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MODULARIZED INSTRUMENT SYSTEM FOR TURBOJET ENGINE TEST FACILITIES

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ABSTRACT

A new modular instrument system is being developed to handle the many channels of data commonly encountered in turbojet engine testing. Each module contains a group of transducers and all the signal conditioning, multiplexing, and digitizing electronics necessary for direct interface with a digital computer. The digital interface within each module is the same for all modules. In addition each module provides a controlled environment for its contents. A minicomputer in the control room gathers the data, performs some on-line calculation and display, and interfaces with a shared recording and computing system. The advantages of this system are (1) reduced manpower for system installation, setup, and checkout; (2) standardized equipment interfaces; (3) increased reliability through automatic system testing and through minimization of manual adjustments; and (4) reduced cost through minimization of wiring and simplification of control room display. The system is conceptually well developed and a prototype is being built.

INTRODUCTION

The operation of turbojet engine and engine component test facilities involves the gathering of hundreds of channels of data. As tests become more complex and the cost of test operations increases, both in manpower and hardware, there is great emphasis placed on taking more data in less time and with less manpower. Improvements have been made in measuring systems through the use of modern electronics and digital data handling systems. In most cases, however, these are partial improvements to a measuring system that has been of the same basic form for the last ten to fifteen years. Redesign of the total measuring system, from transducer through final data recording, is proposed.

This report presents a new instrument system concept being developed and tested at the Lewis Research Center to achieve the goals of better data management, lower purchase, installation, and operating cost, reduced manpower requirements, greater flexibility, and enhanced reliability. It has been dubbed the MIS system (Modular Instrument System).

A typical instrument system presently in use at many test facilities is shown in the block diagram of figure 1. It is characterized by transducers at or very near the test engine coupled to the control room with long multiconductor shielded cables (a cable per transducer). In the control room there is some signal conditioning/amplifying box for almost every data channel followed by multiplexers, A/D (analog-to-digital) converters, computers (local or remote) and local displays.

Problems associated with this system are:

1. The transducers must be capable of withstanding the uncontrolled environment of the test area (e.g., pressure transducers).

2. The many long lines carrying low level analog signals are expensive to purchase and to install.

3. Excessive manpower is required to adjust the signal conditioning, amplifying and display equipment prior to running the experiment.

4. Excessive control room panel space is required for this adjustable equipment.

5. If the computing and recording facilities are shared with other test facilities (i.e., no local computer), there frequently arise problems of computing system availability and data rate compatibility. Thus data management and test parameter display are limited. The MIS system is being designed to minimize these problems.

A block diagram of the MIS concept is shown in figure 2. The transducer modules are environmentally controlled boxes containing the transducers and all the signal conditioning, multiplexing, A/D converting, and buffering electronics required to establish a standardized digital data interface. A minicomputer located in the control room interrogates the modules through this interface by sending an address word out and receiving a data word back.

Various types of transducer modules are tailored to specific data needs. A thermocouple box, for example, will contain a reference junction block and a set of electronics. A pressure module will contain a number of transducers or a single transducer with a pressure scanner along with an appropriate set of electronics. In all cases the computer interface will be the same; address word to the module, data word from it.

The minicomputer in the control room performs the functions of transducer module interrogation, data buffering and formatting for the remote computer/recording system, minor data reduction for purposes of control room display, and automatic system calibration and check-out. Some of the advantages of the system are:

1. Greatly reduced wiring.

2. Virtual elimination of manual electronics adjustment prior to an experiment run.

3. Modular flexibility.

4. Reduced control room complexity.

5. Provisions for automatic, on-site pressure transducer calibration and check-out.

6. Enhanced transducer reliability.

In addition, the MIS system leads naturally to better data management, to simplified and consolidated control room displays, and to reduction of some of the problems associated with the use of shared computing and recording facilities. This report will not deal further with these aspects of the system.

At this time the conceptual design of the MIS system is nearly complete. A prototype model, consisting of a limited number of channels, is in the initial stages of construction.

DESCRIPTION OF MODULES

This section will describe the various modules planned for the MIS system. Though each type of module is different internally, all modules have the same digital interface with the computer.

