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ROTATING SHAFT-MOUNTED MICROELECTRONIC DATA SYSTEM

by Daniel J. Lesco, John C. Sturman, and William C. Nieberding

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16. Abstract

A data system, using commercially available microelectronics and a rotary transformer, mounts on and rotates with the shaft of rotating machinery at speeds to 15 000 rpm. As many as 72 channels of steady-state transducer signals are time-division multiplexed and converted to 8-bit binary words by the system. A rotary transformer couples power onto the shaft and binary data from the shaft. A version of this system was tested for use on an experimental jet engine. It exhibited a measured error of less than ±0.5 percent of the 50-mV full-scale input voltage.

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SUMMARY

A data system, using commercially available microelectronics and a rotary transformer, mounts on and rotates with the shaft of rotating machinery at speeds to 15 000 rpm. As many as 72 channels of steady-state transducer signals are time-division multiplexed and converted to 8-bit binary words by the system. A rotary transformer couples power onto the shaft and binary data from the shaft. A version of this system was tested for use on an experimental jet engine. It exhibited a measured error of less than ±0.5 percent of the 50-millivolt full-scale input voltage.

INTRODUCTION

The development of rotating machinery frequently requires that certain physical parameters be measured on the rotating parts. Transferring such measurements across the rotating-to-stationary interface is inevitably a problem which becomes increasingly serious as the speed increases. A typical example of such a problem is the requirement of making multiple temperature and pressure measurements on experimental jet engine turbine blades.

Many ways have been devised in the past to effect the transfer across such an interface. Pneumatic tubulation has been used to conduct pressure to the interface, where it was passed from the shaft through a rotating seal and then to a stationary transducer. The shortcomings of this technique are the errors caused by seal leakage, the requirement of considerable maintenance on the rotating seal, and the bulk and complexity which results when a large number of pressure measurements are required.

Slip rings have been used extensively to transmit electrical signals from thermocouples or other signal generating transducers. The problems here are that the sliding contacts develop sufficient electrical noise and/or thermal potential to degrade accuracy.

Even when the electrical noise problems are not significant, such as when high-level signals are being transmitted, slip rings present a maintenance requirement which rapidly becomes more serious with increasing speed.

Radio-frequency transmission, usually in the form of FM/FM, has been used successfully. It is quite capable of handling the many channels usually required by means of time and/or frequency multiplexing. This scheme, however, along with other techniques which have been used, requires electrical power on the rotating shaft to operate electronics.

A number of means have been used to obtain power on a rotating shaft. Batteries can be used to store the energy but have limited power, life, and durability under the high centrifugal accelerations encountered. Slip rings can be used but the maintenance problem is still severe. As is shown in this report, a rotary transformer can be used to transfer power to the rotating system and the data from it if the electronic data system on the shaft is capable of accepting ac power and transmitting ac data. This requires sufficient complexity in the data system to convert ac input power into the required dc levels to operate the system and to condition many channels of data into a form suitable for transmission through the rotary transformer.

This report describes the application of commercially available microelectronics and a rotary transformer to the problem of obtaining many channels of steady-state data from a rotating shaft in a maintenance free, accurate manner. While we deal herein with a specific system built to mount on an experimental jet engine shaft, the design, with slight modifications, is applicable to a wide variety of similar rotating machinery applications.

The electronic system converts the input ac power into the dc power required for its operation. It time-division multiplexes 72 differential channels of data, converts each channel into an 8-bit digital word, and transmits this data off the shaft by means of the rotary transformer. The large quantity of electronics required to perform these functions was packaged in a cylindrical configuration 9 centimeters in diameter by 6 centimeters long exclusive of the rotary transformer. Although the design goal was 9000 rpm, the system was successfully operated at 15 000 rpm, which resulted in a maximum acceleration on the components of 8000 g's.

APPLICATION

The system was designed to obtain temperature data from experimental jet engine turbine blades during engine testing. A diagram showing how the data system fits into the test engine is shown in figure 1. Figure 2 is a block diagram showing the functional relations of the various parts of the overall system.

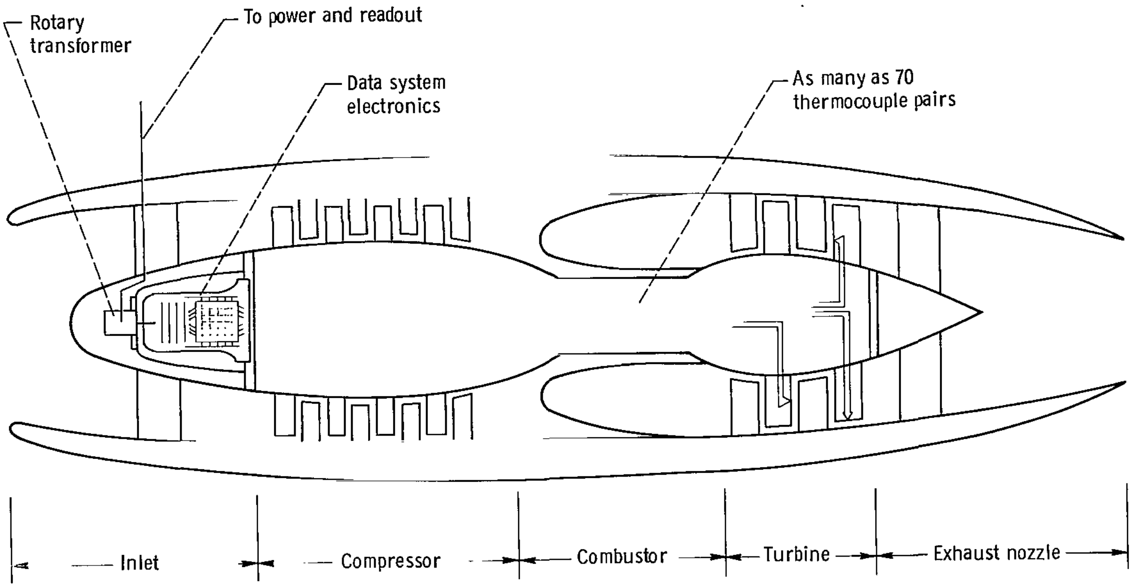


Figure 1. - Engine - data system configuration.

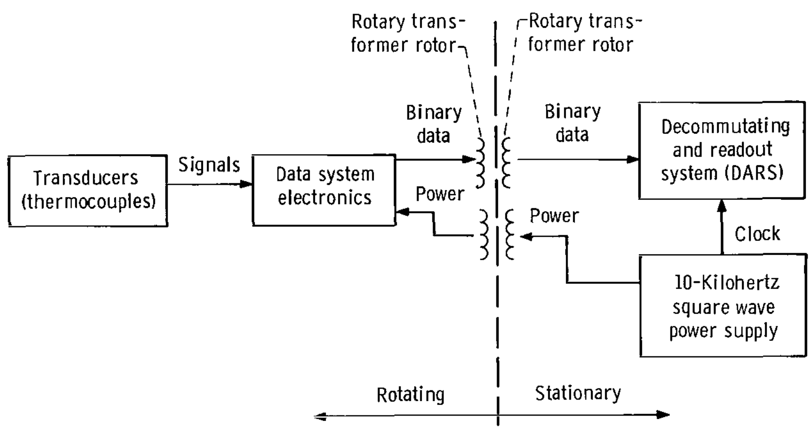


Figure 2. - Overall functional block diagram.

