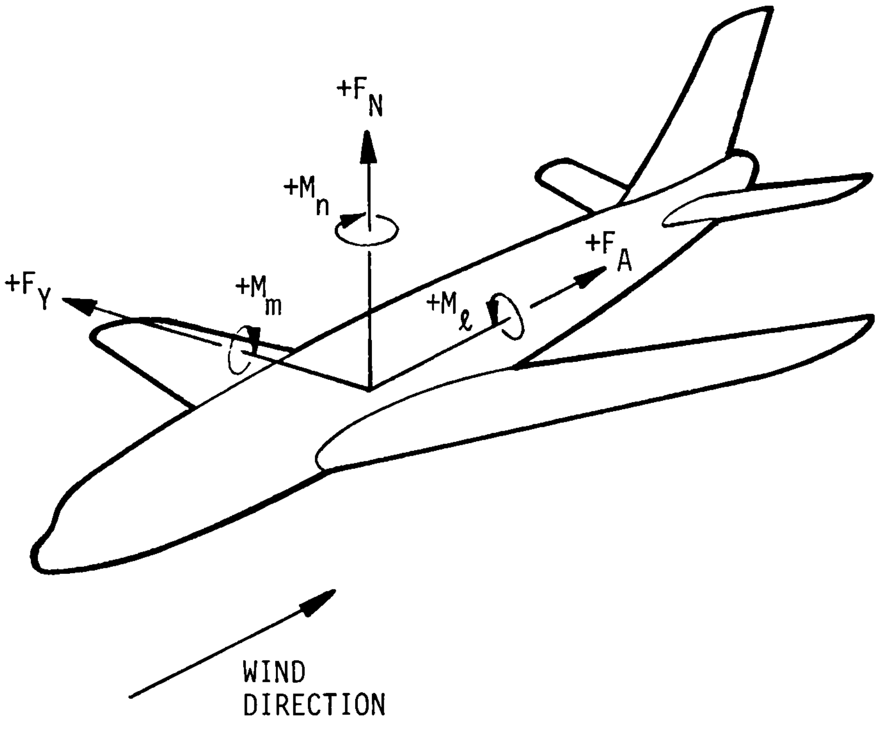


Figure 1. Conventional coordinate system.

Table 1. Component Order for Three Balance Cases

Gage No.	Case I Direct Reading Balance	Case II Force Balance	Case III Moment Balance
1	Normal Force, F_N	Forward Normal Force, F_{N1}	Forward Pitching Moment, M_{m1}
2	Side Force, F_Y	Forward Side Force, F_{Y1}	Forward Yawing Moment, M_{n1}
3	Axial Force, F_A	Axial Force, F_A	Axial Force, F_A
4	Rolling Moment, M_ℓ	Rolling Moment, M_ℓ	Rolling Moment, M_ℓ
5	Pitching Moment, M_m	Aft Normal Force, F_{N2}	Aft Pitching Moment, M_{m2}
6	Yawing Moment, M_n	Aft Side Force, F_{Y2}	Aft Yawing Moment, M_{n2}

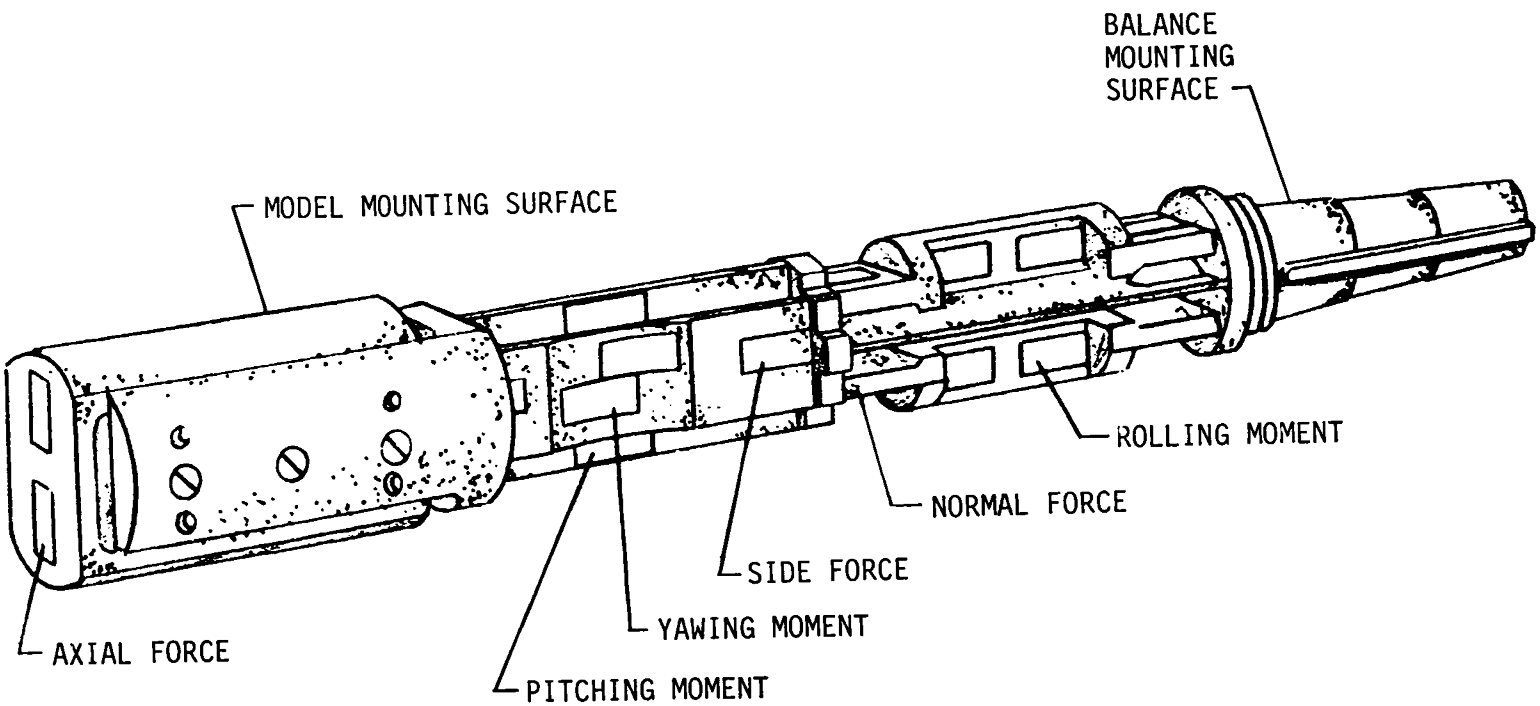


Figure 2. Typical six-component, direct-reading balance.

of the six components acting on the model. The balance measures a pure force in each axis and a pure moment about the center of each moment gage; therefore, a force is determined and the location is found by dividing the moment by this force. This type of balance is constructed from a single piece of metal, except for a removable axial-force sensing element.

A Case II balance measures pure forces, with the exception of rolling moment. This balance is often a floating frame-type balance, as shown in Fig. 3. The primary frame consists of an inner rod, which fastens to the balance support and cylindrical outer case, which is inserted into and attaches to the model. Forces and moments are resisted by individually removable elements employing flexure pivots connected between the inner rod and outer case of the balance [2]. A Case II balance measures axial force and rolling moment directly, but secondary force and moment equations must be used to calculate the four remaining components. The secondary equations are:

$$F_N = F_{N1} + F_{N2} ,$$

$$F_Y = F_{Y1} + F_{Y2} ,$$

$$M_m = (F_{N1} - F_{N2}) \frac{\Delta X_n}{2} ,$$

and

$$M_n = (F_{Y1} - F_{Y2}) \frac{\Delta X_n}{2} ,$$

where ΔX_n is the distance between the bridges.

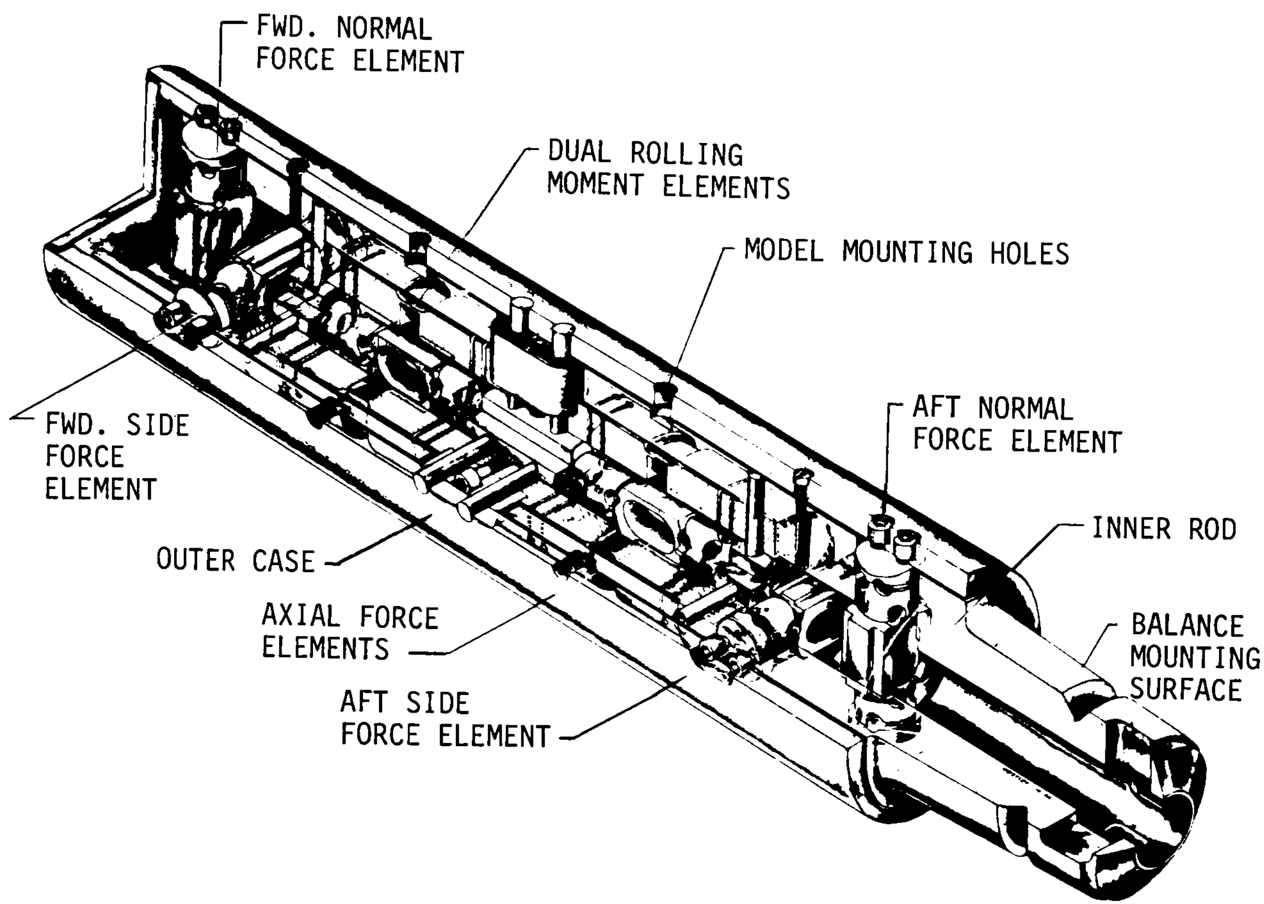


Figure 3. Typical six-component, floating frame-type balance.

A Case III balance measures all moments, with the exception of axial force. It is usually a beam deflection-type balance on which secondary equations must again be used to calculate four of the six common components. The secondary equations are:

$$F_N = \frac{M_{m2} - M_{m1}}{\Delta X_n} ,$$

$$F_Y = \frac{M_{n2} - M_{n1}}{\Delta X_Y} ,$$

$$M_m = 1/2(M_{m1} + M_{m2}) ,$$

and

$$M_n = 1/2(M_{n1} + M_{n2}) .$$

II.2. Description of Angular Position Indicators

Although the system is used mainly for calibrating balances, strain gage angular position indicators (API) are also calibrated on the system. The API are relatively simple devices consisting of a gaged deflection beam fixed on one end with a weighted mass attached to the other end. The API are rotated to known angles and the output of the gages is recorded so that the gage readings can be used to determine model angles during testing. The deflection beam and weight are mounted in an oil-filled enclosure to reduce output noise due to model vibration.

II.3. Previous Calibration System

The previous calibration system consisted of a deadweight calibration rig in which the balances are mounted and loaded, and a Force and Moment Readout System (FAMROS) which was used for measuring and digitizing the strain gage balance output voltages.

To simulate the model to be tested, the balance is installed in a fixture called the calibration body. The calibration body transmits loads to the balance just as the model will during testing. It is attached in the same manner as the model and has reference surfaces which remain fixed with respect to the balance reference surface during testing. The balance and calibration body are mounted in the deadweight calibration rig, shown in Fig. 4. Positive loads are applied to the balance in increments less than 20% of the maximum design load. All loads are applied in such a manner that only one force or moment is varied [2]. The sign of the applied normal or side force is determined by the degree of roll at which the calibration body is positioned.