Present plans are for this computer interface to be TTL (transistor-transistor logic) compatible and to consist of a sixteen bit address word and a sixteen bit data word. Each will be handled in a bit parallel, word serial mode. The data lines and address lines of all the modules are tied to the computer data bus and address bus, respectively (wire OR). Thus only a single address cable and a single data cable (approximately

20 wires in each) traverse the distance between the control room and the modules. Sixteen bits were chosen to be compatible with the majority of available mini-computers. Sixteen bits in the address word is sufficient to specify the module, the channel within the module, and also to control various functions or sequences within the module. Sixteen bits in the data word is sufficient for 12 bit data resolution, leaving four bits for transmission of module status information.

Electrical power will be supplied to the modules in the form of various voltage levels of regulated DC from a common source. Within each module will be final conversion and regulation to fit the specific needs of the module. DC was chosen as a source, rather than 60 Hz line power, to keep the sources of hum minimized. An exception to this rule is the use of 60 Hz line power for module temperature control. In this case the use of controllers which switch only at zero current has proved successful so far in preventing noise. However, DC proportional control will be used for the heaters if hum or noise problems develop in the prototype system.

Of the various modules in the MIS system, the one that embodies more of the principles and advantages of the system than any other is the pressure transducer per channel module. Though this type of module may not be the most numerous in a given system, it will be described most fully to illustrate the system concept. The remainder of the module descriptions will then point out only that which is specific to that type of module.

Pressure Transducer-per-Channel Module

Basic description. - The pressure transducer-per-channel module is a building block element of the MIS system for measuring a group of eight pressure signals. A block diagram of this module is shown in figure 3. The components specific to this module are transducers, calibrate valves, amplifiers, multiplexer, and an analog to digital converter. The calibrate valves are part of a proposed in-place calibration system; the rest of this calibration system is shown in figure 3 as external to the module because this part services all of the pressure modules in the facility. Other components shown in the module are identical in all modules. These are the digital interface, the address logic, the temperature control, and the power converters and regulators.

Noteworthy features of this module are: (1) the controlled environment, (2) the in-place calibration system, and (3) an automated system checkout procedure. These features will be discussed in the following paragraphs.

Environment control. - Aerospace type pressure transducers have traditionally been built to withstand the environment in which they were used. As a result transducer designs have evolved which include precision temperature compensation, ruggedization to withstand vibration and shock, and environmentally resistant electrical and pneumatic connectors. In most applications such features are entirely justified and necessary.

However, in turbojet-engine and engine-component test facilities where large numbers of such transducers are used within a rather confined space, many advantages can be realized by mounting groups of transducers into modules within which the environment is controlled. In this way the cost of "environment proofing" each transducer can be avoided. Also, the cost and effort of testing each transducer for conformance to environmental specifications is avoided. Proper control of transducer environment can also improve reliability by eliminating such hazards as shock, vibration, transient temperature extremes, and dirt and moisture in electrical connections. Finally, the use of environmentally controlled modules facilitates the location of transducer power supply and readout electronics in close proximity to the transducers. This reduces wiring costs and eliminates the problems associated with transmission of low level analog signals over long cable runs.

The extent to which such advantages are actually realized depends, of course, on the specifications of the controlled environment and the relative cost of achieving it.

The primary specifications for the transducer environment in this module are temperature level, constancy of temperature, and vibration isolation. The temperature level for the transducers in this system was chosen as 325 K (125^{o} F), although this level is not critical. A higher than ambient level was chosen so that the air in the reference volume of dry differential transducers used in the system would remain at low relative humidity. Of course, the temperature must not be so high as to deteriorate the performance of the transducers.

The desired constancy of pressure transducer temperature was determined from an error budget analysis. The target probable error for pressure measurement was set at 1/4% of full scale. Sources of error considered were nonlinearity, hysteresis, uncertainty in calibration, probable error in transducer signal readout, and changes in zero offset and sensitivity due to temperature fluctuations. The results of this analysis indicated that for transducers with thermal coefficients as high as 0.1%

of full scale/K for zero shift and 0.1%/K for sensitivity change, temperature control constant to within ±1 K would suffice. These numbers appear to be a good choice; transducer thermal coefficients of the order of 0.1%/K should be achievable with little or no temperature compensation and temperature control to within ±1 K is within the capability of inexpensive electronic proportional temperature controllers.