The following sections describe the design and testing of the data system. A brief description of the decommutation and readout system (DARS) is contained in the section TESTING under Data readout.

SYSTEM DESIGN

Two rotating-shaft data systems were built during the course of this research and development program. The first system was an experimental one to be used only for the evaluation of the electronic design and the durability of the components under conditions of high centrifugal stress. The second system was fabricated for use on a jet engine.

The two systems differ slightly in their details. The first system, which is referred to hereinafter as the prototype, is more versatile; the other system, the engine unit, is capable of handling more channels of data. The general data system concept and design is the main theme of this section, with the two data systems delineated as the design is described.

Data System Operation

The operation of the data system can be separated into four major functions, as shown in the block diagram in figure 3. These functions are time-division multiplexing, data amplification, analog-to-digital (A/D) conversion, and dc voltage and timing generation.

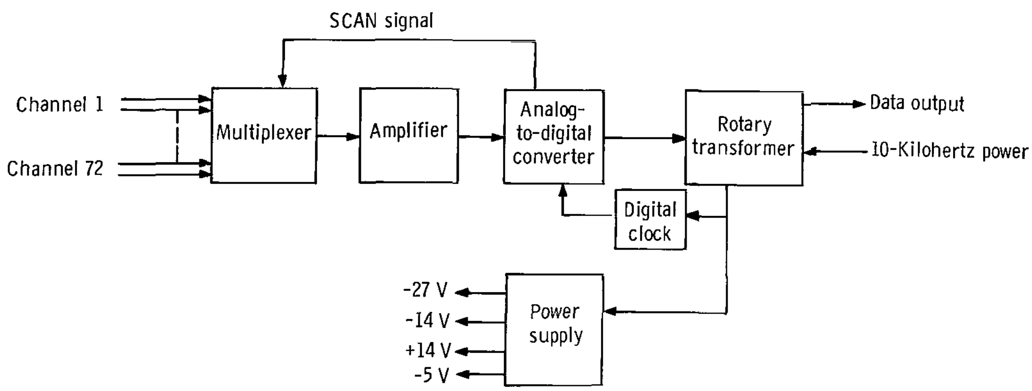


Figure 3. - System block diagram.

The multiplexer sequentially scans a large number of analog data signals, connecting one data signal at a time to the data amplifier (or amplifiers). This multiplexing of the input signals is an efficient method for processing large numbers of data channels, since only one signal path is then necessary through the amplification and digital conversion functions of the system.

The data amplification matches the input signal voltage level to the proper magnitude for conversion to a digital signal. More than one amplifier is required if the data system must handle input signals with different full-scale voltages.

The analog-to-digital converter transforms the input voltage to an 8-bit digital word proportional to the input. The digital information of each conversion is generated serially (1 bit at a time) on a single output line in a form ready for transmission from the rotating shaft.

This data transfer off the shaft and the transfer of power onto the shaft are accomplished with a set of rotary transformer windings. External power in the form of 10-kilohertz square waves is applied to the primaries of the power windings. Electronics on the shaft convert the transformer secondary voltage to the dc voltage supply levels necessary for operation of the system. The 10-kilohertz power input is also used (counted down in frequency) as a timing (clock) signal by the A/D converter.

The SCAN signal from the A/D converter sequences the multiplexer to the next channel upon completion of a conversion.

This concludes the summary of the data system operation; the following sections present in detail the circuit design of the system.

Circuits

As was the philosophy for the entire system design, commercially available integrated circuits (IC) were used in the system wherever possible. Due to the extensive selection of integrated circuits available, the multiplexer and A/D converter are comprised almost exclusively of digital integrated circuits.

Multiplexer. - The data system is designed to process differential input signals, such as those provided by thermocouples. This specification requires that both the high and low sides of a differential input signal be switched by the multiplexer For the 72 channels of the engine data system, a total of 144 input switches are needed, 12 pairs of which are shown in the partial multiplexer schematic of figure 4.

The semiconductor switches (E, F, G, and H in fig. 4) used are metal-oxide-silicon-field-effect-transistor (MOSFET) switches packaged in groups of six per integrated circuit (ref. 1). These MOSFET switches have the ideal switch characteristic of zero offset voltage, but are limited in some applications by slow switching speed and high "on" resistance. The "on" resistance is about 300 ohms, while the "off" resistance is of the order of 10^{11} ohms. The switch turnon and turnoff times are about 2 microseconds.

For each polarity of voltage, there is a limiting voltage with respect to ground that can be applied to either input terminal of the differential switch pair. No voltage greater than +0.5 volt can be switched by the MOSFET devices, and the switch characteristics degrade if an input more negative than -5 volts is applied.

Other restrictions on the input voltages are due to the amplifier and A/D converter characteristics. With the noninverting amplifiers of this specific system design, the