The previous six-channel FAMROS used a voltage-to-frequency conversion to digitize output voltages. The strain gage output voltage was fed into a voltage-to-frequency converter. The output frequency was then read by a five-digit frequency counter with a binary coded decimal (BCD) output. This BCD output was read by a digital scanner and punched onto paper tape. The paper tape was then read into a Digital Equipment Corporation (DEC) 10 computer, where all data reduction takes place. All constants required for

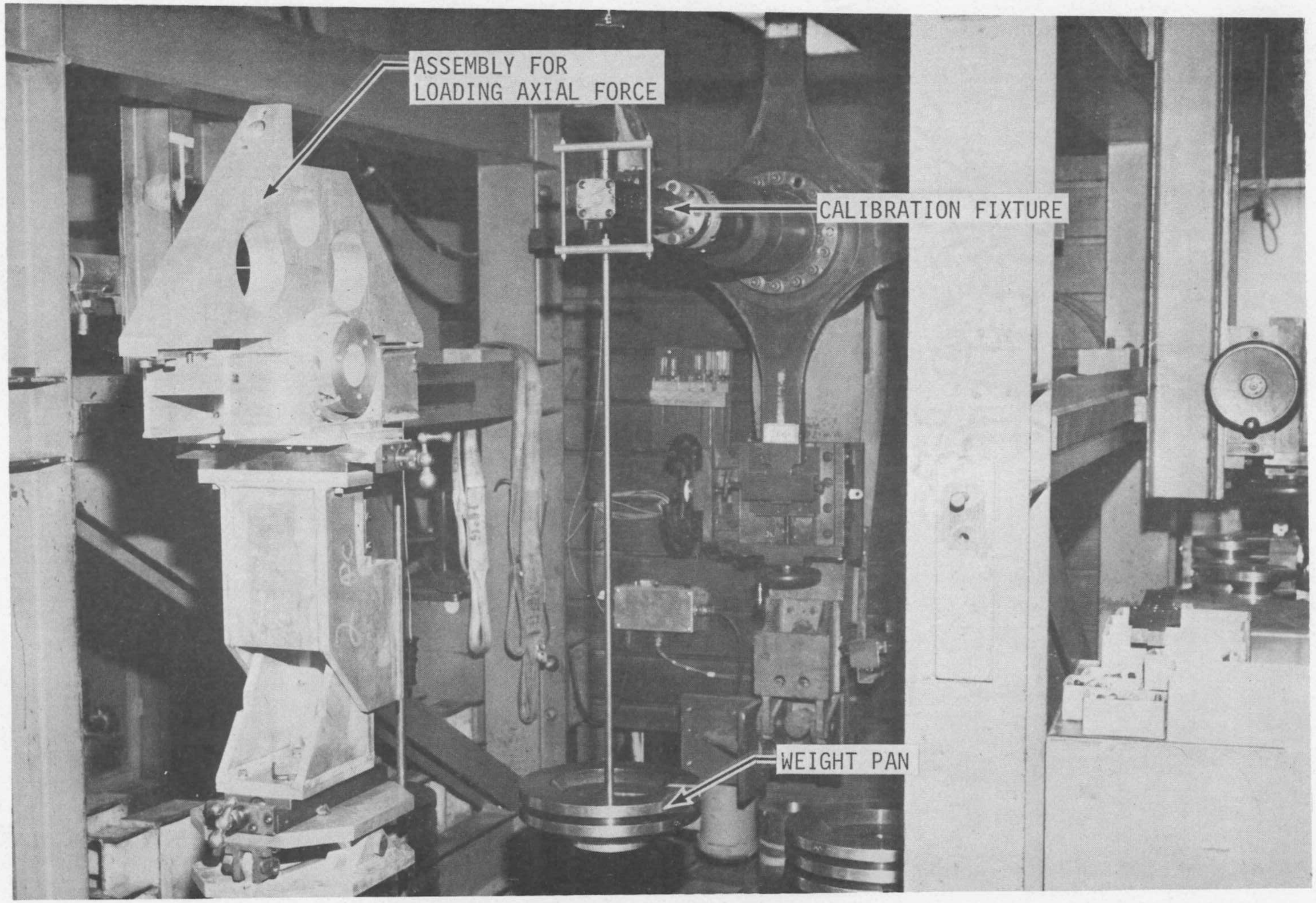


Figure 4. Propulsion Wind Tunnel deadweight calibration rig.

data reduction were provided on BCD switches which were read by the digital scanner. The gage supply voltage was provided by individual power supplies capable of supplying 0 to 12 volts direct current (D.C.) at 200 milliamperes (mA). Setup of the FAMROS was accomplished using manual switching units in which known voltages were applied to the system.

Because balances are calibrated in a laboratory, on a different system than used during tunnel testing, readouts may vary between calibration data and tunnel data as a result of sensitivity differences. These differences must be accounted for when applying the results of the laboratory calibration to the wind tunnel model installation. A shunt calibration is used to determine the ratio of tunnel sensitivity to laboratory sensitivity. The calibration is accomplished by shunting each arm of the strain gage bridge with a known resistance. This was done with a manual switching unit.

II.4. Proposed Calibration System

Because of major advancements in the fields of instrumentation and computers, and the fact that the previous FAMROS required excessive maintenance to keep it in operating condition, a new calibration system was required. The problem was to develop, design, and fabricate a system to calibrate balances and API using state-of-the-art equipment and techniques. The calibration system proposed in this study is a versatile 16-channel minicomputer-based system. The new system uses chopper stabilized amplifiers and a 15-bit analog-to-digital converter to digitize data. This method is much more accurate than the voltage-to-frequency converters used in the previous system. In addition to digital filtering, the system provides two hardware filters for increased data accuracy and repeatability, whereas the previous FAMROS provided no filtering. The computer is programmed to provide automatic setup and calibration for the system instead of using the manual switching units of the old system for these tasks. Data are recorded on magnetic disk and transferred directly to a DEC10 computer for the increased computational capabilities required. This method of data transfer is much faster than the paper tape system of the previous FAMROS. The same deadweight calibration rig and loading techniques are used in the new system.

CHAPTER III

THEORY OF OPERATION

The heart of a strain gage balance is the gage itself; thus, it is necessary to discuss how a strain gage works and the problems associated with using strain gages.

The strain gage was developed independently and almost simultaneously in 1938 by two men: Simmons at the California Institute of Technology, and Ruge at the Massachusetts Institute of Technology [3]. Both men developed techniques for bonding a length of fine wire to the surface to be investigated so that all surface strains were transmitted directly to the wire. Advances in the strain gage field include development of new types of gages, such as foil gages, weldable gages, and self-compensating gages, but the basic theory remains unchanged [4].

The load-carrying abilities of the material used in construction of aircraft are normally characterized in terms of stress; that is, the amount of load carried by a given area. Therefore, stress is quoted in pressure units, force per area. However, stress itself cannot be measured, it must be deduced from the mechanical dimensions and the applied load. A direct relationship exists between stress and strain; they satisfy

$$Y = \frac{\text{stress}}{\text{strain}} ,$$

where Y is known as Young's Modulus. From the foregoing, it can be seen that if the Young's Modulus of the material is known, and the strain is measured by the strain gage, it is a simple matter to calculate the stress. This is true when the direction of the stress is known, which is the case with a strain gage balance.

The gage is very small and compact, having negligible mass to exert a minimal influence on the measuring object. The length changes in the wire cause alterations in resistance of the wire which are measured electrically. The change in gage resistance is related to the change in gage length by the Gage Factor k:

$$k = \frac{\delta R}{R} / \frac{\delta \ell}{\ell} = \frac{\delta R}{ER} ,$$

where,

R = gage resistance ,

δR = change in gage resistance ,

ℓ = gage length ,

$\delta \ell$ = change in gage length ,

E = strain .

A basic device that can be applied to the measurement of all classes of strain is the Wheatstone bridge. Its function is to measure a resistance or a change in resistance with a high degree of precision. The standard Wheatstone bridge arrangement is shown in Fig. 5; if R1 x R3 = R2 x R4, the bridge is balanced and no current will flow. However, the readout instrumentation used in the calibration system is voltage-sensing; therefore, the bridge will be discussed in terms of voltages. The Wheatstone bridge may be used

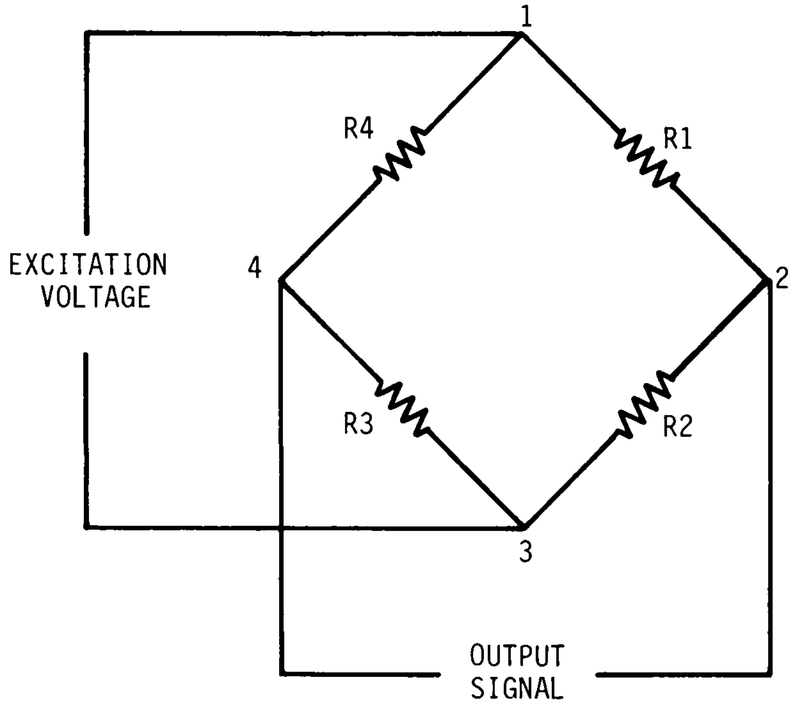


Figure 5. Standard Wheatstone bridge strain gage configuration.

with one, two, or four active arms. Essentially all balances to be calibrated use four-active-arm bridges with 350- or 120-ohm gages. In a four-active-arm bridge, the gages are physically located on the balance so that when R1 and R3 are in tension, R2 and R4 will be in compression, or vice versa. This gage arrangement gives a four-active-arm bridge increased sensitivity over a one- or two-active-arm bridge. The gages are also placed on the balance so that each bridge measures only one component of force or moment.

In order to resolve accurately the forces acting on a balance, the output of the balance must be due solely to the force acting on it and not environmental changes. Changes in temperature are almost always present in wind tunnel testing, and since strain gages are very temperature-sensitive, balances must be compensated so that there will be no apparent force changes due to a change in temperature.

Temperature compensation begins with the fabrication and gaging of the balance. The balance is heat-treated after machining to attempt to relieve any residual stresses introduced during fabrication [1]. The four individual gages in each bridge are then selected from the same manuacturer's lot number and are resistive-matched in the laboratory. The interbridge wiring is kept as short as possible and is inserted in a manner to maintain a resistive balance of the bridge. The balance and its associated lead wire are then temperature-cycled, normally over a range of 70 to 180^{0}F [2] for two or three cycles, to obtain thermal stability. On the succeeding cycles, the temperature compensation is completed by inserting a length of resistance alloy wire with the proper temperature coefficient of resistance into the appropriate leg of the bridge. This compensation is performed by first calculating the amount of compensating wire required and then adjusting the quantity experimentally until the proper compensation is achieved.

The major objectives kept in mind during the development of the new system were the improvement of data accuracy and repeatability, and a decrease in time required to perform a balance calibration.

Three major deficiencies were discovered in the previous FAMROS. All desired balance data are steady-state, yet the previous system provided no filtering to limit high-frequency noise. Second, the operator could view data only in real time since no printout of recorded data was provided in the calibration area. Third, all system setup and calibrations were performed manually.

To ensure that only steady-state data are recorded, two methods of filtering were implemented in the new FAMROS. Since the full-scale output of the strain gage bridge is only a few millivolts, preamplifiers are required to obtain a voltage level capable of being digitized. Preston Scientific Wideband D.C. amplifiers, which provide an active two-pole, critically damped filter, were chosen for the new FAMROS. The amplifiers provide variable filter settings from 100 kHz to 2 Hz; the filter will be operated in the 2-Hz mode. Unfortunately, these filters are located in the output stage of the amplifiers; therefore, high-frequency noise can still cause saturation of the input [5]. To alleviate this problem, 4-Hz, low-pass filters were installed just before the amplifiers.

To further improve data accuracy, a recursive digital filter was implemented in the system software. The filter is of the form,

$$Y_K = A\,Y_{K-1} + (1 - A)X_K \,,$$

where X_K is the input and Y_K is the filtered output. The output of this recursive filtering process depends not only on the present and past values of the input, but also on the past values of the output. To prepare a continuous signal for a sampling operation, the signal must be bandlimited by a low-pass filter to fs/2, where fs is the sampling rate. This is essential to minimize errors due to frequency aliasing [6]. The sampling rate must, therefore, be greater than 4 Hz when used in conjunction with the Preston amplifier filter of 2 Hz.

In order to efficiently use this digital filter, a method for specifying the filter constant (A) and the sample rate must be determined. These two parameters determine the frequency response of the digital filter. From the linear difference equation that describes the filter, the frequency response H(f) for the filter is found to be

$$H(f) = \frac{1 - A}{1 - Ae^{-j2\pi f\Delta}} \,,$$

where Δ is the sampling interval and f is the input frequency. After the sampling rate and filter constant are chosen using the above equation, the 3-db cutoff frequency fc is determined by the equation,

$$\frac{fc}{fs} = \frac{1}{2\pi} \cos^{-1} \frac{1}{2A} (-1 + 4A - A^2) .$$

The 3-db cutoff frequency and frequency of maximum attenuation can be determined easily for specific sampling rates and filter constants by viewing the plot of this equation in Fig. 6. In the FAMROS, the major noise component was found to be 60 Hz; therefore, the sampling rate was chosen to be 120 Hz in order to provide maximum attenuation of the 60-Hz noise. After experimentation under noisy conditions and as a compromise between production and data accuracy, the filter constant was chosen to be 0.98. Although these two values were chosen as the best values, the FAMROS software will allow the operator to change the sampling rate and filter constant as special circumstances arise. To determine the number of samples required for the filter to settle, assume a unit step is input to the filter. Then,

$$Y(K) = (1 - A) \sum_{i=0}^{k-1} A^i = 1 - A^k ,$$

and the number of samples required to settle to amplitude ratio (r) can be found by