Specification of the vibration isolation was based on the results of a study of failure modes of strain gage pressure transducers over a three year period at the Lewis Research Center. Results of this study showed that open circuits were the cause of failure in roughly 35% of 240 recorded failures in transducers of both bonded and unbonded strain gage construction. Although samples were not available for determination of the exact point and cause of failure, the implication is that vibration induced fatigue of unsupported lead wires is a factor. It is expected that transducer mounting assemblies with natural frequencies of 50 Hz or less and with damping ratios not less than 0.2 will be sufficient to minimize vibration induced fatigue of the lead wires within the transducers.

In-place calibration system. - The choice of calibration method to be used on the pressure measuring portion of this system was strongly influenced by the overall objectives of reliability and decreased operational costs. Specific requirements set for the pressure calibration system included the following: (1) uncertainty of transducer calibration of 0.1% of full scale, (2) recording of the calibration information for each transducer directly with the data, (3) minimization of manual operations in the calibration and prerun preparation of the system, (4) elimination of "people links" in the flow of calibration information, and (5) emphasis on user confidence.

One of the original concepts of the system was to eliminate the conventional strain-gage signal conditioner with its manual adjustments. Instead of adjusting the zero offset of each transducer, the initial zero offset was to be recorded prior to a run and stored in the minicomputer. This stored value of zero offset would be used as a zero offset correction to the measured data. An extension of this concept put valves ahead of the transducers such that zero offsets could be recorded without requiring the entire experiment to be opened to atmospheric pressure. Further extensions led to the proposed in-place calibration system.

This calibration system involves the connection of precisely known pressures to each pressure transducer in an automatic, computer controlled sequence. Because the transducers are assumed to be linear, only two pressure levels for each transducer range need be used for this calibration; a low pressure and one near full scale. From the measured output signals of the transducer when pressurized at these levels, the sensitivity and the zero offset are calculated and stored in the minicomputer. The calibration process can be repeated as desired, even during operation of the experiment.

Two subsystems form the heart of this in-place calibration system: the valving and the calibrate-pressure generator. The valves proposed for this system are based on a design described in reference 1 and are shown schematically in figure 4. Prototype valves of this type have been built and tested at the Lewis Research Center. The valves are closed by supplying to the domed side of the assembly an operate pressure which is higher than the pressure to be measured; they are opened when the operate pressure is decreased to below the measured pressure. Satisfactory operation has been achieved with a nominal sealing pressure difference of 7 N/cm^2 (10 psi) and a nominal opening pressure difference of 3.5 N/cm^2 (5 psi). Valves of this type have been operated successfully for 25 000 cycles with 400 N/cm^2 (600 psi) difference across the diaphragm. The valves are manifolded together in groups of six. They can then be stacked together so as to minimize the number of external pressure connections. Each group of six valves will perform the necessary interconnections to calibrate two gauge or absolute pressure transducers or one differential pressure transducer as shown in figure 5. The operating sequence of the calibrate valve system for the whole facility can be controlled by five three-way electrical solenoid valves.

The design of the calibrate-pressure generation system has not been completed at this time. Two approaches capable of meeting the basic requirements are under consideration. One approach is to use commercially available precision pressure controllers of the dead-weight type. The other approach is to use manually adjusted pressure regulators to obtain the approximate pressure levels required, and then to measure these pressures with calibrated high precision transducers. These transducers would be located in a special calibration module which would be addressed and read out like any other module.

Problems associated with the first approach include vibration sensitivity of the controllers, physical size of the units, the recovery time of the controllers after the flow transient experienced when the calibration valves open, and cost (especially for the high pressure level controllers). With the second approach, the accuracy of the entire system is dependent on the stability of calibration of the calibrate system transducers. The performance of these transducers must be adequately demonstrated to obtain user confidence and the system design must be such that these transducers can be periodically recalibrated conveniently. With either approach the cost is strongly dependent on the number of different calibrate-pressure levels required; this, of course, varies from experiment to experiment.

System checkout. - An important step in the prerun preparation of a large scale test facility is a check to make sure that the instrumentation is in an operational status. For the MIS system, the requirement is that such check-out be done via computer control. Thus, criteria for an adequate check-out must be established and incorporated into the computer software.

Check-out of the pressure-transducer-per-channel module is somewhat simplified by the existence of the in-place calibration system. In this case the results of the in-place calibration of each channel (sensitivity and zero offset) can be examined to see if they are within acceptable bounds. It is expected that the tolerance on such a check can be rather wide, perhaps ±15%, since the objective of the check is to see that each channel is operating and that the calibration has not shifted by an amount large enough to indicate that a transducer has been damaged. This procedure also checks the electronic modules used to read the transducer signal.