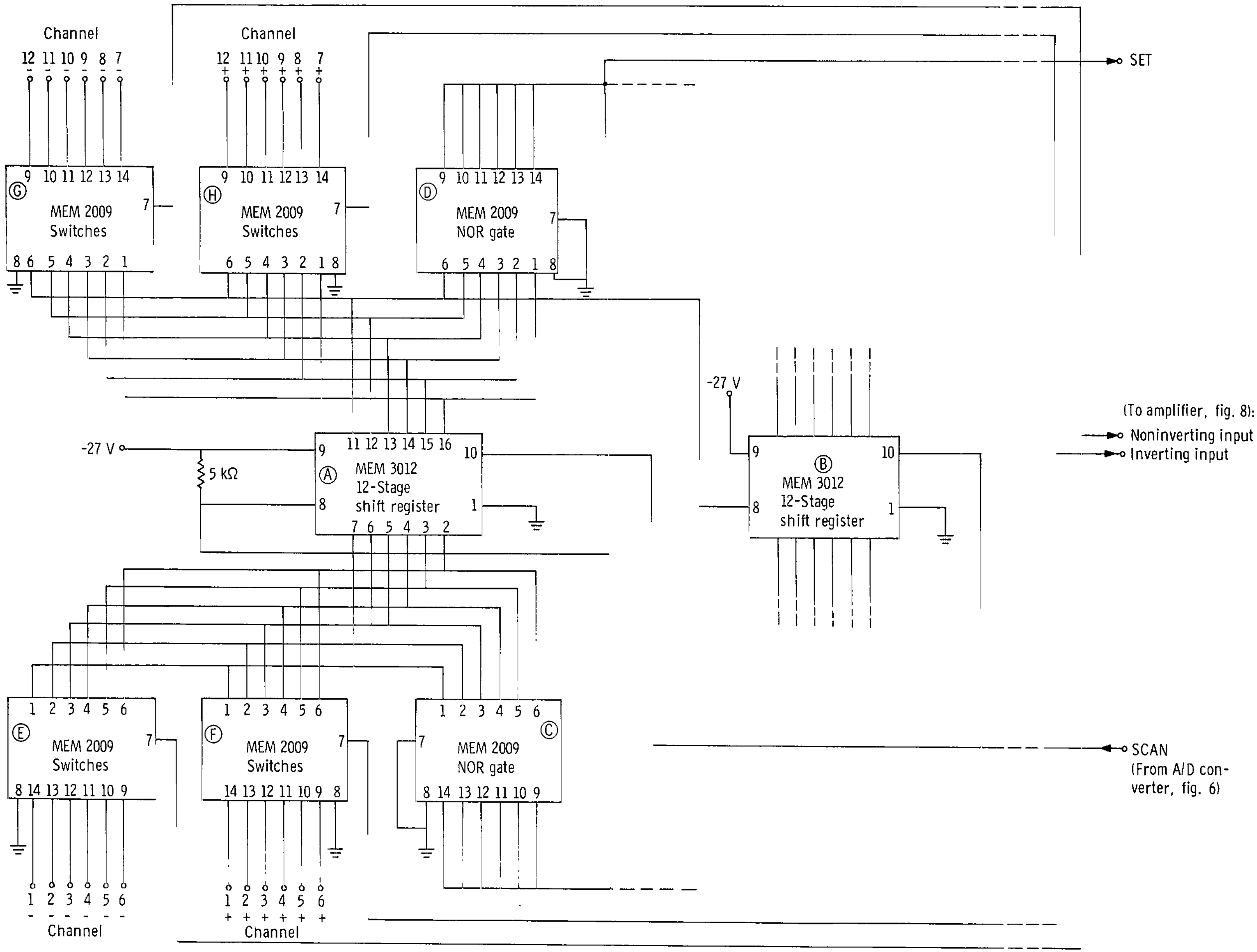


Figure 4. - Schematic diagram of multiplexer.

noninverting side of the differential input must be negative with respect to the inverting input, since the A/D converter can handle only negative voltages. Also, for the amplifier design used, a bias path to ground must be supplied through the differential input (i.e., the input cannot be floating).

The pairs of switches for each input channel are sequentially turned on by a ring counter whose number of stages is equal to the number of data channels. The ring counter is composed of a series of integrated circuit 12-stage MOSFET shift registers (A and B in fig. 4) (ref. 2) and a restart circuit using six-switch integrated circuits (C and D in fig. 4) in a multi-input NOR gate configuration. The NOR gate detects when the last channel has been turned off, and its output (SET) turns on the first channel after a one-period delay. The turnon voltages for the multiplexer switches are obtained from the parallel outputs of the shift registers.

The shift register is also used in the prototype system to select the correct data amplifier to be switched to the A/D converter. The multiplexed output for channels 1 to 12 is connected to one amplifier, and the output for channels 13 to 36 is processed through the second amplifier. A simple two-input MOSFET multiplexer is used to alternately switch the amplifier outputs to the converter. The switches are controlled by a flip-flop, which is, in turn, triggered at the appropriate times (channels 1 and 13) by the shift register outputs of stages 1 and 13.

The multiplexer scan rate is controlled by the A/D converter. When the A/D has finished converting a channel signal voltage to a digital signal, a step command (the SCAN signal) is applied to the shift register to turn on the next channel. A timing diagram for the multiplexer is shown in figure 5 for the 72-channel engine system. With the de-

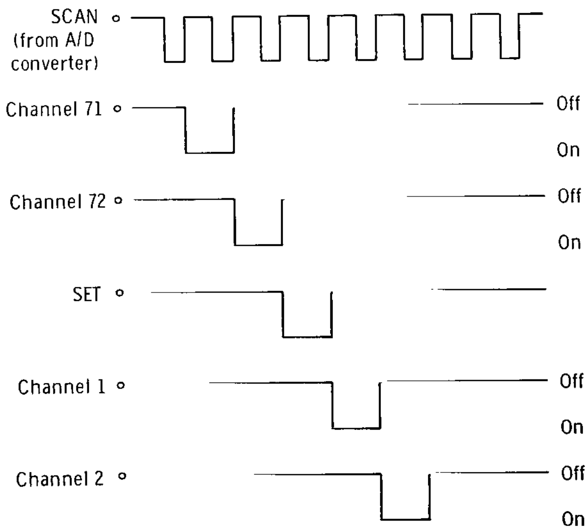


Figure 5. - Multiplexer timing diagram.

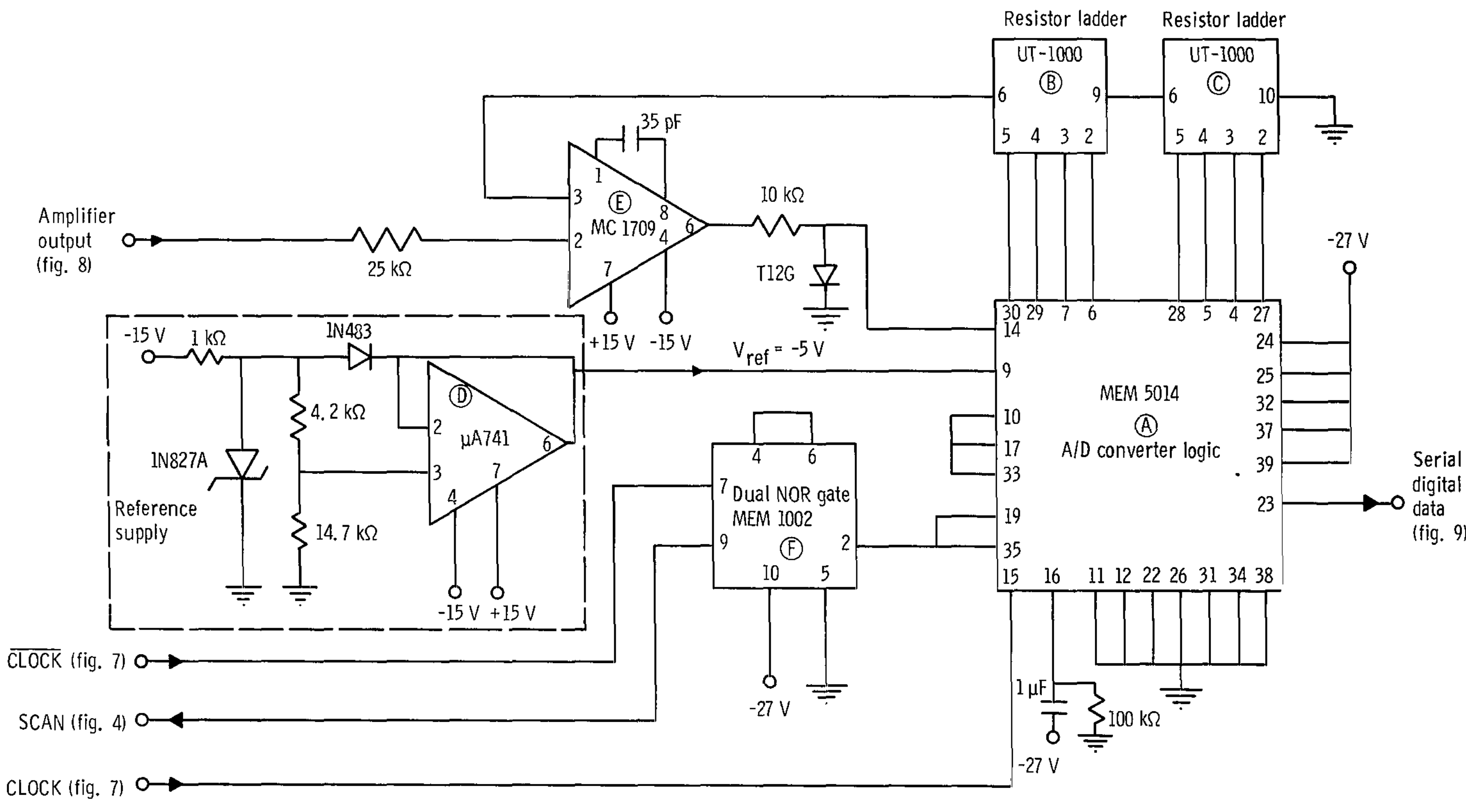


Figure 6. - Schematic diagram of analog-to-digital converter.

signed scanning frequency of about 156 channels per second, all 72 data channels are sampled about twice per second. A similar diagram applies to the prototype system.