$$K = \frac{\ell n(1 - r)}{\ell n\ A} .$$

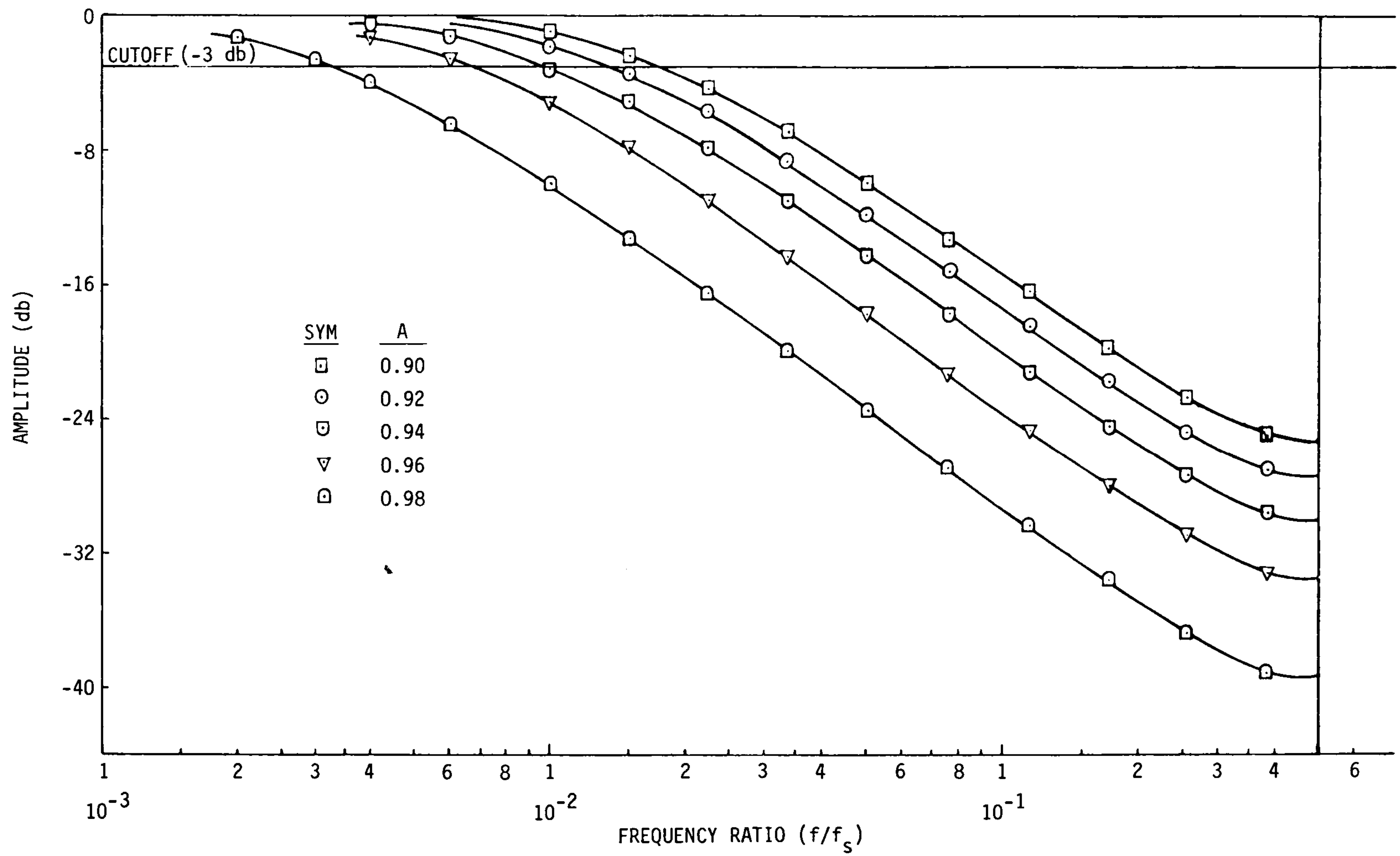


Figure 6. Frequency ratio versus amplitude for A = 0.90 to 0.98.

The amplitude ratio for the FAMROS was chosen to be 0.9999, since the system must provide data accurate to 0.01% of full-scale load.

In order to alleviate the second problem of no data printout, which caused time-consuming repetition of balance loadings, a printer and a cathode-ray tube (CRT) are used in conjunction with a computer-based system. Real-time data are displayed on the CRT. This real-time display is necessary so that the operator may determine the amount of noise on the balance data. One of the major sources of noise is the swinging of the weights used to load the balance; if the operator can view this noise, he can minimize it by stopping the weight motion. Also, when large loads are applied, the weights may swing at a frequency below the cutoff frequency of the digital filter; when this occurs, the operator must stop the weight swing to prevent recording this low-frequency noise. The filtered data are then printed in hard copy form for further analysis, and for future reference if needed. By viewing the printed data, the operator can spot excessive nonlinearity or other errors immediately and correct the problem before proceeding with the calibration. This also saves time on the facility computer, since less bad data are transmitted from the FAMROS.

To further reduce the time required to calibrate a balance, all system setup and calibration was automated. The automation procedure will be discussed in detail in the section on hardware implementation (Chapter IV).

CHAPTER IV

IMPLEMENTATION

IV.1. Overview

The system is implemented using a Computer Automation Model LSI 4/30 minicomputer and five-megabyte disk storage system. The minicomputer provides a very flexible system by allowing the operator to adapt the software package to meet the specific requirements of any calibration. The minicomputer is used to record all data and control the setup and calibration of the system. The software and data are stored on the disk storage system.

Several other items are necessary to complete the system. An analog-to-digital converter/multiplexer is included to read all balance and system calibration data. Signal conditioners are used to provide gage power, zero suppression, gage shunting capabilities, and automatic system calibration. A Signal Conditioner Control/Status Panel is used to decode the binary code sent by the computer and select the requested setup or calibration function. Wideband direct current (D.C.) amplifiers are used to amplify and filter the data signals. Low-pass filters are installed in front of the amplifiers to prevent saturation of the input transistors. A D.C. voltage standard is used to provide calibration signals for the system. A terminal consisting of a keyboard, which is used by the operator to communicate with the computer, and a cathode-ray tube (CRT), which is used to display data and communication messages, is used as an operator's console. A printer is used to provide a hard copy printout of all constants and data.

In the design of a system such as this, it is necessary to consider hardware and software development simultaneously. However, in presenting the design it is not practical to present both hardware and software together. In this study, the hardware will be presented first and then the software specifications.

IV.2. Description of Hardware

The FAMROS is a 16-channel system, consisting of both analog and digital instrumentation. A block diagram of the instrumentation is shown in Fig. 7.

The strain gage balance is connected to the FAMROS by soldering the balance leads to a Gage Junction Panel. The wiring between the panel and signal condition is a 10-wire system with shields being carried through to the signal conditioner guard. Bridge input wiring to the signal conditioner is shown in Fig. 8.

The heart of the analog instrumentation is the signal conditioner. The signal conditioner used is the Model IS-102, manufactured by Signal Laboratories, Inc. The Model IS-102 is designed to accept a four-arm strain gage-type input. The signal conditioner supplies constant voltage or constant current excitation to the strain gages. The excitation power supply is an individual isolated supply which provides 0 to 25 volts D.C. at a current of 0 to 200 mA. The excitation regulation is the greater of 0.005% of output, or 0.1 millivolt in the voltage mode, and 0.01% of full scale, or

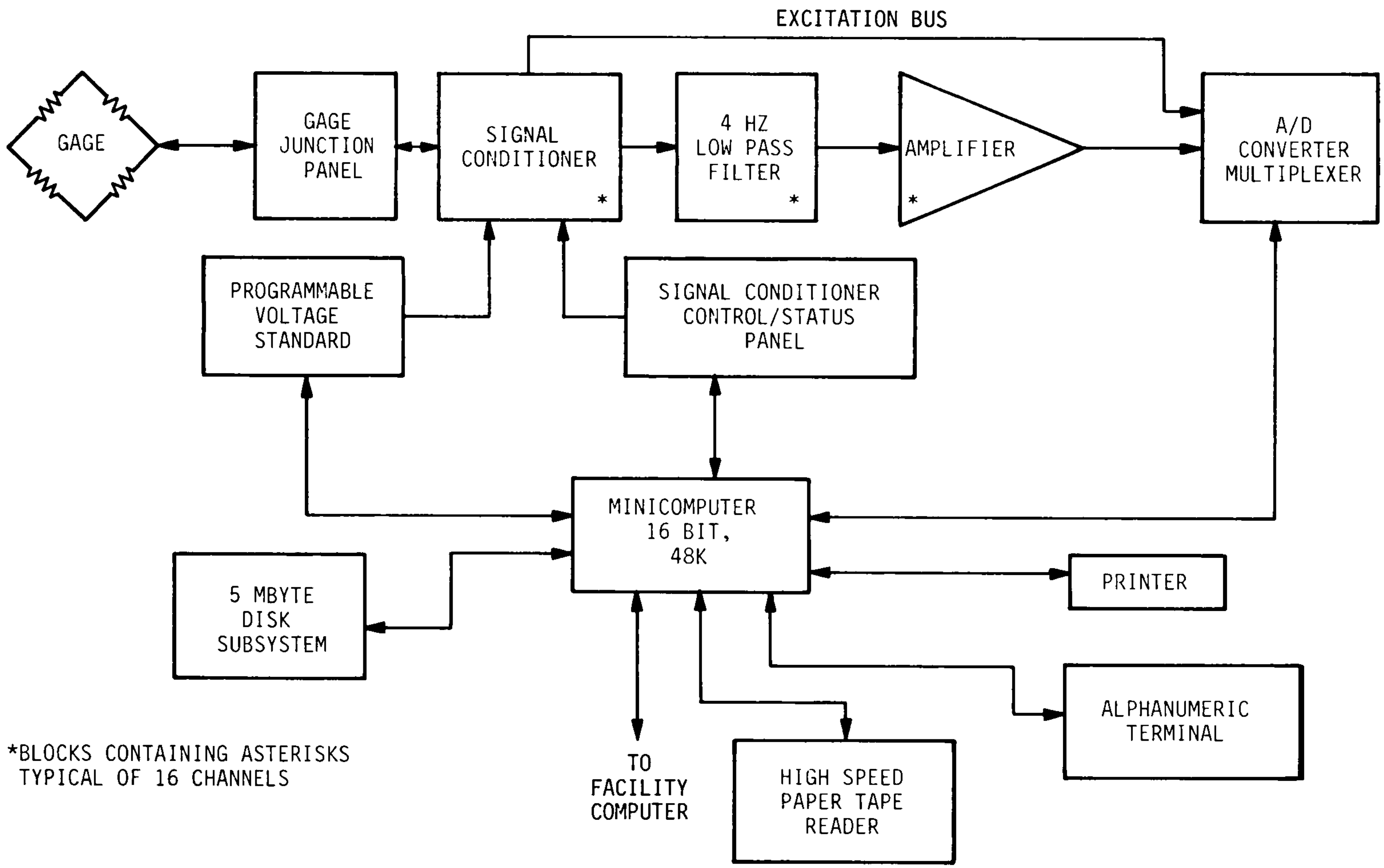


Figure 7. Instrumentation block diagram.

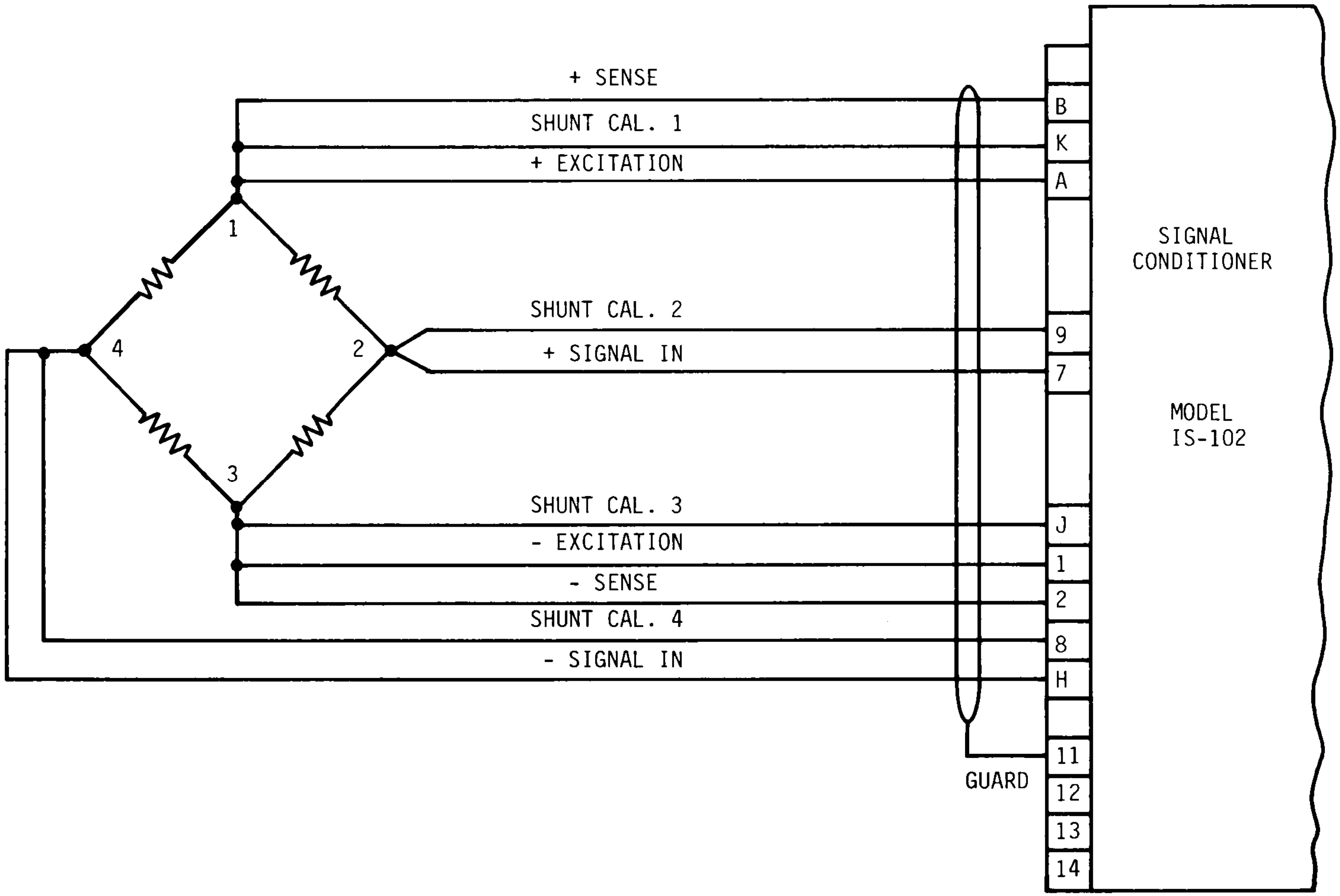


Figure 8. Bridge input wiring.

25 microamps in the current mode from no load to full load. For a line voltage of ±10% of 115 volts A.C., the excitation regulation is the greater of 0.005% of output, or 0.1 millivolt in the voltage mode, and 0.01% of output, or 0.1 microamp in the current mode [7]. When operating in the constant voltage mode, sensing capability for the excitation supply, selectable by an externally provided switch, is available at the Gage Junction Panel or at the strain gage.