One further check-out test is planned for the pressure transducer-per-channel module; a leak check. This leak check would detect leaks in the calibrate valves and the interconnections between these valves and the transducer in each channel within the module and also in the lines supplying calibrate pressures to the module. Such a check can be accomplished by trapping calibrate pressures in the transducer with all the valves closed. The output of each transducer can be read out over a given period of time; a change in output signal would indicate a leak.

Pressure Scanning Module

In modern engine test facilities extensive use has been made of various pressure scanning techniques. In most cases these techniques have been adopted in order to reduce the overall cost of making the required number of pressure measurements. In the MIS system such techniques will also be used for cost saving reasons even though the projected cost of transducer-per-channel measurements is reduced compared to typical systems in use today.

The pressure scanning module will use commercial electromechanical sequential pressure switching systems in which a single transducer is sequentially connected to a number of unknown pressure inputs. The typical commercial scanner of this type has 48 input channels; however, this can be reduced by paralleling input connections. The actual number of input channels adopted as a standard for the MIS system has not been set. It will be primarily influenced by the number of pressure measurements of a given pressure range in typical experiments.

The pressure scanning module will consist of the scanner with its transducer, an analog-to-digital converter, a buffer memory, and controls for driving the scanner. The arrangement is shown schematically in figure 6. A noteworthy feature of this module is the use of a buffer memory to store the data. Intermediate storage of data in this memory allows the scanner to be driven at a rate which is independent of the data collecting rate of the minicomputer. Data in the buffer memory will be continuously updated by the scanner. The minicomputer will interrogate the buffer memory whenever it requires data from a channel in the scanner module. The maximum time delay between a measurement and the minicomputer readout of that measurement is then determined by the scanning rate and the total number of channels fed to the scanner.

Other features of the pressure scanning module are similar to those of the transducer-per-channel module. The environment control specifications will be the same for both modules. In-place calibration of the scanner pressure transducer will be accomplished by connecting high and low calibrate pressures to two channels of the module. The transducer signals for these two channels will be used to calculate the sensitivity and zero offset of the transducer. Transducer check-out will be based on comparing these values of sensitivity and zero offset with stored nominal values plus-and-minus a tolerance as discussed previously. Leak checking of the high and low calibrate pressure channels can be accomplished by stopping the scanner on these channels, closing valves in the calibrate pressure supply lines, and looking for a constant transducer output with time. Leak checks on other channels cannot be accomplished with this system; there will be no valves in these tube connections.

Thermocouple Module

The thermocouple module centers around a reference junction block which is shown in figure 7. Thermocouple alloy wire is brought directly from the experiment into the module. This alloy wire is crimped to copper wire forming the reference junction for the thermocouple circuit. These reference junctions are embedded in grooved plates which are in turn stacked to form the isothermal reference junction block. The copper wires are connected to the immediately adjacent electronics within the module.

No attempt is made to control the temperature of the reference block more closely than the normal tolerance in the module. Instead, a resistance thermometer located in the center of the block measures the block temperature. This temperature is then used as the reference junction temperature for all the thermocouples in that block.

The electronic portion of the thermocouple module is essentially the same as that in the pressure transducer-per-channel module. However, amplifier zero offset is more critical in the thermocouple module because of the lower signal levels encountered. This is particularly true in the case of differential temperature measurements where the allowable zero offset is as low as 10 microvolts. Correction for amplifier zero offset (as well as transducer zero offset) is achieved in the pressure transducer-per-channel module by means of the in-place calibration system. An analogous method for thermocouples is difficult to achieve because of the difficulty in producing a known (or zero) input.

This problem is not unique to the MIS system. Potential solutions are being investigated throughout the measurements community.

A desirable feature which will be incorporated in the thermocouple module is the ability to detect broken thermocouple wires. This will be accomplished by shunting the amplifier input with a solid state switch in series with a few thousand ohms. Since a good thermocouple presents a very low source resistance and a broken one a very high source resistance, the difference in data readings between the shunted and unshunted states will be large for an open circuit thermocouple, but negligible for a good one. This kind of check can be computer controlled and can be done at any time even during an experiment run provided there is a detectable signal (i.e., the measured temperature differs from the reference junction temperature). A channel which exhibits a large change will be flagged as bad.