Analog-to-digital converter. - The system A/D converter uses the sequential approximation technique (ref. 3). The conversion from analog voltage to a serial 8-bit digital word is an eight-step process, each step yielding one of the information bits. Each conversion step requires one clock period to complete. (The clock frequency, as described in the next section, is 1.25 kHz.)

The heart of the A/D converter is a complex integrated circuit, shown as A in figure 6, incorporating all the logic needed for A/D conversion. The converter IC uses MOSFET circuitry with over 350 devices on one semiconductor chip. This IC controls the A/D timing, performs the data storage, and provides the switching functions for the ladder network.

A thin-film resistor ladder network (B and C in fig. 6) generates the digital-to-analog (D/A) feedback voltage for the comparator. The reference voltage is switched to the ladder through the eight input terminals by the converter IC (A in fig. 6). Internal resistance dividers reduce the reference voltage to the proper fraction at the ladder output.

The regulated reference supply in figure 6 uses a temperature-compensated 6.4-volt zener diode and a resistor divider to generate a -5-volt reference. The zener diode voltage has a temperature coefficient of 0.001 percent per $^{\circ}C$. An IC operational amplifier (D in fig. 6) in a noninverting gain-of-1 configuration is used to provide a low output impedance for load regulation.

Another IC operational amplifier (E in fig. 6), in its open-loop, high-gain configuration, is used for the voltage comparator. This amplifier has an open-loop gain of about 45 000; therefore, the differential input change necessary to cause logic switching causes negligible error. The comparator offset is of the order of 1 millivolt.

A comparator with a large negative voltage swing is required for operation with MOSFET logic voltage levels. However, it is also important to prevent any input to a MOSFET IC from going positive by more than 0.5 volt. Therefore, a germanium diode is used at the output of the comparator to clamp the output at 0.3 volt.

Digital clock. - Figure 7 shows the schematic of the circuit used to generate the 1.25-kilohertz clock signal from the 10-kilohertz input power frequency. A -20-volt square wave obtained from one secondary of the power windings is counted down by a factor of 8 to 1.25 kilohertz by an IC binary counter (A in fig. 7). (IC outputs are also available for frequency division by 2, 4, or 16.) The resulting square wave is then wave-shaped to a 5-microsecond-wide, -15-volt clock pulse signal by the resistor-capacitor circuit and an IC logic gate (B in fig. 7). An inverted clock signal ($\overline{\text{CLOCK}}$) is also provided.

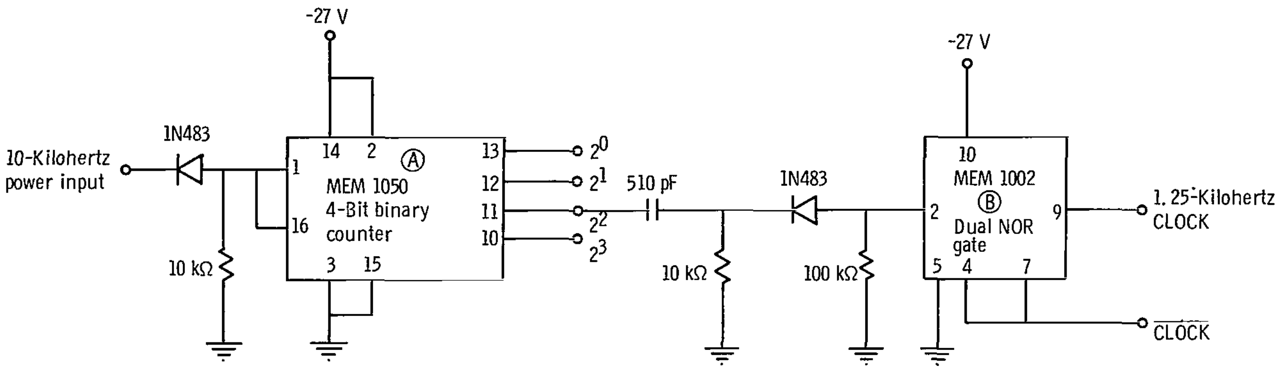


Figure 7. - Clock generator.

The clock frequency of 1.25 kilohertz was chosen for two reasons:

(1) Since the data system is used to measure steady-state data, a low scan rate is permissible.

(2) Since only one data amplifier is used for a number of channels, sufficient settling time must be allowed for the amplifier output after switching input channels. The settling time obtained is equal to 1 clock period, or about 800 microseconds.

Amplifiers. - The limited availability of linear integrated circuits required the use of discrete active components. An example of this is the low-level (or high gain) amplifier used with the thermocouple channels. This amplifier, shown in figure 8, is required to accept a differential input from a source impedance of about 600 ohms. It has a gain of 100 and a dc drift of less than 1 microvolt per $^{\circ}C$.

One of the main reasons that this amplifier was built by using discrete active components is the difficulty of providing gain stabilization with feedback, low drift, and a high-impedance differential input simultaneously, by using available IC operational amplifiers. Use of a selected dual transistor input stage operating at a collector current of 30 microamperes provided high input impedance (greater than 1 MΩ) and made the emitters available for negative feedback. The high input impedance is necessary because of the high "on" resistance of the MOSFET switches.

Various integrated operational amplifiers were tried in this configuration with varying degrees of success. All the older designs oscillated and could not be easily stabilized, or else tended to latch up when subjected to input transients (i.e., the output remains in saturation after the input overload has been removed). The RA 2909 proved quite stable, once a feedback diode had been added from pin 8 to the inverting input to prevent latch-up caused by the added input circuitry and nonlinear loading of the output. In addition, it has a convenient point (pin 8) that can be used to limit the band-