In addition to the excitation supply, another individual isolated supply is provided for zero suppression. This supply provides 0 to ±40 millivolts for insertion in the input signal to balance the strain gage bridge so that the output signal is zero when no load is applied to the balance. The resistor used for this voltage insertion does not unbalance the signal input by more than 100 ohms. Both supplies are adjustable from a 10-turn precision potentiometer having a resolution of at least 0.01% of full scale. The signal conditioner also provides methods for calibrating both the strain gages and instrumentation. These calibration functions may be controlled locally from the front panel or remotely by the computer. The mode of control is dictated by a switch on the signal conditioner front panel. The following functions are provided by the signal conditioner:

1. Operate: The unit is set for normal operation; suppression voltage is in; gage signal is connected to the output terminals.
2. System Zero: The gage input signal is replaced with a short circuit and the suppression voltage is not applied.

3. Absolute Zero: The suppression voltage is out and the gage input signal is connected.
4. Suppression Calibrate: The gage signal is disconnected and the suppression voltage is connected to the signal output.
5. System Calibrate: The gage is disconnected, suppression voltage is out, and the output signal is connected to the calibration signal input.
6. Shunt Calibration: The selected bridge arm is shunted by a 0.01%, 40K- or 80K-ohm resistor. Shunt resistor is selectable by an externally provided switch.

A simplified schematic of the signal conditioner is shown in Figs. 9 and 10.

Following the signal conditioner is a passive 4-Hz low-pass filter. This filter is used to prevent saturation of the input transistors of the Preston amplifiers by high-frequency noise. A schematic of the low-pass filter is shown in Fig. 11.

The amplifiers used in the FAMROS are Preston Scientific Wideband D.C. amplifiers, Model 8300-XWB. This amplifier is a wideband floating differential amplifier which provides complete isolation between input and output circuits. The amplifier provides a gain of 1 to 1,000 with a filtered output selectable at 2 Hz, 100 Hz, 1 KHz, 10 KHz, or 100 KHz, and a common mode rejection of 120 decibels from D.C. to 60 Hz. Since a shunt calibration is used to check the sensitivity of the FAMROS, the most important specification of the amplifier is gain linearity. This amplifier, with a

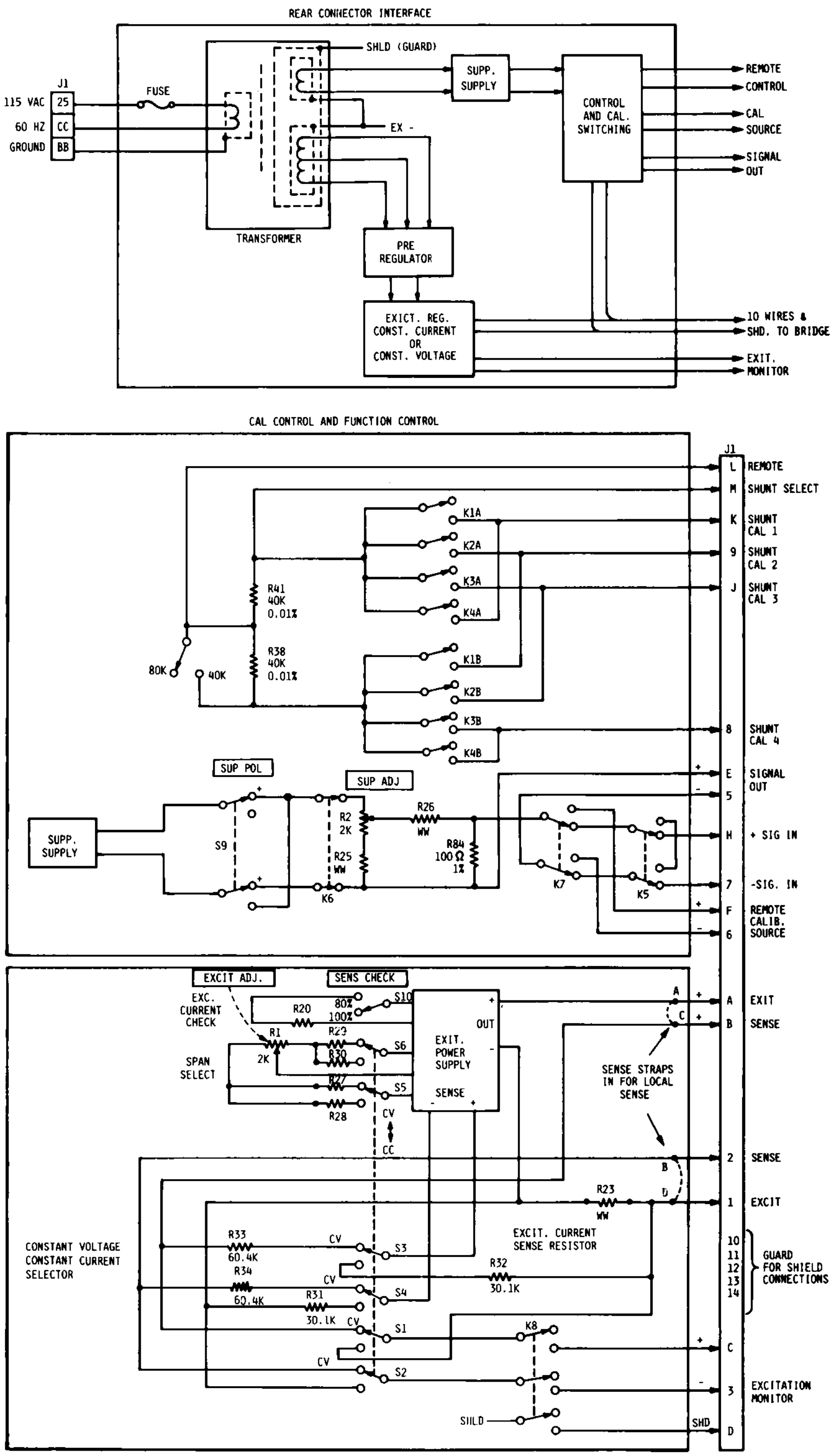


Figure 9. Signal conditioner schematic.

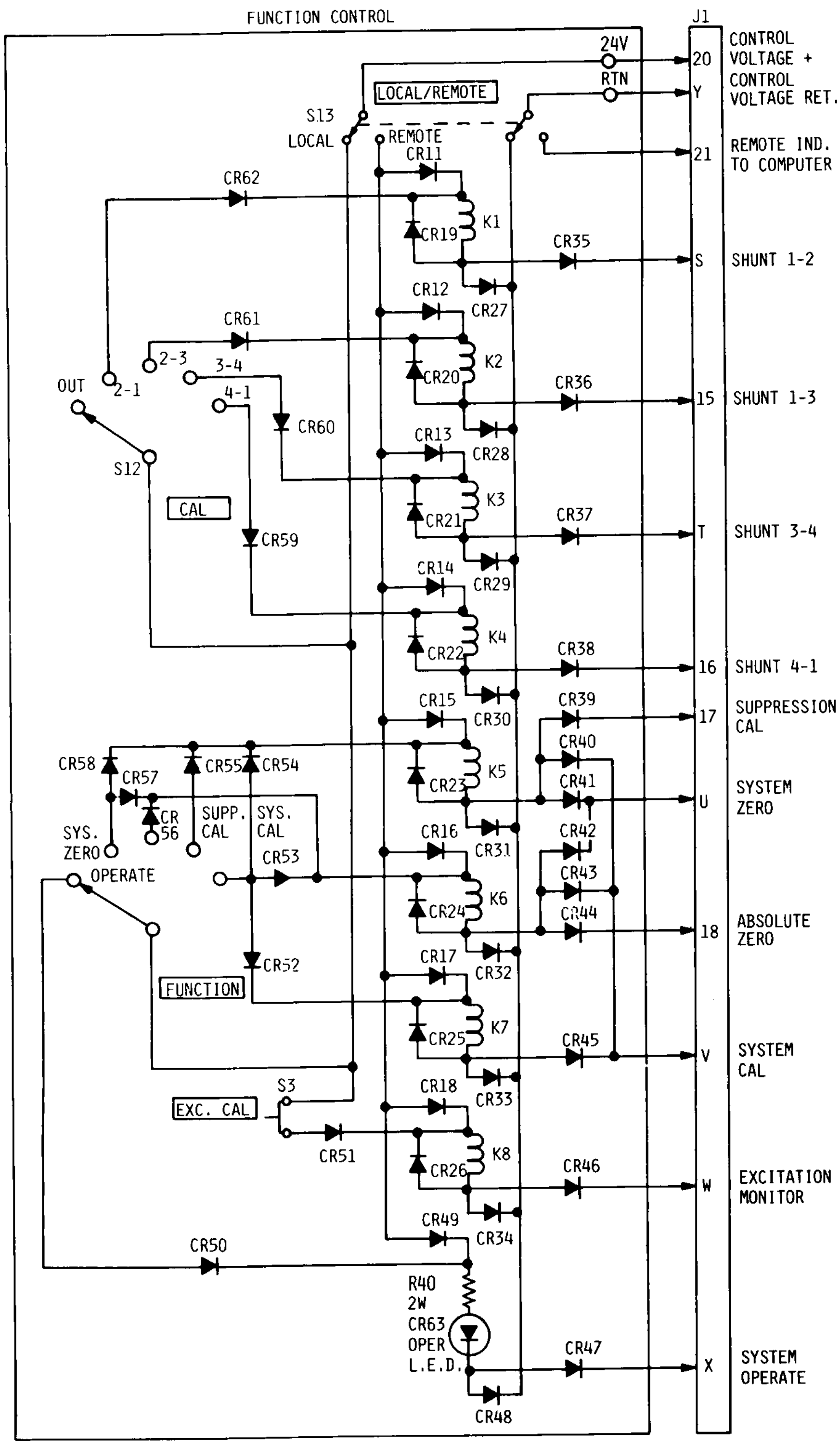


Figure 10. Signal conditioner function control.

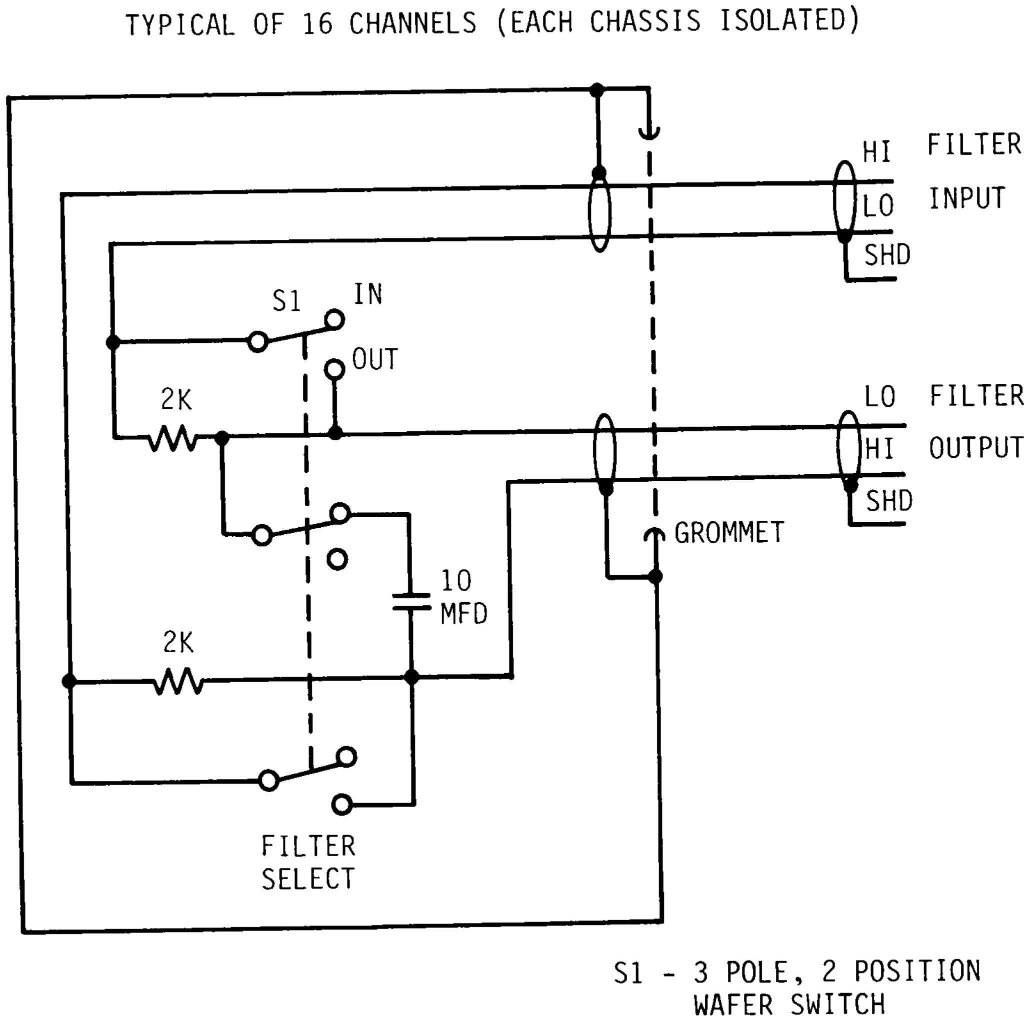


Figure 11. The 4-Hz low-pass filter.

gain linearity of ±0.01% full scale, provides the required resolution of one microvolt on all balance data since the full-scale output is ±10 volts [5].

The conversion of data from analog to digital form takes place in a 15-bit analog-to-digital (A/D) converter/multiplexer. A Preston Scientific Model GMAD4 converter/multiplexer is used to perform this function. This 32-channel, single-ended device switches input signals of ±10 volts full scale to a 15-bit A/D converter, which performs a two's complement conversion of the data. The 15-bit converter gives a resolution of 0.61 mV on all digitized data; thus, when the amplifiers are operated at a gain of 1,000, a resolution greater than one microvolt is achieved for all balance data. The single-ended multiplexer can be used to reduce cost since the Preston amplifiers have already isolated the strain gage from the multiplexer. In addition to all data channels, an excitation bus is wired into the A/D from the signal conditioners so that excitation can be monitored or recorded during system setup. Channel selection is controllable from the front panel of the multiplexer, or remotely, by the computer.