Speed-Flow Module

A number of commonly encountered measurements result in the need to measure the frequency of an electrical signal. Two of these are the measurement of rotational speed and the measurement of fluid flow by means of turbine flowmeters. A MIS module is being developed specifically to handle these measurements but will be quite capable of measuring the frequency of other signals as well.

A block diagram of one channel of the frequency measuring scheme in the speed-flow module is shown in figure 8. Unlike the previously discussed modules, this one contains only electronics. Each signal is first fed into a pulse shaper so that the frequency measuring circuitry deals only with standard pulses.

The frequency measuring cycle begins with an internally generated start pulse. The clock counter begins to total clock pulses at the first data pulse after the start pulse. The data counter begins to count data pulses at this same time. The value in the clock counter is continuously compared with a "flag" number preset by the computer. When the clock counter reaches the flag number, logic to terminate the measurement is enabled. Both counters stop counting at the next data pulse. At this time the number stored in the data counter is the total number of data pulses counted. The number stored in the clock counter is proportional to the time required for that number of data pulses to be counted. Both of these numbers are fed to the module-located memory for subsequent computer interrogation. The ratio of these numbers, multiplied by the clock frequency, is the data frequency.

The flag number determines the time during which the frequency is averaged and is controlled by the computer. With this number set for about a one-quarter second averaging time (clock frequency is 100 kHz), frequencies from 12 Hz to 130 kHz are resolved to within about one part in 24 000 using 15 bit counters. Frequencies below this range will cause an overflow in the clock counter; frequencies above this range will cause an overflow in the data counter. Overflow in either counter is sensed with the appropriate sixteenth data bit and causes the computer to change the flag number so that an accurate reading can be taken.

Summary of Modules

The pressure transducer-per-channel module, the pressure scanning module, the thermocouple module, and the speed-flow module have been described. These descriptions are not meant to present design details so much as to present the multiplicity of forms that the modules can take within the MIS system concept. Many other measurements can be readily fit to this concept.

The kernel of the transducer module concept in the MIS system is that a module can take on any of a large variety of forms and still be directly compatible with the remainder of the system. This allows continuing development of new modules to take advantage of developments in the transducer and electronics fields as well as to respond to new measurement requirements.

CONCLUDING REMARKS

A new concept in instrument systems for turbojet engine and engine component test facilities has been described. It is built around modular instrument packages containing transducers, electronics, and environmental control and around the readily achieved compatibility of these diverse modules with a minicomputer.

The reader familiar with the problems associated with currently used measurement systems will appreciate the advantages which this approach can bring. Modularity and standard computer interface permit installation and check-out of the instrumentation on the experiment before the experiment is installed in the facility. The resulting savings in manpower and facility time would be appreciable. The authors believe that automated check-out and calibration will save a great deal of manpower and time as well as enhance the system reliability. Use of the minicomputer for data management should greatly simplify and standardize control room displays and interfaces with shared computing and recording systems. In addition, as improvements in transducers or electronics develop or as new measurement requirements become necessary, the modules can be changed to suit the needs without major system upheaval.

REFERENCE

1. Cole, Michael H.; Wise, Larry E.; and Henderson, John: Real Time Engine Test System. Instruments and Control Systems, Vol. 41, No. 6, June 1968, pp. 95-99.