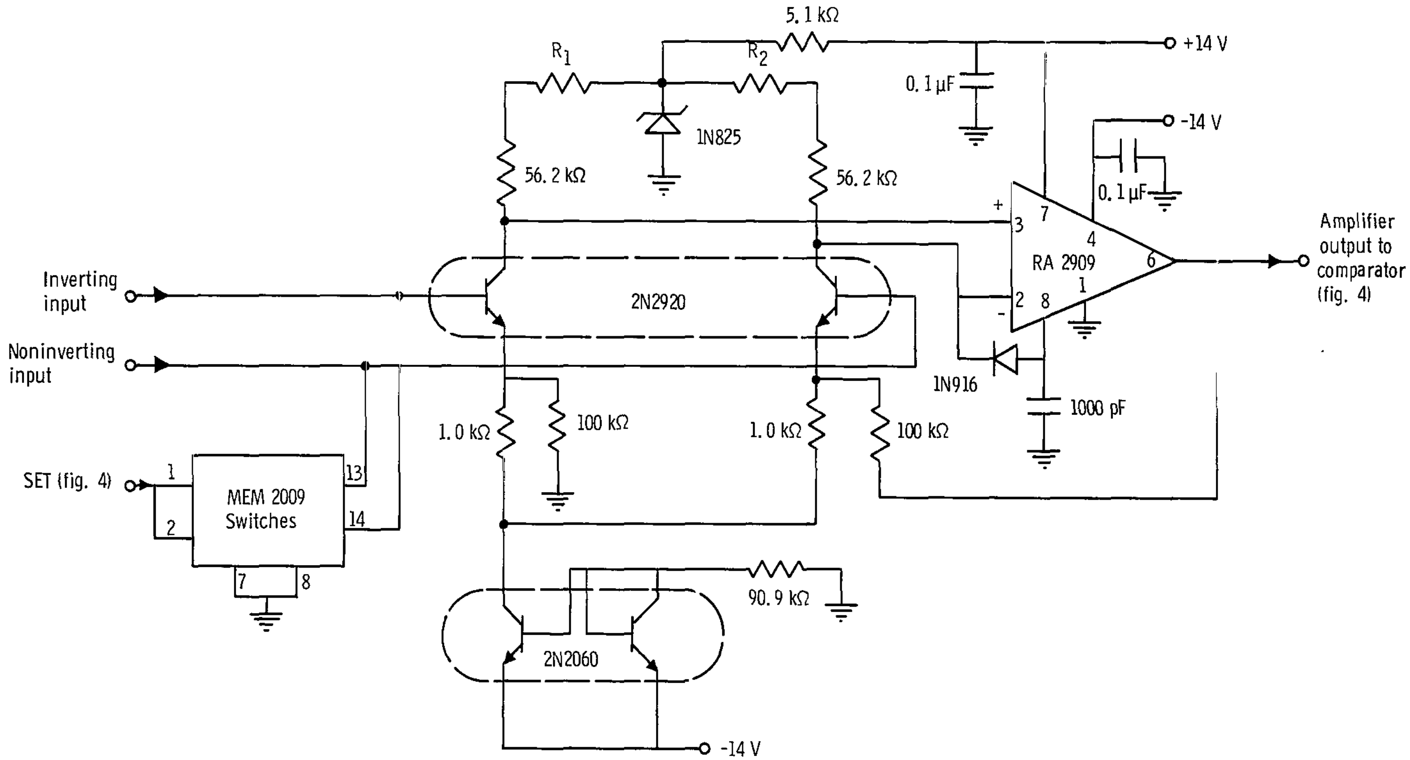


Figure 8. - Schematic diagram of low-level differential data amplifier. Note: R1 and R2 are trim resistors.

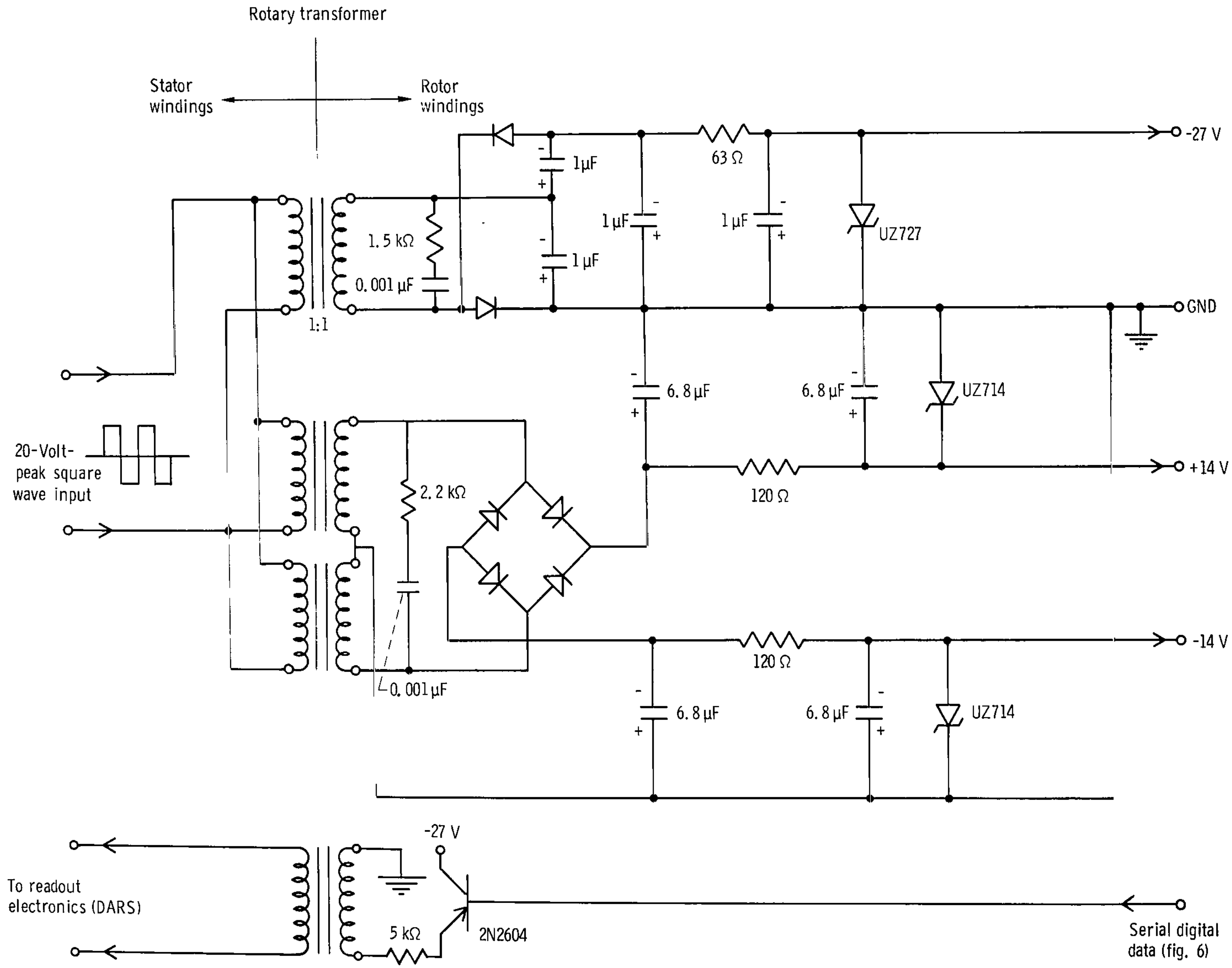


Figure 9. - Power supply and rotary transformer. Note: All rectifiers are T12G.

width of the amplifier by using a single capacitor, without degrading its common-mode rejection. This bandwidth limiting proved difficult to achieve by using capacitive feedback, or by limiting the response of the preamplifier stage. These methods either degraded common-mode rejection drastically or caused oscillation. Common-mode rejection of the complete amplifier is greater than 80 decibels for frequencies to 1 kilohertz.