The control center of the FAMROS is a Computer Automation LSI 4/30 minicomputer. This is a versatile computer capable of being configured for specific user applications, since various memories and peripheral interfaces may be purchased separately on individual cards and plugged into a common backplane. Physically, the cards are one of two sizes: 15.0 in. by 16.9 in., or 7.5 in. by 16.9 in., and have plated edge connectors. All cards fit into a standard 19-in. card rack and require three supply voltages: +5V, +12V, and -12V. These voltages are provided by a single multi-output supply capable of providing +5V at 36 amps, +12V at 6 amps, and -12V at 9 amps. The minicomputer configuration is fully expandable for future modifications of the FAMROS. The existing system includes:

1. An LSI 4/30 CPU with an optional instruction set.
2. A 48K core memory.
3. A five-megabyte disk subsystem.
4. Two distributed input/output (I/O) cards capable of interfacing 12 peripheral devices.

The existing configuration is shown in the block diagram in Fig. 12.

The LSI 4/30 CPU is a high performance minicomputer capable of executing 102 standard instructions and 24 optional instructions, including floating point arithmetic instructions, in either the word or byte mode. The CPU provides eight program addressable 16-bit registers including four general purpose registers, a program counter, a status register, and two stack registers. In addition, the CPU provides a real-time clock, power-fail restart, and an Autoload capability. Autoload uses a bootstrap program stored in Read Only Memory (ROM) to load a system operating program from the disk. The CPU is also interfaced to a programmer's console which is used to assist a programmer or operator in debugging and running software. The console provides switches which may be used to examine and alter CPU registers and memory. Switches are also provided for functions such as Autoload, Stop, Run, Console Interrupt, Clear, and Reset.

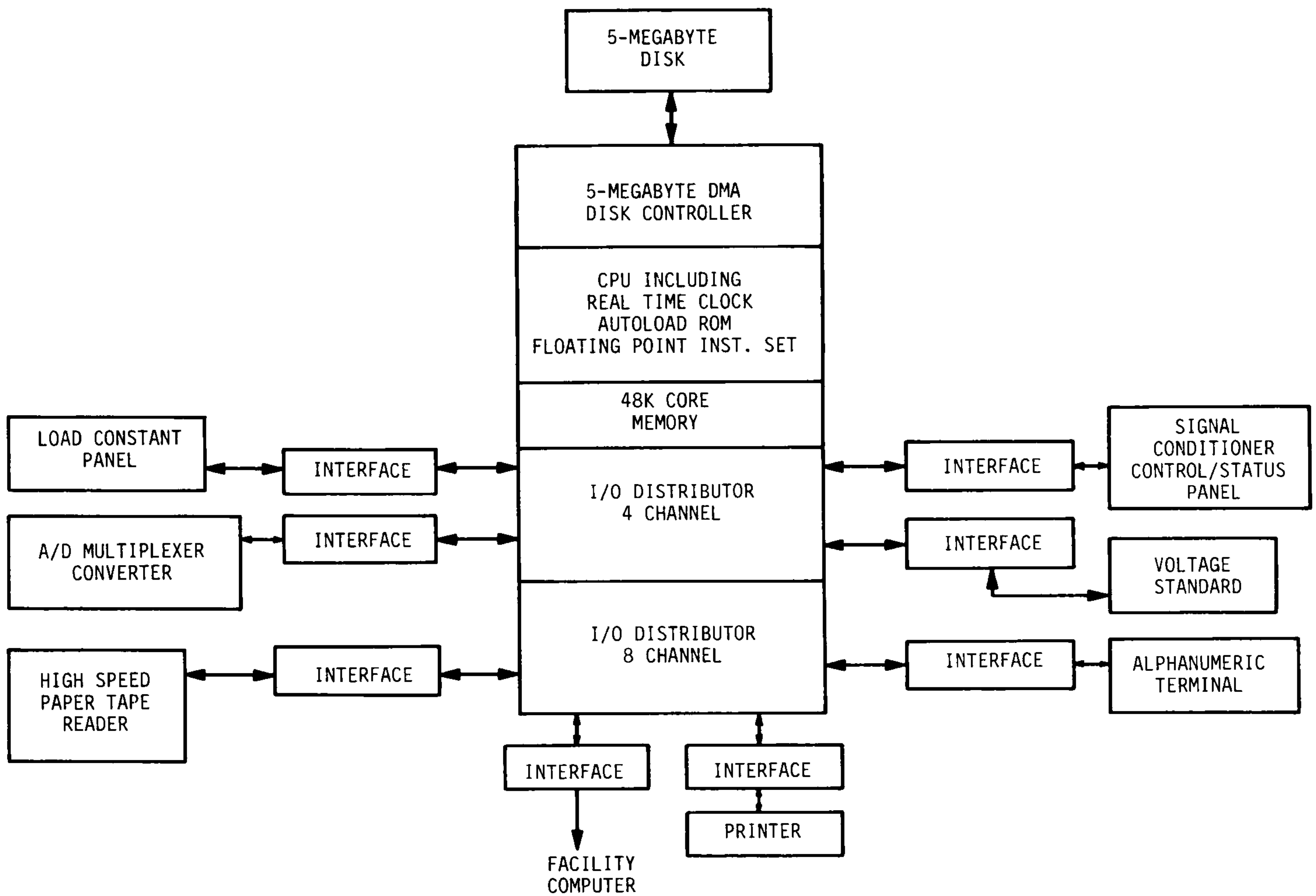


Figure 12. Existing minicomputer configuration.

The system uses 48K core memory, provided on three 16K cards, for program and data storage. Memory is expandable to 64K using Random Access or core memory; therefore, ample memory is available for future software expansion. A five-megabyte Pertec disk system is used to store data and system-operating software. The disk system consists of a 2.5-megabyte fixed platter which is used to store all system software, and a 2.5-megabyte removable platter for data storage. A Direct Memory Access (DMA) controller is used to transfer data to and from system memory.

The I/O system consists of two main parts: the I/O distributors which are multiport interface control systems, and the Intelligent cables which are Picoprocessors microprogrammed for operation with specific peripheral devices. The I/O distributors are programmed with standard instructions to handle data transfers using interrupts with the automatic I/O feature of the LSI 4/30 minicomputer or using direct program control. The I/O distributors are available with either eight or four channels; the FAMROS configuration contains one of each. Four channels are available on the eight-channel distributor for future expansion. Two types of interrupts are used when data are transferred under interrupt control. Each channel of the I/O distributors is assigned a block of memory containing eight words to be used as interrupt vectors. The first four words are associated with a Data Service interrupt. In this memory block the CPU stores an automatic input or output instruction. This is a three-word instruction which contains the number of bytes to be transferred and the beginning address of the data buffer. Each time a Data Service interrupt is received, a data byte is transferred from the Intelligent cable and stored at the memory address for an input operation and vice versa for an output operation. When each byte is transferred the address is incremented and the byte count is decremented. When the byte count is decremented to zero the second type of interrupt, an End-of-Block (EOB) interrupt, is received. This interrupt causes the instruction stored in the next four words of the interrupt vector to be executed. An EOB interrupt instruction usually causes program operation to branch to an EOB subroutine. Interrupts are given priority from the lowest address to highest address with all Data Service interrupts given priority over EOB interrupts. The programmer's console interrupt has priority over both Data Service and EOB interrupts. Channel addresses and interrupt vector addresses for each Intelligent cable are shown in Table A-1 (Appendix A).

The second part of the I/O system is the Intelligent cables. The I/O system allows any mix of Intelligent cables to be attached to the I/O distributors. The cables are attached to the I/O distributors by cables terminated with 16-pin dip sockets. Each Intelligent cable contains a Picoprocessor which is a small special purpose processor designed to control the transfer of data between the peripheral device and the I/O distributors. The operation of the Picoprocessor is sequenced and controlled by microprogrammed firmware instructions. The firmware instructions are arranged into one or more programs that are tailored to the specific needs of the peripheral device. A command word is sent to a Picoprocessor to cause firmware to branch to the desired firmware program. Each Picoprocessor also contains a status register which contains information about the status of the attached peripheral. Figure 13 shows a typical Picoprocessor with the cover removed.

The current FAMROS configuration uses eight Picoprocessors. The I/O ports are listed in Table A-2 (Appendix A) and the status bits of each Picoprocessor are listed in Table A-3 (Appendix A) [8]. The peripherals attached to the computer include an Infoton Alphanumeric terminal which is used to display data and control system operations, a Centronics 80-character-per-line printer used to provide a hard copy printout of data, and a Remex high-speed paper tape reader for reading various operating and diagnostic programs. A high-speed serial interface is provided to transfer data to the facility computer for increased data reduction capabilities.

The above devices were attached directly to their respective Picoprocessors, but the remaining devices required line drivers. Open-collector line drivers (SN7407) were used to interface the Preston A/D multiplexer/converter and the Electronic Development Corporation (EDC) voltage standard. The voltage standard is used to inject a known voltage into the FAMROS for calibration. Two special devices and interfaces were designed at the Arnold Engineering Development Center (AEDC) for the FAMROS. The first is a Load Constant Panel. This panel provides a constant on BCD switches for entering the load applied to the balance or the angle of an API. A data request switch is also provided for the operator to request that the CPU take a data point. This panel uses standard TTL logic

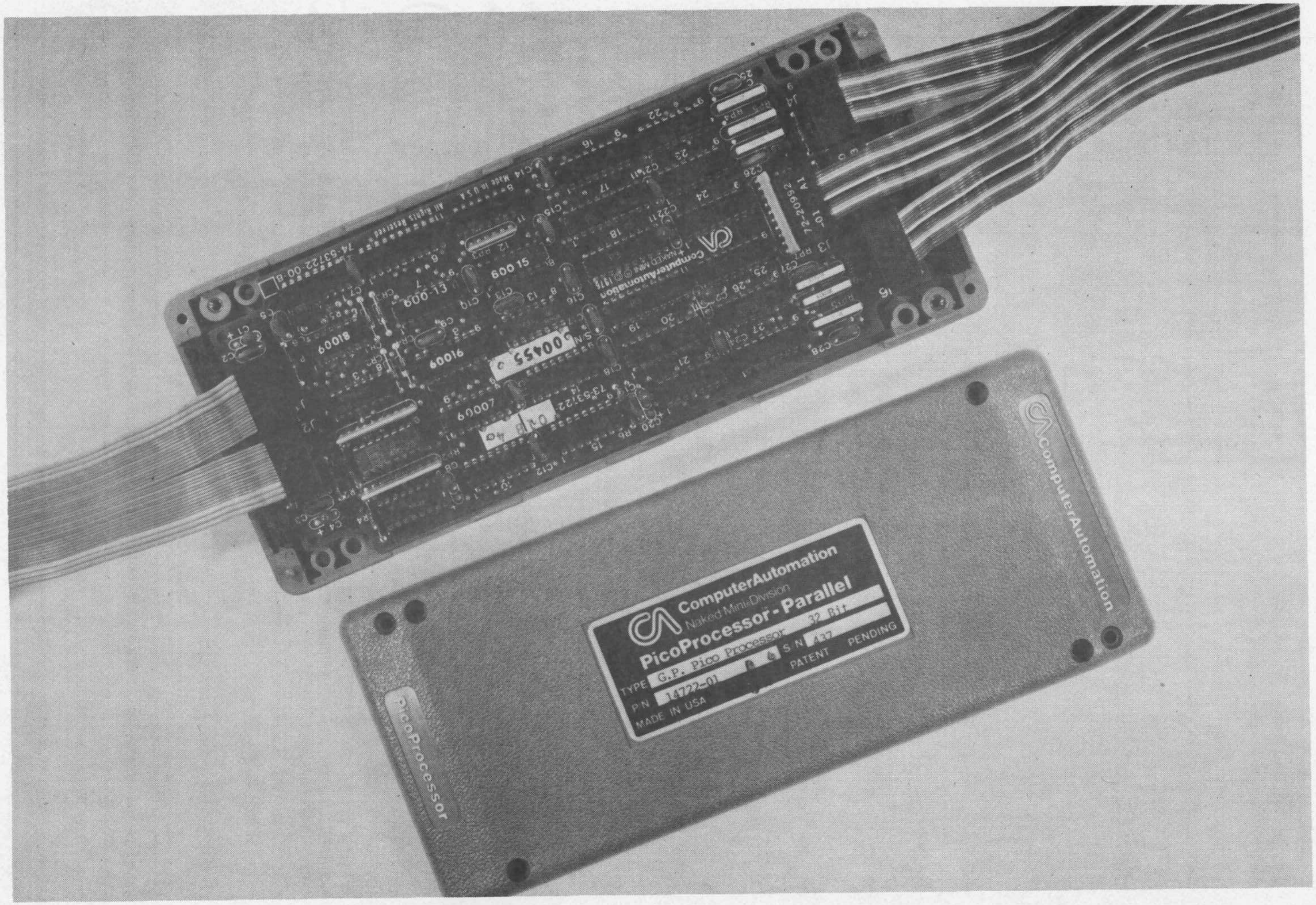


Figure 13. Picoprocessor.

gates to provide latches for the data request interrupt and the ready signal from the computer. A simplified schematic of the Load Constant Panel is shown in Fig. 14. The second special device is the Signal Conditioner Control/Status Panel. This device uses two 4- to 16-line decoders to select the various calibration and setup functions for the FAMROS. After the binary code sent by the computer has been decoded, the output of the decoder is used in conjunction with inverting line drivers to turn on a transistor. This saturated transistor provides a ground which pulls in the appropriate relays, provided in the signal conditioners, for the desired setup function. The function and excitation bus control/status logic circuits are shown in Figs. 15 and 16, respectively. A picture of the completed FAMROS is shown in Fig. 17.