E-7089

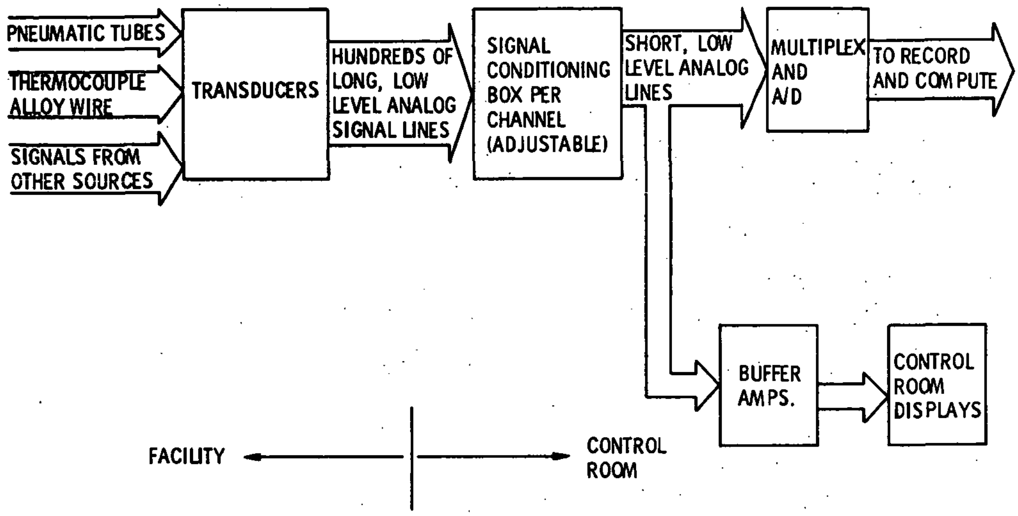


Figure 1. - Typical present instrument system.

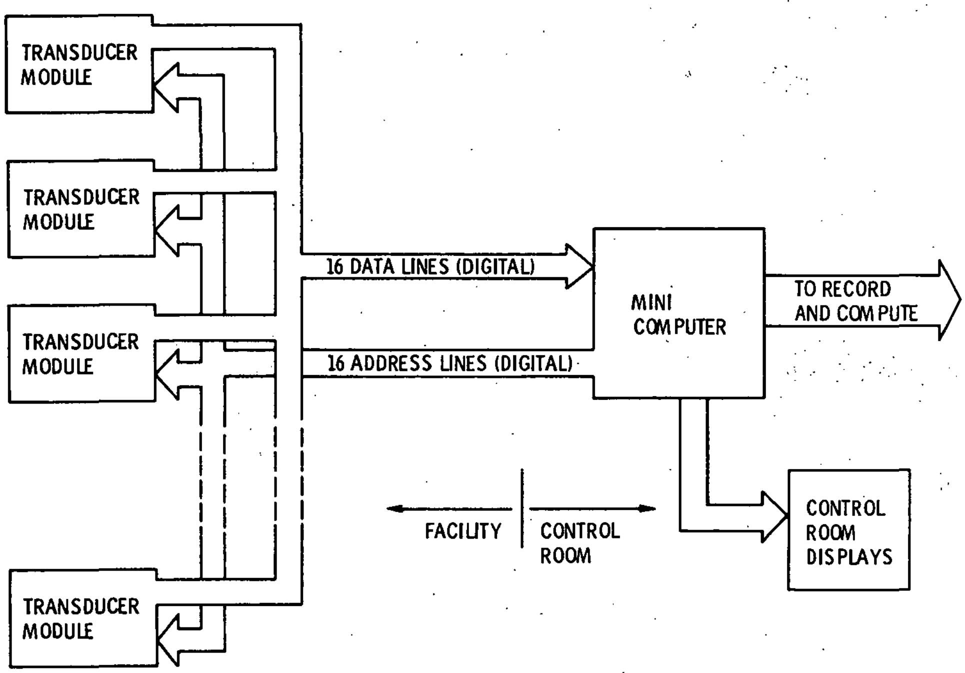


Figure 2. - MIS system.

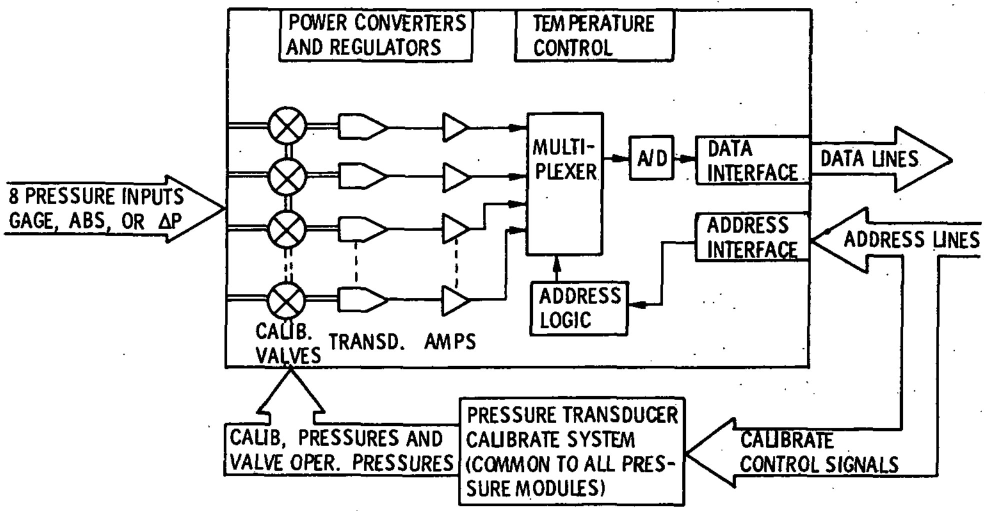


Figure 3. - Pressure transducer-per-channel module.