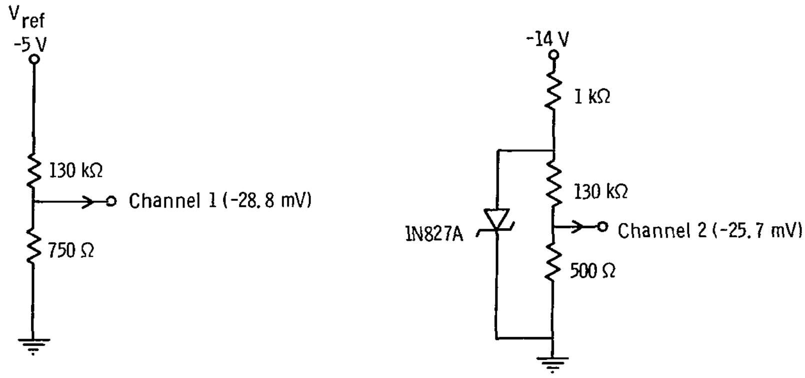
Other than this one amplifier and the output driver, all other functions were implemented by using only integrated circuits and discrete passive components. The low-gain amplifier, the comparator, and the reference supply regulators all use standard operational amplifiers.

The pair of switches shown in figure 8 ground the amplifier input lines during the SET time. These switches were used on the low-gain amplifier on the prototype system. Their purpose is to allow the measurement of amplifier offset during this time.

Power supply and rotary transformer. - Power to the rotating data system, as well as data from it, are transferred by means of a rotary transformer. The rotary transformer consists of four separate, isolated transformers all mounted in a common housing. Each of the four nonrotating stator windings is magnetically coupled to its corresponding rotor winding in such a fashion that transformer operation is not influenced by rotation. All transformers have a 1 to 1 ratio and are shielded from each other to prevent cross coupling. As shown in figure 9, three of the rotary transformer windings feed power to the data system as 20-volt-peak square waves. These are rectified, filtered, and regulated by zener diodes to provide the necessary voltages for the system. Zener regulation was chosen for simplicity and is adequate since none of the basic supply voltages require close regulation. The fourth transformer winding is used to transfer the serial digital data from the system to the readout electronics. An emitter follower stage is used to buffer the output from the A/D converter and drive the transformer. The result is approximately 5-volt pulses from the rotary transformer stator.

Calibration signals. - Calibration voltages are internally generated in the data system to provide a check on the system operation. In the engine system, two of the data channels are used for calibration signals. For channel 1, an input voltage proportional to the reference supply is generated by a simple resistor divider from V_{ref} (fig. 10(a)). The channel 1 digital output provides a monitor primarily on the data amplifier gain. Channel 2 is connected to a calibration voltage generated independently of V_{ref} by a separate temperature-compensated zener diode and a divider network (fig. 10(b)). This calibration signal provides information primarily on the stability of the system reference voltage.

A third check on the system operation is provided during the multiplexer SET time (see fig. 5). During this time, the data amplifier inputs are shorted to ground through MOSFET switches. The A/D converter output during the SET pulse is a measurement of negative-polarity data amplifier offset voltage.



(a) Channel 1. (b) Channel 2.

Figure 10. - Engine system calibration input voltages.

Although the information obtained from the three calibration signals does not provide independent information on amplifier gain, amplifier offset, or reference voltage, the combination can be used to interpret most discrepancies which could occur in the system operation.

Mechanical Design

A logical configuration for a rotating system is a round package. Therefore, this system was built using round, double-sided printed circuit boards with plated-through holes. This concept worked very well in practice. Components considered to be most sensitive to acceleration were mounted near the center of the board when possible. All interboard connections were made near the periphery of the boards, which facilitated testing of the assembled system. The four types of boards used in the prototype system are shown in figure 11, along with the rotary transformer. Note that the A/D converter board has been heavily coated with a clear epoxy to hold all components securely to the board. The other boards in this figure were not yet coated at the time the picture was taken.

The complete system is assembled by stacking the circuit boards together with spacers and making the required interconnections. Figure 12 shows this stage in the construction of the engine system. Since it has twice as many inputs as the prototype, it requires two multiplexer boards, bringing the total board count to five. The five-board module, which is 9 centimeters in diameter by 6 centimeters long, mates at one end to a circular terminal ring which is the interface between the data system and the thermocouples from the engine. The terminal ring also serves as the cold junction for the thermocouples, and its temperature is monitored by a thermistor cemented to it. One input channel is used to read out this thermistor signal.

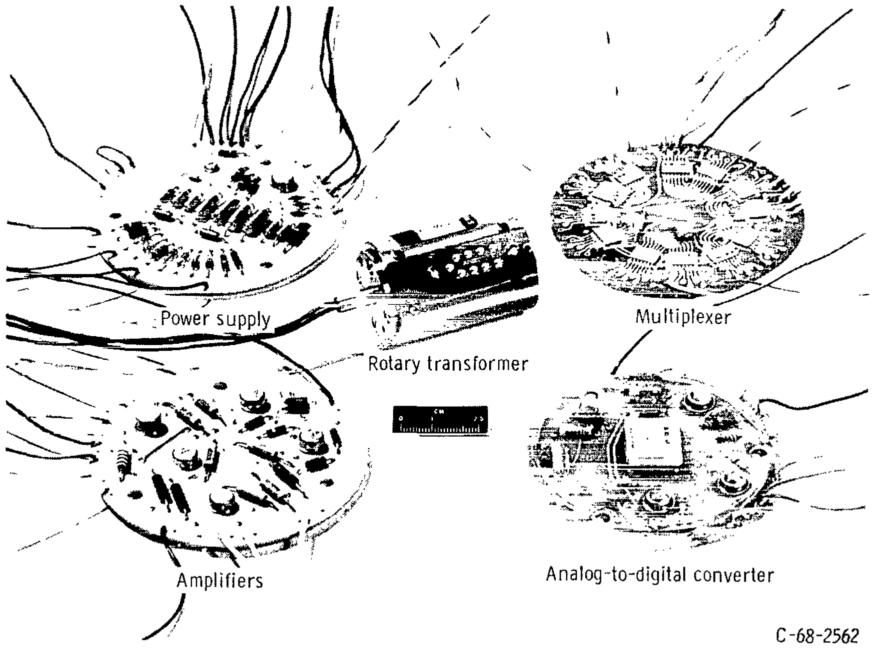


Figure 11. - Circuit boards and rotary transformer.

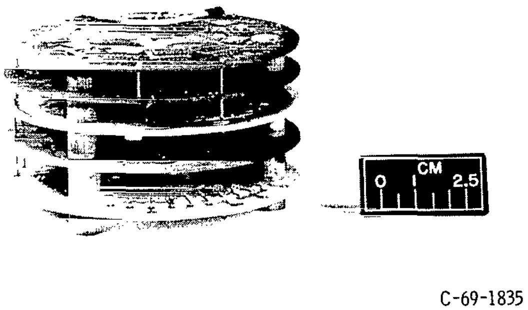


Figure 12. - Assembled electronics package.