IV.3. Software Description

The operating software for the FAMROS is to provide a very flexible system allowing the operator to adapt the software package to meet the specific requirements for any strain gage balance or API calibration. This will be accomplished through the use of a conversational format in which the operator is asked for specific information. This information establishes the channels to be used, the time constant for the digital filter, and the automatic calibration control. The operating software currently consists of seven individual programs. These programs are loaded into the computer using an operating system program (OS4) purchased from Computer Automation. The operating system program is also linked with each individual

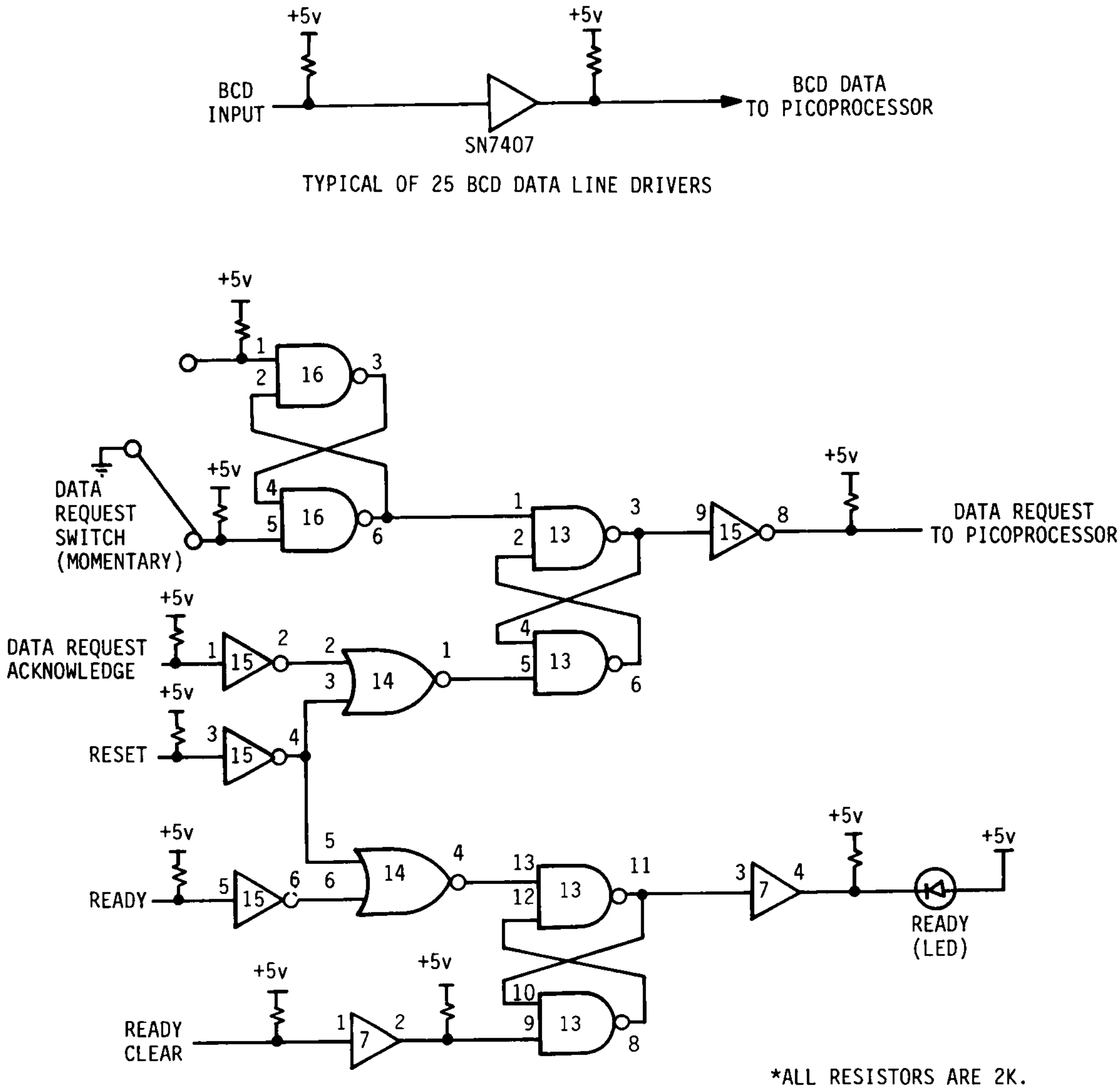
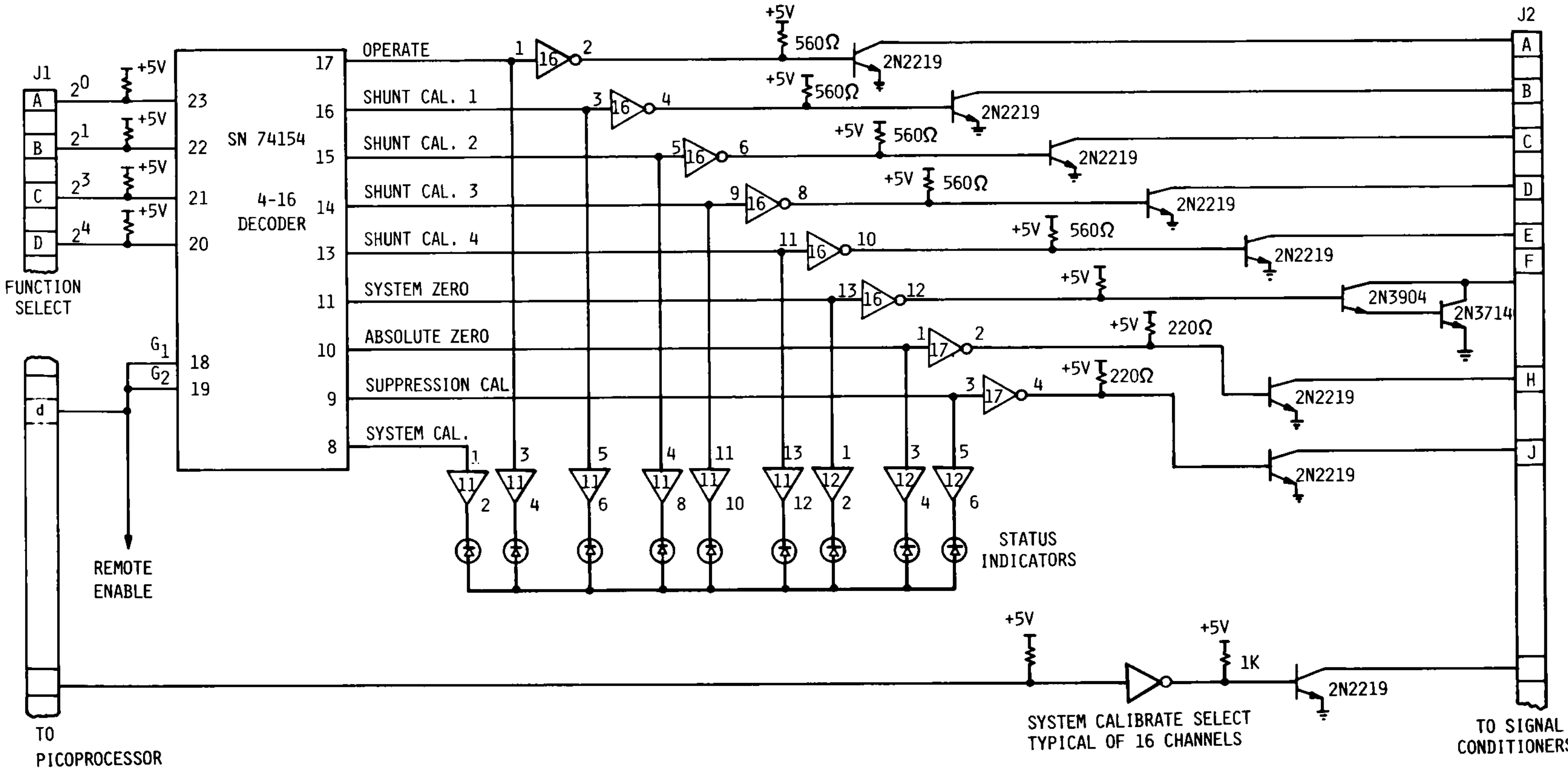


Figure 14. Load constant panel schematic.



NOTES: ALL RESISTORS ARE 2K UNLESS NOTED.
J1 AND J2 ARE 56 PIN ELCO CONNECTORS.

Figure 15. Function control/status logic circuit.

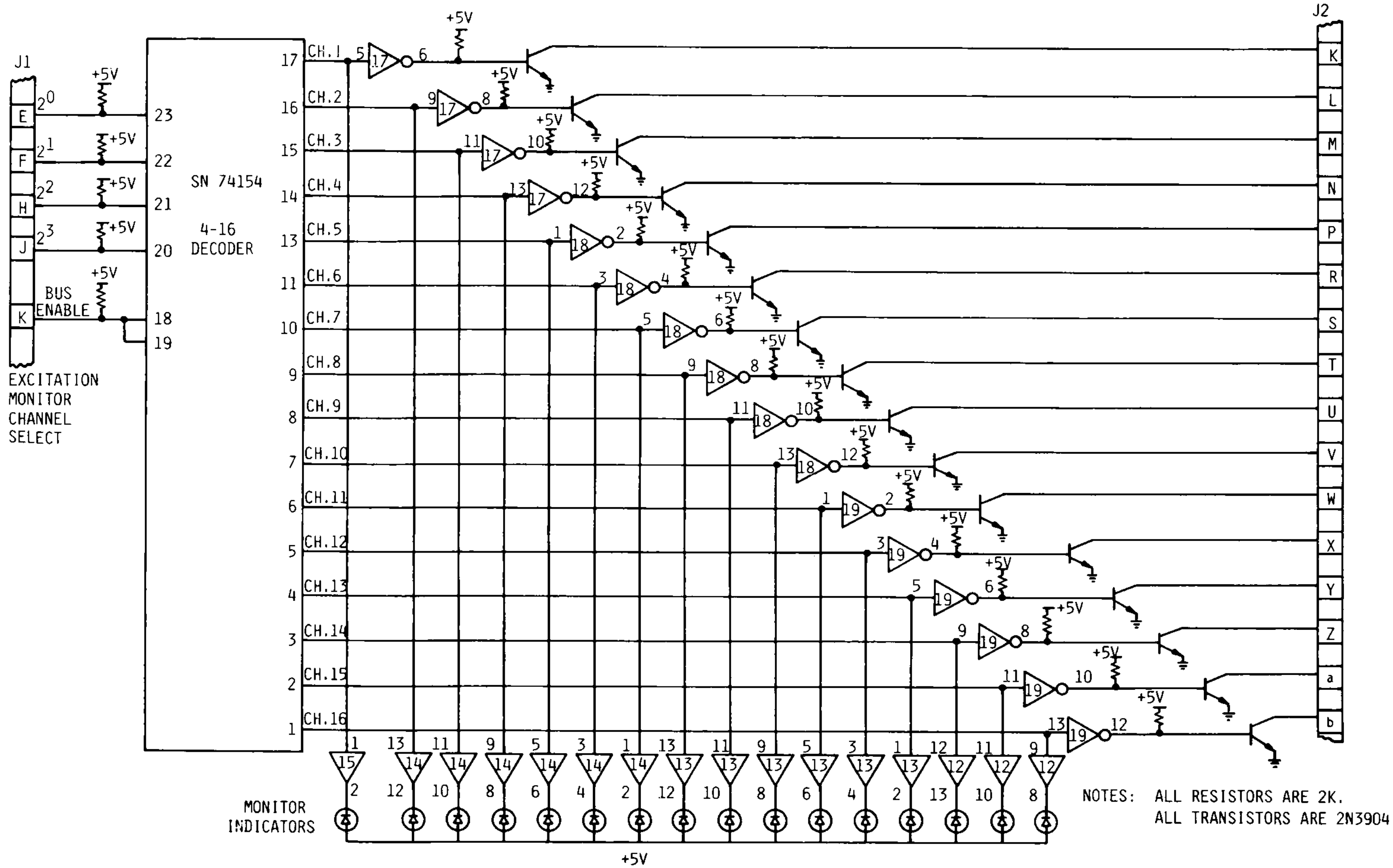


Figure 16. Excitation bus control/status logic circuit.

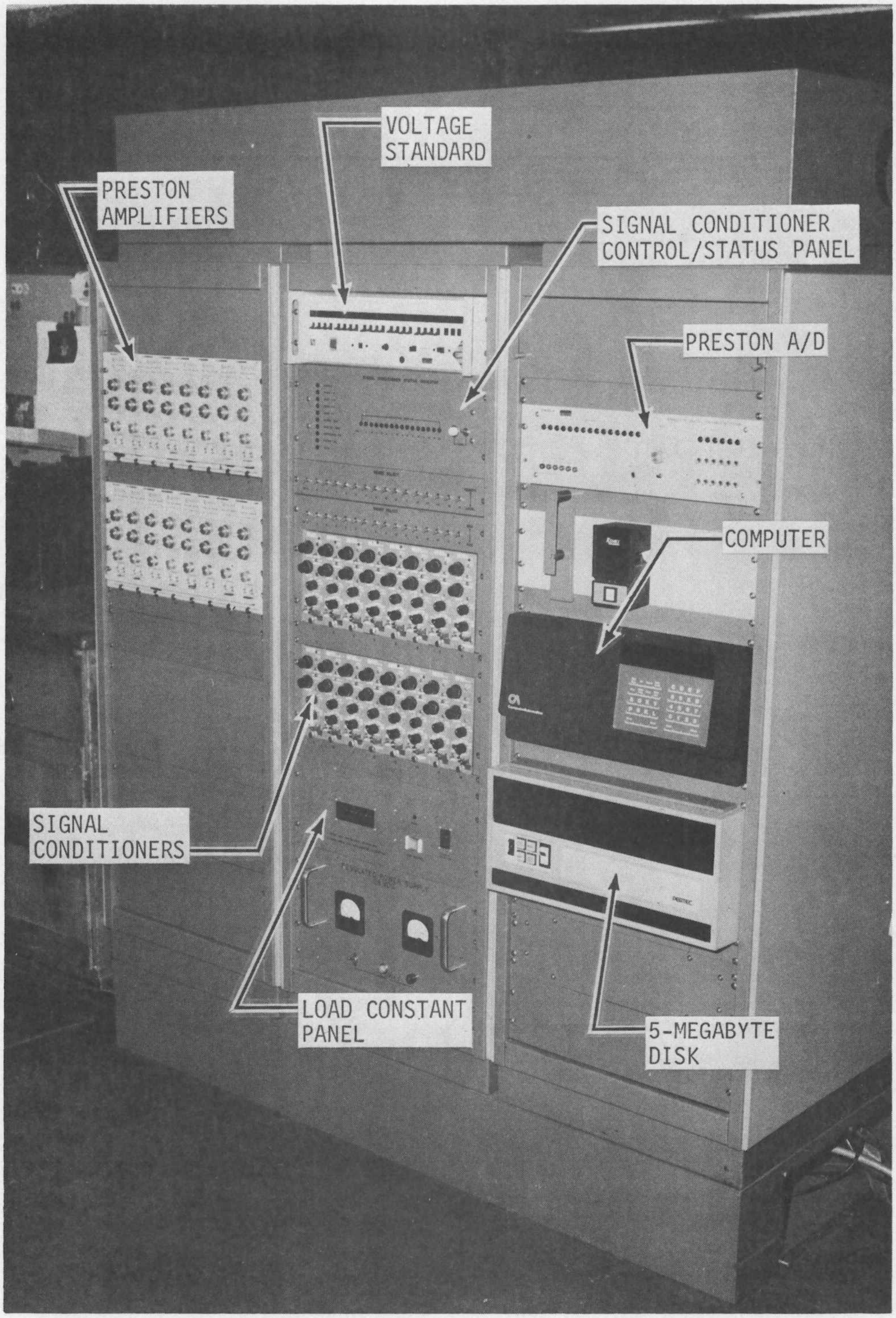


Figure 17. Force and moment readout system.

program since it provides a number of service and utility programs which simplify the task of creating user software. The name and use of each user program can be found in Table 2. Each user program allows various functions to be executed upon operator command. The operating system program can be entered from a user program at any time by using a Function X or pressing the interrupt switch on the computer console.