E-7089

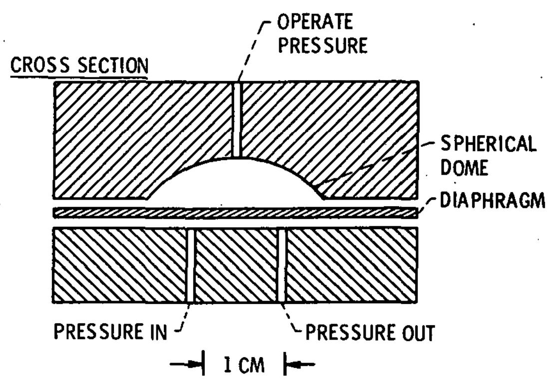
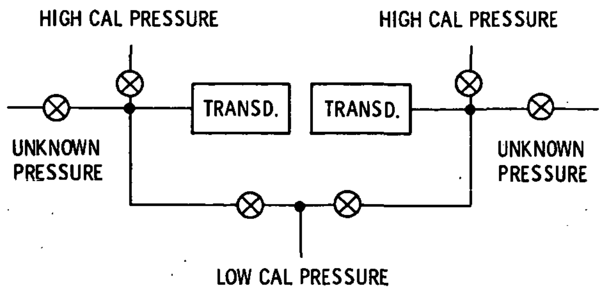
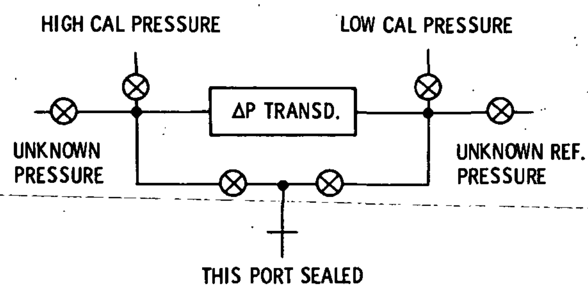


Figure 4. - Basic diaphragm valve.



(a) CALIBRATION OF TWO GAUGE OR ABSOLUTE PRESSURE TRANSDUCERS.



(b) CALIBRATION OF ONE DIFFERENTIAL PRESSURE TRANSDUCER.

Figure 5. - Valve interconnections for in-place pressure calibration system.

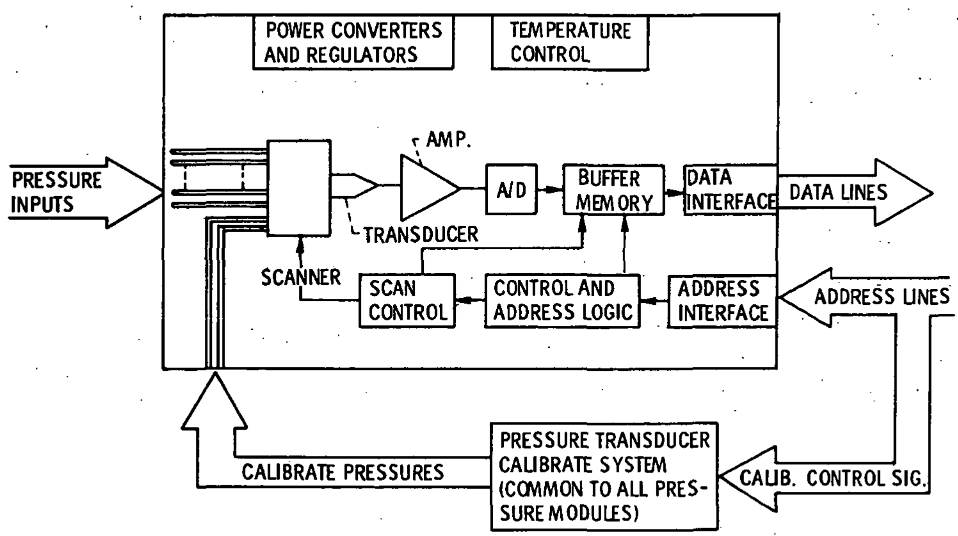


Figure 6. - Pressure scanning module.