Rigid mounting of the complete electrical assembly is accomplished by clamping it to the inner rotating support plate with three tie rods. A metal spacer is used at the opposite end for alinement so that any small irregularity in the boards will not affect the mechanical mounting. The complete system showing the wired electronic assembly and partial housing is shown in figure 13. Connections to the rotary transformer are made at the end of the package through the hollow shaft and to an eight-pin terminal ring. Use of the two terminal rings, accessible through a slotted housing, makes it possible to connect or disconnect the data system in a minimum amount of time. The housing shown in figure 13 is considerably larger than necessary to properly support the elec-

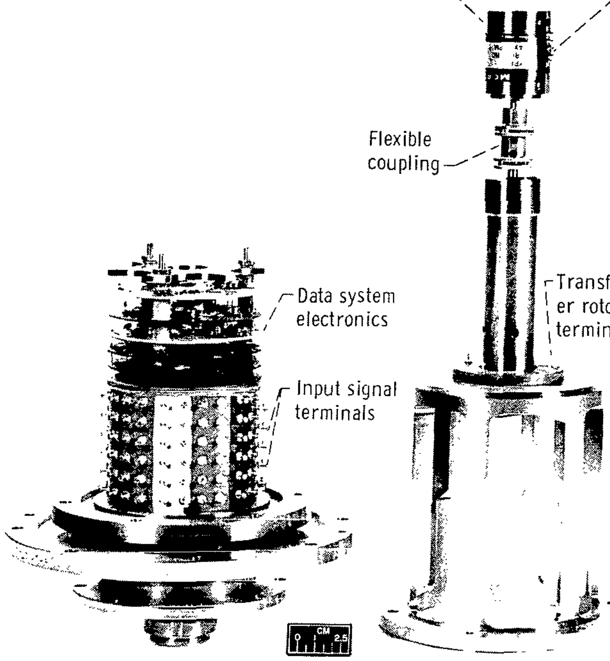


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Figure 13. - Engine data system and housing.

tronics package. Its dimensions were dictated by the practical requirement that it be identical in size to a slip ring assembly which it replaces.

TESTING

Mechanical

Each heavily coated circuit board was rotated at 10 000 rpm for 1 hour. Electrical tests were performed only before and after rotation at this stage. Once assembled, the complete prototype system was rotated at 10 000 rpm for 1 hour and 15 000 rpm for 10 minutes, during which times the electrical operation was monitored. Although for this test no independent voltage inputs were applied to the system, the calibration voltage channels were read to provide information on system operation. For the prototype system, one calibration input channel was allocated for each amplifier, and the SET time output was a measurement of the low-gain-amplifier offset voltage. During the spin tests, no changes in the calibration digital words were noted. This result limits any probable internal changes in the system repeatability to the system resolution, ±0.2 percent.

Electrical

Data readout. - As mentioned previously in this report, the only output from the rotating shaft data system is the serial digital data transmitted through one winding of the rotary transformer. Clock synchronization for reading the binary information can be derived from the 10-kilohertz power frequency, but it is also necessary to externally generate word synchronization (the correct grouping of 8 data bits to form one data point) and frame synchronization (identifying the channel 1 data word). A frame of data is defined as the group of data bits generated from the SET time of the multiplexer through the last data channel.

For data handling during system test programs, a decommutating and readout system (DARS) was designed to provide synchronization and display of the data system output. The DARS derives its synchronization signals from the known system outputs generated by the calibration voltage channels. Specifically, the DARS scans the output data until it finds a 14-bit sequence corresponding to the amplifier offset plus the first 6 bits of the calibration voltage on channel 1. For example, this pattern for the engine data system is 0000 0000 1001 01. Once the DARS has detected this sequence, it can generate the word synchronization for the remaining 71 channels of data.

A simplified block diagram of the DARS is shown in figure 14. Data from the rotat-

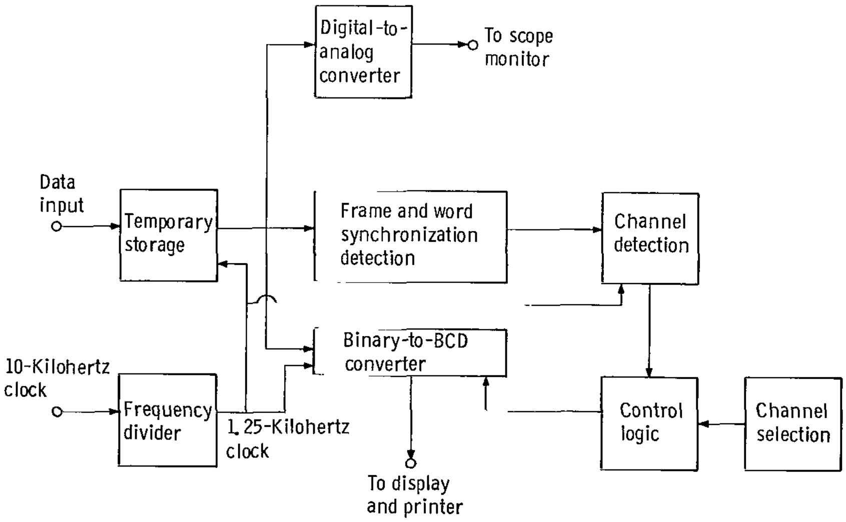

Figure 14. - Block diagram of decommutating and readout system (DARS).

ing system pass first through a temporary storage stage, where 14 bits of data are stored during each 1.25-kilohertz clock period. At successive clock periods, the most recent bit b_i is added, while the data bit b_{i-14} appears at the serial output of the storage. The storage also provides the 14 bits in parallel output form for examination by the synchronization detection logic. Once synchronization has been achieved, the channel detection logic identifies the channel designation for the rest of the frame of data as it passes through the temporary storage. The operator selects the channel for display at the channel selection control. The DARS control logic sequences the binary-to-BCD (binary coded decimal) converter, thereby providing the selected channel data in decimal digits for numeric display. An alternate logic mode controls an automatic scan through a selected number of channels to provide BCD outputs to a data printer.

The digital-to-analog (D/A) converter transforms the binary data to a 2-percent-accurate analog signal for display on an oscilloscope used to monitor data profiles. All 72 channels can be displayed in a bar graph form on the oscilloscope during one horizontal sweep. The display is updated for each frame of data.

The DARS is capable of handling either the 36-channel prototype system or the 72-channel engine system.

System calibration. - The shaft data system is calibrated while it is not rotating, so that the external input signals may be accurately measured with laboratory equipment. The internal calibration signals are used to determine the calibration stability for the system while it is rotating.

Prototype system: The -5-volt reference voltage and the gain of the data amplifier determines the full-scale input voltage of the system. For the prototype system, two data amplifiers provide two full-scale ranges of 1 volt and 40 millivolts, for the first 12 channels and the remaining 24 channels, respectively.

The input signal voltage V_{in} can be related to the value of the digital output word N by

$$(V_{in})_i = \frac{1}{G_i}\left(\frac{N}{256} V_{ref}\right) - V_{oi}$$

where

G_i gain of data amplifier i

V_{ref} A/D reference voltage

and

V_{oi} offset voltage composed of $V_{oc} + V_{oa} - \frac{1}{512\, G_i} V_{ref}$

where

V_{oc} comparator offset voltage referred to data amplifier input

V_{oa} amplifier offset voltage referred to data amplifier input

$\frac{1}{512 G_i} V_{ref}$ one-half the system resolution (i.e., 1/2 count)

This last term centers GV_{in} in a 20-millivolt range for a given N.