The "Operate" program is used during the actual calibration operation. Function A is used for a balance calibration. When Function A is executed, the operator enters the load number, type load, and the load position. The load number is used to identify a set of data points taken at one position on the balance. After the appropriate constants are entered, data from the balance are displayed in real time on the system console CRT. A data point is recorded when a data request is received from the Load Constant Panel. The software prepares for a data request by setting the load constant I/O port for automatic input and turning on a ready indicator. An EOB interrupt is then generated after the data request switch has been pressed and the load constant has been read by the computer. The load constant is a six-digit signed constant which signifies the load amount applied to the balance. Each data point is recorded using the digital filter with the filter constant and sampling rate entered in the "Setup" program. Each data point is also assigned a record number by the operating software. Data are displayed and printed in engineering units of millivolts. Data are printed in blocks of eight channels; the first eight channels are

Table 2. User Operating Program Names and Uses

Program	Use
1. OPERATE	Used in the recording of balance and API data
2. SETUP	Used to enter various balance calibration headings and constants
3. API SETUP	Used to enter various API calibration headings and constants
4. SHUNT	Performs system setup and balance shunt calibration
5. CALIBRATE	Performs 21-point system voltage calibration
6. ABSOLUTES	Records balance weight
7. TRANSMIT	Sends calibration data to facility computer for further data reduction

printed as the data are taken and all remaining channels are printed upon completion of a loading. The operator denotes the end of a loading by pressing the sense switch on the computer console. The slope, intercept, and correlation coefficient of the data for each channel are calculated using a least-square curve fit.

Function B is used to display the excitation voltage for each channel on the operator's console. Sometimes a constant load is applied to a balance while another load is varied. Function C is used to enter the type, amount, and position of this constant load.

Function D, which denotes an API calibration, is approximately the same as Function A; only the manipulation of the data is different. The constant read by the computer is an angle instead of a load, and the data printout headings are different.

The "Setup" program is used to enter specific requirements of the balance calibration program. When a setup function is entered, the software will print the constant name followed by its current value and ask if the operator wants to change the constant. If the operator wishes to change the constant, he types Yes and enters the new value. If no change is desired, a carriage return is used. The following is a list of each setup function and its use:

1. Function A: Test No., Project No., Calibration No., Balance Name, Reference Location, Calibration Distance, Balance Case, and Plot Scale.
2. Function B: Sampling Rate.
3. Function C: Digital Filter Constant.
4. Function D: Spare.

5. Function E: Spare.
6. Function F: Enter channels to be scanned and gain of each channel.
7. Function G: Lists scan sequence, channel number, and amplifier gain on operator's console.

The definition of the above constants and the remaining constants in this section are given in Table C-1 (Appendix C).

The "API Setup" program is identical to the "Setup" program, except it is used to enter the specific requirements for an API calibration; API setup functions are:

1. Function A: Test No., Project No., API No., I No., and Initial Roll Position.
2. Function B: Sampling Rate.
3. Function C: Digital Filter Constant.
4. Function D: Computing Code.
5. Function E: Roll Angle.
6. Function F: Enter channels used and gain of each.
7. Function G: Output Array entered in Function F.

The "Shunt" program executes automatically the system setup routine for each channel that is being used. The program outputs all data to the system printer and returns automatically to the operating system program if the operator indicates he is finished by typing Yes on the console upon completion of the setup routine. The program provides a one-second delay after the selection of each control bus, except the Excitation bus, which requires a 100-millisecond delay. The smaller delay for the Excitation bus is permissible since the Excitation bus does not contain a 2-Hz, low-pass filter. Digital filtering is used on all recorded data. The setup functions performed are:

1. Gage Zero: Gage readings with no load applied and suppression voltage applied.
2. System Zero: The gage input signal is replaced with a short circuit and suppression voltage is not applied.
3. Absolute Zero: Gage readings with no suppression voltage applied.
4. Suppression Calibrate: The gage signal input is disconnected and the suppression voltage is connected to the signal output.
5. System Calibrate Zero: Readings are recorded with zero volts injected into the signal conditioners.
6. System Calibrate (70% full scale): Readings are recorded with 70% of full-scale input injected into the signal conditioners.
7. Excitation: Excitation voltage for each channel is recorded.
8. Shunt Calibration: Gage readings are recorded with each arm of the strain gage shunted by the calibration resistor.
9. Shunt Average: The average of the absolute value of the readings taken during the shunt calibration.

The "Calibrate" program is used to perform a complete 21-point calibration of the system. Function A is used to enter the voltage range over which the system is to be calibrated, the channels to be calibrated, and the gain of each channel. If a gain is entered such that the gain times the maximum voltage of the calibration range is greater than 10 volts, an error message will be printed on the system console. Function B is used to execute the calibration. A one-second delay is required after each voltage setting is sent to the standard, and digital filtering is used on all data readings. The voltage increment is calculated as,

$$\text{Increment Size} = \frac{\text{Max. Voltage - Min. Voltage}}{20}$$

Errors are then tabulated for each channel, at each voltage setting, as a percentage error in the gain. The equation is,

$$\text{Percent Error} = \left[\frac{\text{Reading - Zero Reading}}{\text{Voltage Input x Nom. Gain}} - 1\right] \text{x } 100\% \text{ .}$$

Before each calibration is started, the balance itself is weighed using the strain gages. This is accomplished using the "Absolutes" program. When the program is executed, the software will request a type load. After the type load is entered, the Gage Zero, Absolute Zero, and Suppression Calibrate readings are printed. This process is repeated until the balance has been rolled to all four possible positions.

The "Transmit" program is used to send calibration data to the facility computer. The data are transferred by calibration number and record numbers. The data buffer sent to the facility computer is shown in Table C-2 (Appendix C). The data printouts for each program can be found in Appendix B.

CHAPTER V

RESULTS

The Force and Moment Readout System (FAMROS) has been fabricated and tested at Arnold Engineering Development Center (AEDC). Checkout of the analog portion of the FAMROS was accomplished by attaching a strain gage bridge to each channel at the Gage Junction Panel and simulating all calibration and setup conditions. The low-pass filters were checked by attaching an oscillator to the signal input of the FAMROS and using an oscilloscope at the output of the Preston amplifiers to check that all high-frequency signals were filtered. Data accuracy was checked by attaching a voltage standard to the signal input and comparing the known input to the value recorded by the A/D converter. The resolution of the system was found to be better than that of the one microvolt required. Diagnostic programs were written or purchased to check all digital interfaces and devices used in the FAMROS.

The system is currently being used daily in performing the calibration of strain gage balances and angle position indicators used in the Propulsion Wind Tunnel Facility at AEDC. The system has resulted in more accurate and faster calibrations due to the increased capabilities in the areas of automatic calibration and data reduction.

CHAPTER VI

FUTURE PLANS

Work is already underway to expand the FAMROS to 24 channels so that it will be capable of calibrating the more complicated balances expected in the future. Further hardware additions planned are a digital plotter and a graphics terminal. This will allow the operator to view data and residual plots, giving him a greater capability to determine the validity of calibration data.

During the calibration process, the balance must be leveled after each load is applied to ensure that all output data are due to the load and not the angle of the balance. This leveling is presently done manually, but plans are to develop automatic leveling capabilities for the FAMROS. The automation of loading the balance is also planned for a future project.

It is recommended that further development efforts be made in the software areas to provide increased data reduction capabilities for the FAMROS. Software could eventually be used to identify data points that cause the derived equations to produce values that are outside the required accuracy. An editor program is also planned to enable the operator to view and correct data stored on the disk. Presently, API calibration data are not sent to the facility computer. Future plans include a program for the facility computer to accept and reduce data on all API calibrations.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. "Strain Gage Balances, Their Uses and Their Calibration." Lecture presented at Arnold Engineering Development Center, Arnold Air Force Station, Tennessee, September 1975.

2. Blevins, J. C. "Calibration-Strain Gage Balances," Arnold Engineering Development Center Instrumentation Procedure No. PM5002, Arnold Air Force Station, Tennessee, June 1974.

3. Vaughn, John. Strain Measurements. Copenhagen, Denmark: B&K Instruments, Inc., 1975.

4. Strain Gage Handbook. Waltham, Massachusetts: Baldwin Lima Hamilton Corporation, [n.d.].

5. Preston Instruction Manual Model 8300-XWB Floating Differential Amplifier. Anaheim, California: Preston Scientific Inc., 1971.

6. Kaiser, J. F. "Digital Filters," Digital Filters and the Fast Fourier Transform. Bede Liu, editor. Stroudsburg, Pennsylvania: Holsted Press, 1975. Pp. 5-65.

7. Signal Labs Operation and Maintenance Manual for Model IS-102 Signal Conditioners. Orange, California: Signal Laboratories, Inc., 1975.

8. Intelligent Cables Reference Manual. Irvine, California: Computer Automation, Inc., February 1980.

APPENDICES

APPENDIX A

INPUT/OUTPUT DESCRIPTION

Address maps of the input/output (I/O) ports are necessary for a complete understanding of the interfaces between peripheral devices and the computer. The I/O addresses and descriptions are shown in Table A-1. Table A-2 lists the data bits for each parallel interface. The bits that contain I/O status information are shown in Table A-3 and are defined in Table A-4.

Table A-1. Input/Output Ports

Peripheral Device	Data Address (HEX)	Vector Address	Type Interface
Preston A/D Multiplexer Converter	E8	A0	Parallel: 8 Bits Output 16 Bits Input
Voltage Standard	EA	A8	Parallel: 32 Bits Output
Signal Conditioner Control/Status Panel	EC	B0	Parallel: 30 Bits Output 2 Bits Input
Load Constant Panel	EE	B8	Parallel: 2 Bits Output 30 Bits Input
Facility Computer	F4	D0	RS-232 Serial
System Console	F8	E0	RS-232 Serial
Paper Tape Reader	FA	E8	Parallel: 8 Bits Input
Centronics Printer	FE	F8	Parallel: 8 Bits Output

Table A-2. Parallel Input/Output Data Bits

DEVICE	BIT CONFIGURATION																COMMENTS
A/D INPUT			2^{13}	2^{12}	2^{11}	2^{10}	2^{9}	2^{8}	2^{7}	2^{6}	2^{5}	2^{4}	2^{3}	2^{2}	2^{1}	2^{0}	10 VOLTS = FULL SCALE
		SIGN	A/D DATA														
A/D OUTPUT											2^{5}	2^{4}	2^{3}	2^{2}	2^{1}	2^{0}	
											MUX ADDRESS						
VOLTAGE STANDARD LOW	2^{5}	2^{6}	2^{7}	2^{8}	2^{9}	2^{10}	2^{11}	2^{12}	2^{13}	2^{14}	2^{15}	2^{16}	2^{17}	2^{18}	2^{19}	2^{20}	$V_{OUT} = \frac{\text{FULL SCALE}}{2^N}$
VOLTAGE STANDARD HIGH													2^{1}	2^{2}	2^{3}	2^{4}	
	RANGE 1 = 10 VOLT 0 = 100 MV	POLARITY															
CONTROL PANEL LOW	2^{1}	2^{0}							2^{3}	2^{2}	2^{1}	2^{0}	2^{3}	2^{2}	2^{1}	2^{0}	
	DISPLAY CONSTANT							EXCITATION BUS ENABLE	EXCITATION SELECT				FUNCTION SELECT				
CONTROL PANEL HIGH	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	1 = SELECTED
	SYSTEM CALIBRATE CHANNEL SELECT																
LOAD CONSTANT LOW	2^{3}	2^{2}	2^{1}	2^{0}	2^{3}	2^{2}	2^{1}	2^{0}							2^{1}	2^{0}	READY 01 = ON, 10 = OFF
	TENTHS				HUNDREDTHS				CONSTANT SIGN						READY		
LOAD CONSTANT HIGH	2^{3}	2^{2}	2^{1}	2^{0}	2^{3}	2^{2}	2^{1}	2^{0}	2^{3}	2^{2}	2^{1}	2^{0}	2^{3}	2^{2}	2^{1}	2^{0}	
	THOUSANDS				HUNDREDS				TENS				UNITS				
PRINTER									2^{7}	2^{6}	2^{5}	2^{4}	2^{3}	2^{2}	2^{1}	2^{0}	
PAPER TAPE READER									2^{7}	2^{6}	2^{5}	2^{4}	2^{3}	2^{2}	2^{1}	2^{0}	

Table A-3. Peripheral Devices Status Bits

DEVICE	ADDRESS (HEX)	BIT CONFIGURATION	
A/D CONVERTER	E9	2^0	CONTROL MODE
		2^1	CONVERSION DONE
		2^5	SECOND BYTE
VOLTAGE STANDARD	EB	2^0	CONTROL MODE
		2^3	OVERLOAD
		2^7	DATA SERVICE REQUEST
SIGNAL CONDITIONER CONTROL/STATUS PANEL	ED	2^0	CONTROL MODE
		2^7	DATA SERVICE REQUEST
LOAD CONSTANT PANEL	EF	2^1	DATA REQUEST
		2^7	DATA SERVICE REQUEST
FACILITY COMPUTER AND SYSTEM CONSOLE	F5 F9	2^0	READY OUTPUT
		2^1	READY INPUT
		2^3	DATA READY
		2^4	TRANSMITTER EMPTY
PAPER TAPE READER	FB	2^1	READER READY
		2^3	DATA READY
CENTRONICS PRINTER	FF	2^0	BUSY
		2^1	POWER
		2^2	ACKNOWLEDGE
		2^4	PAPER LOW
		2^5	PRINTER CONNECTED

Table A-4. Status Bit Descriptions

Status Bit	Description
Acknowledge	A logic 0 signals printer acceptance of transferred data
Busy	A logic 1 indicates printer is busy processing a data byte
Control Mode	A logic 1 indicates manual control; a logic 0 indicates remote control
Conversion Done	A logic 0 indicates A/D conversion is complete and data are ready for transfer to computer
Data Ready	A logic 1 indicates data byte has been received and is ready for transfer to computer
Data Request	A logic 0 indicates that operator has requested a data point be taken
Data Service Request	A logic 0 indicates that the Picoprocessor is transferring a data byte during automatic I/O
Overload	A logic 0 indicates that the voltage standard is in an overload condition
Paper Low	A logic 1 indicates printer paper is exhausted
Power	A logic 1 indicates printer power is On
Printer Connected	A logic 0 indicates printer is connected to the Picoprocessor
Reader Ready	A logic 0 indicates reader power is On
Ready Input	A logic 0 indicates the device is ready to send data
Second Byte	The A/D Picoprocessor transfers only eight bits at a time; a logic 0 indicates the second byte is to be transferred
Transmitter Empty	A logic 1 indicates that the Picoprocessor is ready to receive another byte for transmission

APPENDIX B

FAMROS DATA PRINTOUTS

Tables B-1 through B-4 contain the hard copy computer printouts that are currently available using the software described in Chapter IV.