E-7089

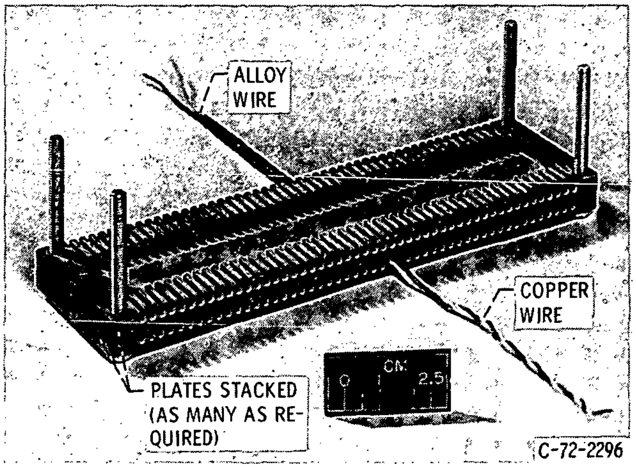


Figure 7. - Reference junction block.

E-7089

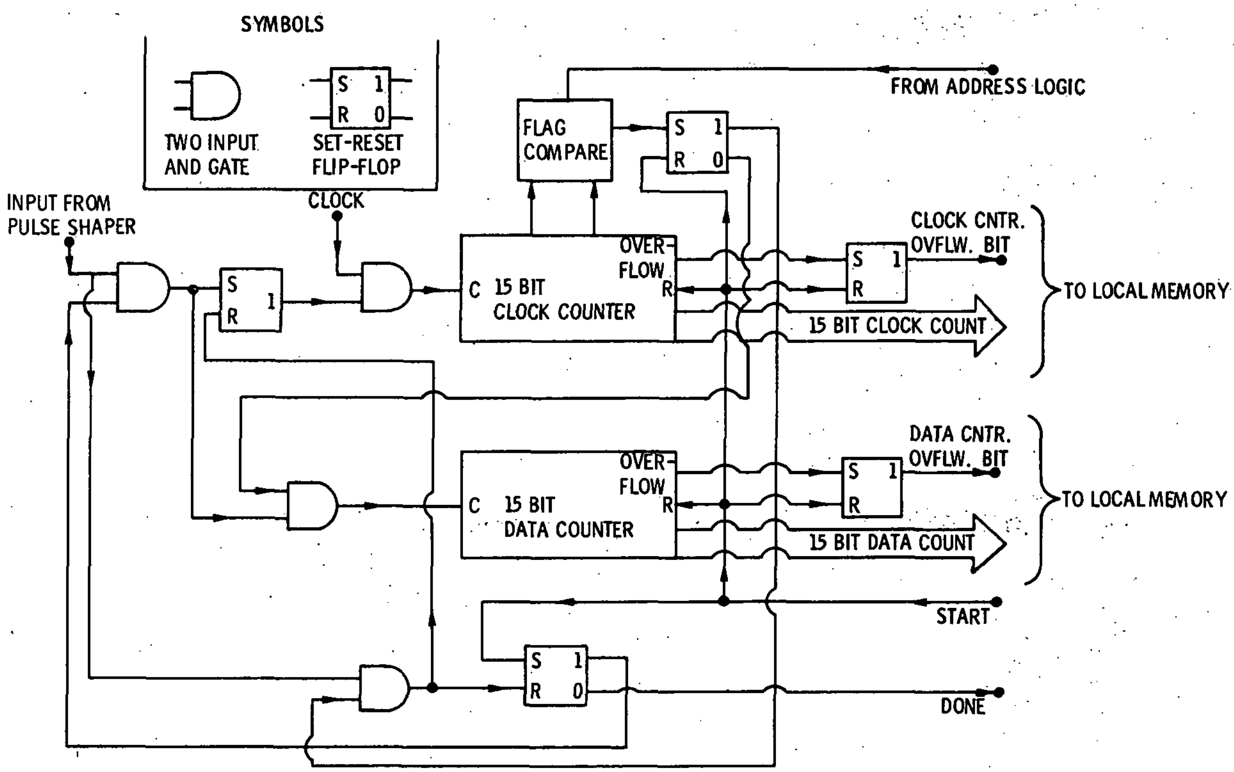


Figure 8. - Frequency measuring scheme.