For the prototype system, two calibration equations were derived for the low-gain and high-gain amplifiers:

(1) For amplifier A1,

$$V_{ref} = -5.016 \text{ V}$$

$$G_1 = 5.07$$

$$(V_o)_1 = 0.0020 \text{ V}$$

and

$$(V_{in})_1 = 3.86\times10^{-3} N - 2.0\times10^{-3}, \text{ volts}$$

Table I illustrates the comparison between the measured and calculated values of V_{in} required to produce the listed values of N. Calculated V_{in} was obtained from the preceding equations and measured parameters.

TABLE I. - PROTOTYPE CALIBRATION - AMPLIFIER A1

Digital output word, N	Input signal voltage, $(V_{in})_1$, mV		Error, percent of full scale
	Calculated	Measured	
1	-5.9	-5.3	-0.1
10	-40.6	-41.5	+.1
100	-388	-386	-.2
255	-986	-986	.0

The system resolution is $\pm(V_{ref}/512G_1) = \pm0.002$ volt, or about ±0.2 percent of full scale. All the calibration data for A1 were within ±0.3 percent of full scale of the calculated values.

(2) For amplifier A2,

$$V_{ref} = -5.016 \text{ V}$$

$$G_2 = 132$$

$$(V_o)_2 = 0.008 \text{ mV}$$

and

$$(V_{in})_2 = -0.148\times10^{-3} N - 0.008\times10^{-3}, \text{ volts}$$

Table II lists typical calibration data for the A2 data channels. The system resolution

TABLE II. - PROTOTYPE CALIBRATION - AMPLIFIER A2

Digital output word, N	Input signal voltage, $(V_{in})_2$, mV		Error, percent of full scale
	Calculated	Measured	
1	-0.16	-0.17	+0.03
10	-1.49	-1.48	-.03
100	-14.8	-14.8	.0
255	-37.9	-37.8	-.3

for this amplifier is ±0.07 millivolt, also equivalent to ±0.2 percent of full scale. All the calibration data were within ±0.3 percent of full scale of the calculated values.

Although complete calibration of the prototype system over the full design temperature range of 25° to 70° C was not obtained, specific parameters were measured to assure no problems would occur with the engine system. The amplifier gains, G_1 and G_2, changed by less than ±0.2 percent (system resolution) over the full temperature range. Variations in $(V_o)_1$ and $(V_o)_2$ were also well within ±0.2 percent of full scale from 25° to 70° C.

In summary of the prototype system data, a system accuracy of better than ±0.5 percent of full scale, for full-scale ranges of 1 volt and 40 millivolts, was obtained.

Engine system: The engine data system uses one amplifier for all 72 channels to obtain a full-scale input of 50 millivolts. Calibration data were taken over the 25° to 70° C temperature range. Table III lists the equation parameters and their values at

TABLE III. - ENGINE SYSTEM CALIBRATION PARAMETERS AS FUNCTION OF TEMPERATURE

Parameter	Temperature, °C		
	25	50	70
Gain of data amplifier, G	100.0	100.0	100.0
Analog-to-digital reference voltage, V_{ref}, V	-5.00	-5.00	-5.00
Offset voltage, V_o, mV	0.03	0.13	0.23

TABLE IV. - COMPARISON OF MEASURED ENGINE SYSTEM CALIBRATION AND CALCULATED VALUES

Digital output, N	Type of calibration	Temperature, °C		
		25	50	70
		Input signal voltage, V_{in}, mV		
1	Calculated	-0.23	-0.33	-0.43
	Measured	-.23	-.34	-.38
10	Calculated	-2.00	-2.10	-2.20
	Measured	-2.01	-2.09	-2.16
100	Calculated	-19.5	-19.6	-19.7
	Measured	-19.6	-19.6	-19.8
255	Calculated	-49.8	-49.9	-50.0
	Measured	-49.9	-50.0	-50.1

25°, 50°, and 70° C. Table IV illustrates the comparison between the measured engine system calibration and the values calculated by using table III. All the calibration data were within ±0.2 percent of full scale of the calculated values. The data variation with temperature was about 0.01 percent per degree C over the 25° to 70° C temperature range, corresponding to a total maximum error of ±0.4 percent of full scale if no corrections are applied to the data. Table V lists the calibration signal output words for the channel 1 and channel 2 voltages as a function of temperature. The maximum variation of

TABLE V. - CALIBRATION

SIGNAL OUTPUTS

Channel	Temperature, $^{\circ}$C		
	25	50	70
	Digital output word, N		
1	147	147	146
2	132	132	131

one count is equivalent to 0.4 percent of full scale. In conjunction with thermistor temperature measurements on the data system housing, the channel 2 calibration signal will also allow for temperature corrections for data from the rotating system.

SUMMARY OF RESULTS

A data system, using commercially available microelectronics and a rotary transformer, mounts on and rotates with the shaft of rotating machinery at speeds to 15 000 rpm. Two versions of the data system were built, a prototype version for testing purposes, and an engine version to process thermocouple signals from experimental jet engine turbine blades. The prototype is capable of processing two groups of differential, steady state, input signals, 12 channels at 1 volt full scale and the other 24 at 40 millivolts full scale, making a total of 36 channels. The engine system processes 72 channels of 50-millivolt full-scale differential signals.

Each system consists of four basic sections: (1) power conditioning, (2) time-division multiplexing, (3) amplification of the multiplexed signals, and (4) analog-to-digital conversion of the amplified signals. The prototype system uses two amplifiers, one for each of the two different voltage level signal groups. The engine system uses just one amplifier since it is required to process just one full-scale voltage level.

A rotary transformer with four separate windings is used to send power to the electronics in the form of 10-kilohertz square waves and to send the digital data from the shaft to stationary electronics. The 10-kilohertz square waves (counted down by a factor of 8) are also used as a clock signal for the whole system.

Most of the electronics in the shaft data system (as well as in the stationary readout system) was constructed with readily available commercial microelectronics.

The system was tested over a temperature range from 25° to 70° C, and over a rotational speed range from 0 to 15 000 rpm. The measured system error was less than ±0.5 percent of full scale. This error would most likely drop to ±0.3 percent under normal operating conditions since the temperature at the data system location in the engine is fairly constant.

CONCLUDING REMARKS

One modification which might be required in certain applications is the elimination of the rotary transformer as a coupling device. In our application the rotary transformer was chosen because (1) the end of the shaft was available for its location, (2) it simultaneously solves the problems of power to the shaft and data from it, (3) it is commercially available, and (4) there were no size or shape restrictions which prevented its use. If for some reason this device cannot be used, the problem of coupling data from the shaft can be resolved by optical, capacitive, or radio-frequency means. The problem of coupling power onto the shaft, however, is not as simply solved. Power for the electronics could be supplied by batteries on the shaft if batteries can be found which meet all the restrictions on size, capacity, and environmental tolerance. The advent of micropower complementary MOSFET integrated circuits could greatly reduce the battery capacity required.

Another modification, which would be worthwhile under certain circumstances, is to provide a separate signal path from the shaft for the SET output from the multiplexer for frame synchronization. This would certainly simplify the readout equipment synchronization scheme and enhance synchronization reliability.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 18, 1969,
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