Table B-1. Operate Program Data Printout

BALANCE CALIBRATION

TEST: DATE: 06/22/81 TIME: 14:06:15

CN	LN		TL	X, IN.	Y, IN.	Z, IN.	
2085	2	VARYING LOAD:	1	2.1900	.0000	.0000	
		CONSTANT LOAD:	0	.0000	.0000	.0000	.00 LBS.

L	REC	R 1	R 2	R 3	R 4	R 5	R 6
.00	37	.000	.000	.000	.000	.000	.000
400.00	38	.614	.013	.000	.003	-.096	.000
800.00	39	1.229	.028	.003	.002	-.185	.000
1200.00	40	1.845	.043	.009	.002	-.276	.002
1600.00	41	2.463	.058	.012	.003	-.365	.002
2000.00	42	3.077	.073	.019	.004	-.452	.004
1600.00	43	2.464	.060	.019	.005	-.366	.004
1200.00	44	1.849	.045	.013	.004	-.277	.002
800.00	45	1.233	.029	.006	.003	-.186	.001
400.00	46	.618	.012	.001	.003	-.093	.000
.00	47	.001	-.001	.001	.000	.000	.000
SLOPE		1.5E-03	3.7E-05	1.0E-05	1.8E-06	-2.3E-04	2.1E-06
INTERCEPT		4.2E-04	-1.3E-03	-1.8E-03	1.0E-03	-2.6E-03	-5.6E-04
CORRELATION		1.0E+00	1.0E+00	9.4E-01	7.6E-01	-1.0E+00	9.1E-01

CN	LN		TL	X, IN.	Y, IN.	Z, IN.	
2085	3	VARYING LOAD:	1	7.1900	.0000	.0000	
		CONSTANT LOAD:	0	.0000	.0000	.0000	.00 LBS.

L	REC	R 1	R 2	R 3	R 4	R 5	R 6
.00	48	.000	.001	.000	.001	.002	.000
400.00	49	.292	.008	.000	.004	.294	.010
800.00	50	.589	.016	.001	.005	.583	.020
1200.00	51	.884	.024	.003	.006	.875	.029
1600.00	52	1.178	.033	.007	.008	1.167	.037
2000.00	53	1.472	.041	.009	.010	1.461	.044
1600.00	54	1.180	.033	.006	.008	1.169	.037
1200.00	55	.888	.024	.002	.007	.880	.028
800.00	56	.597	.015	.000	.007	.588	.018
400.00	57	.300	.007	.000	.005	.297	.008
.00	58	.000	.001	.000	.001	.003	.000
SLOPE		7.4E-04	2.0E-05	4.5E-06	4.0E-06	7.3E-04	2.3E-05
INTERCEPT		1.6E-03	1.6E-05	-1.5E-03	2.0E-03	3.0E-03	3.5E-04
CORRELATION		1.0E+00	1.0E+00	9.1E-01	9.5E-01	1.0E+00	1.0E+00

Table B-2. Shunt Program Printout

BALANCE CALIBRATION
SYSTEM SET-UP DATA

DATE: 06/22/81 TIME: 14:51:27

CALIBRATION NO. CN2085
BALANCE: MCAIR/ABLE 2.75 MK III S/N 24620 B

TEST NO. PROJECT NO. P43G 154

CALIBRATION DISTANCE: .9888 PLOT SCALE: 5 BALANCE CASE: 2
REFERENCE LOCATION: BALANCE FACE

SAMPLING RATE: 120.
DIGITAL FILTER CONSTANT: .98

LOAD NO. 5

	REC	R 1	R 2	R 3	R 4	R 5	R 6
GAGE ZERO		.000	.000	.000	.000	.000	.001
SYS. ZERO		-.006	-.009	-.011	-.010	-.005	.002
ABS. ZERO		.011	.119	-.711	.021	.102	-.234
SUPP. CAL		-.017	-.128	.700	-.031	-.107	.238
SYCAL ZERO		-.007	-.009	-.010	-.009	-.004	.003
SYCAL .7FS		6.991	6.987	6.991	6.984	6.989	7.001
EX (VOLTS)		5.999	6.000	6.001	6.000	6.000	5.998
SHUNT 1-2	70	6.685	6.677	3.356	3.351	6.673	6.673
SHUNT 2-3	71	-6.675	-6.664	-3.356	-3.349	-6.671	-6.669
SHUNT 3-4	72	6.673	6.666	3.359	3.353	6.671	6.669
SHUNT 4-1	73	-6.673	-6.670	-3.353	-3.351	-6.670	-6.663
SHUNT AVG		6.677	6.669	3.356	3.351	6.671	6.669

Table B-3. Calibrate Program Printout

BALANCE CALIBRATION
SYSTEM CALIBRATE DATA

DATE: 06/23/81 TIME: 07:14:21

CALIBRATION NO. CN2085
BALANCE: MCAIR/ABLE 2.75 MK III S/N 24620 B

TEST NO. PROJECT NO. P43G 154

MINIMUM VOLTAGE = -9.500
MAXIMUM VOLTAGE = 9.500
INCREMENT SIZE = .950
GAIN CODE = 1000.000

SAMPLING RATE: 120.
DIGITAL FILTER CONSTANT: .98

VOLTAGE SET	R 1 CH 1	R 2 CH 2	R 3 CH 3	R 4 CH 4	R 5 CH 5	R 6 CH 6
-9.500	-.04	-.06	.02	-.08	-.09	-.07
-8.550	-.04	-.06	.04	-.07	-.08	-.07
-7.600	-.04	-.07	.03	-.07	-.09	-.07
-6.650	-.03	-.06	.03	-.06	-.09	-.06
-5.700	-.04	-.07	.02	-.07	-.09	-.07
-4.750	-.02	-.06	.04	-.06	-.08	-.06
-3.800	-.03	-.05	.03	-.08	-.08	-.08
-2.850	-.00	-.04	.04	-.07	-.07	-.11
-1.900	-.00	-.05	.05	-.05	-.05	-.11
-.950	-.00	-.11	.11	-.00	-.00	-.21
.950	-.21	-.21	-.11	-.21	-.32	-.21
1.900	-.11	-.11	-.05	-.11	-.21	.00
2.850	-.07	-.07	.00	-.11	-.14	.00
3.800	-.05	-.05	.00	-.08	-.13	.00
4.750	-.02	-.06	.02	-.06	-.11	.00
5.700	-.02	-.05	.02	-.07	-.11	-.02
6.650	-.02	-.05	.03	-.06	-.09	.00
7.600	-.01	-.04	.04	-.07	-.09	.00
8.550	-.01	-.04	.04	-.06	-.08	.00
9.500	-.01	-.04	.04	-.05	-.08	.00

Table B-4. Absolutes Program Printout

BALANCE CALIBRATION
BARE BALANCE ABSOLUTES

DATE: 07/29/81 TIME: 14:26:43

CALIBRATION NO. CN2091
BALANCE: MCAIR BAL. STING COMBO

TEST NO. TC 713 PROJECT NO. P43B 1E4

CALIBRATION DISTANCE: 4.9152 PLOT SCALE: 0 BALANCE CASE: 3
REFERENCE LOCATION: FACE OF BALANCE

SAMPLING RATE: 120.
DIGITAL FILTER CONSTANT: .98

TYPE LOAD = -1

	R 1	R 2	R 3	R 4	R 5	R 6
GAGE ZERO	.000	.000	.000	.000	.000	.000
ABS. ZERO	-.071	-.258	.000	-.056	-.114	.179
SUPP. CAL	.063	.249	.000	.044	.111	-.184

TYPE LOAD = 2

	R 1	R 2	R 3	R 4	R 5	R 6
GAGE ZERO	.000	.000	.000	.000	.001	-.001
ABS. ZERO	.009	-.169	.000	-.031	.029	.327
SUPP. CAL	-.015	.160	.000	.021	-.031	-.332

TYPE LOAD = 1

	R 1	R 2	R 3	R 4	R 5	R 6
GAGE ZERO	.000	.000	.000	.001	.000	.000
ABS. ZERO	.099	-.252	.000	-.056	.173	.184
SUPP. CAL	-.104	.243	.000	.047	-.176	-.188

TYPE LOAD = -2

	R 1	R 2	R 3	R 4	R 5	R 6
GAGE ZERO	.000	.000	.000	.000	.000	.000
ABS. ZERO	.017	-.340	.000	-.081	.030	.037
SUPP. CAL	-.025	.330	.000	.068	-.034	-.041

APPENDIX C

CALIBRATION CONSTANT AND DATA BUFFER DESCRIPTIONS

Several constants are required for each calibration performed. A complete understanding of these constants is required to comprehend the software specifications. A description of these constants is given in Table C-1. Table C-2 shows the data buffer sent to the facility computer; this buffer represents a record number.

Table C-1. Calibration Constant Definitions

Name	Definition
Balance Case	The number which identifies a balance as a direct reading, force, or moment balance
Calibration Distance	The distance between the face of the balance and the face of the calibration body
Calibration Number	The number associated with the data for each balance or API calibration
Computing Code	The number which identifies the equation to be used during the reduction of API data
Constant Load	During a balance calibration, sometimes one load is applied and held constant while another load is varied; this constant identifies the type, amount, and position of this constant load
Digital Filter Constant	The constant (A) to be used in the digital filter equation
Distance Reference	The point from which all distances are measured, usually the face of the calibration body
Initial Roll Angle	The roll angle at which an API is calibrated; this constant is used when the roll angle does not vary
I-Number	The Air Force identification number associated with each balance or API

Table C-1. (continued)

Name	Definition
Load Number	The number associated with a set of data records; usually the data are recorded while loading a balance at a single position
Load Position	The point, measured in three-dimensional space from the reference, where a load is applied
Plot Scale	The number which identifies the maximum value on the axis of residuals plotted using the derived balance constants
Point Number	The number which identifies the data records within a load number
Project Number	The number used to keep up with labor costs for a calibration project
Record Number	The number which identifies the data records within a calibration number
Roll Angle	The roll angle of an API during calibration; this constant is used if the computing code is 2 or 3
Sampling Rate	The rate in samples per second at which data are sampled
Test Number	The number which identifies the wind tunnel test in which the device will be used

Table C-2. Balance Calibration Data Buffer

Seq. No.	Component	Symbol	Range
1	Calibration No.	CN	0 to 9999
2	Load No.	LN	0 to 999
3	Point No.	PN	0 to 99
4	Record No.	REC	0 to 9999
5	Shunt or Load	SL	0 = Load; 1 = Shunt
6	Balance Case	BC	1 to 3
7	Load Polarity	POL	0 = Pos.; 1 = Neg.
8	Plot Scale	PS	1 to 6
9	Calibration Distance	CD	±99.9999
10	(same as Seq. No. 9)		
11	Type Load	TL	±4
12	Load Position	X	±99.9999
13	(same as Seq. No. 12)		
14	Load Position	Y	±99.9999
15	(same as Seq. No. 14)		
16	Load Position	Z	±99.9999
17	(same as Seq. No. 16)		
18	Load (lb)	XL	±9999.99
19	(same as Seq. No. 18)		
20	Constant Load Type	TLC	±4
21	Constant Load Pos. (X)	XC	±9999.99
22	(same as Seq. No. 21)		
23	Constant Load Pos. (Y)	YC	±9999.99
24	(same as Seq. No. 23)		
25	Constant Load Pos. (Z)	ZC	±9999.99
26	(same as Seq. No. 25)		

Table C-2. (continued)

Seq. No.	Component	Symbol	Range
27	Constant Load (lb)	XLC	±9999.99
28	(same as Seq. No. 27)		
29	Spare		
•	•		
•	•		
•	•		
39	Spare		
40	Gage Reading (MV)	R1	±32.0000
•	•		
•	•		
•	•		
63	Gage Reading (MV)	R24	±32.0000
64	End of Record	EOR	EOR = 32767

VITA

Charles Dennis Rose, son of Mr. and Mrs. Charles E. Rose of Decherd, Tennessee, was born on March 6, 1954. He graduated from Franklin County High School in 1972 and entered The University of Tennessee as an Electrical Engineering student. He participated in a cooperative education program with ARO, Inc., at the Arnold Engineering Development Center. He became a member of Tau Beta Pi, an engineering honor society, and graduated in 1977 with a Bachelor of Science degree in Electrical Engineering. He was employed by ARO, Inc., from June 1977 until December 1980, and has since been employed by Arvin Calspan. Both companies are contract operators at the Arnold Engineering Development Center, Arnold Air Force Station, Tennessee.

He entered The University of Tennessee Space Institute as a part-time student in the winter of 1978, and was awarded the Master of Science degree in Electrical Engineering in June 1982.

Mr. Rose is a registered Professional Engineer in the state of Tennessee. He is married to the former Mary Helen Sherrill of Hillsboro, Tennessee.