# AUTOMATIC STRAIN-GAGE AND THERMOCOUPLE RECORDING ON PUNCHED CARDS*

*By* RICHMOND PERLEY

*Research Department, United Aircraft Corporation East Hartford, Conn.*

## *Introduction*

In the development and testing of jet engines, it is necessary to make many measurements on the compressors, turbines and complete engines. Many of the measurements are pressures and temperatures at various locations in the engine or components. There may be as many as 300 or 400 measurements which must be made in each engine for various combinations of simulated altitude, temperature, speed, and thrust. This means that there is a tremendous amount of data that must be gathered, recorded, and analyzed for each engine configuration.

At present the pressures are measured with manometer tubes. Pressure lines are brought from the test cell to the control room, a distance of some 150 feet, where the tubes are read and recorded by a group of four or five men. The temperatures are measured by thermocouples, the leads being brought to a potentiometer with a multipoint input switch in the control room. The time to make the required measurements for one set of engine operating conditions may be as long as 15 minutes, depending on the amount of data required and the number of people assigned to record the data. The data is then sent to the machine computation group where it is punched on cards and processed.

There are two objections to this system. The first is the errors that result and the second is the time and manpower required to record the data. Errors arise at many points. Perhaps the most significant error is caused by the fact that the operation of the engine does not remain constant over the 15 minute period required to record the data. Therefore the data taken first corresponds to one set of operating conditions and the data taken last corresponds to a different set of conditions. Oscillations in the long pressure lines can also cause errors. The manometer tubes and potentiometer can be read incorrectly and the data sheets can be interpreted incorrectly when the information is punched on cards.

Because of the nature of the engines and test cells, the time that can be saved by an automatic recording system is more than the 15 minutes required to record the data. When the controls are set for a given operating condition, the engine approaches this condition on more or less of an exponential curve. If 15 minutes are required to record the data, a certain amount of stabilization time must be allowed for the engine to approach the operating condition so that the change in condition during the recording period will be less than a tolerable amount. It can be seen that if only 1 minute were required to record the data a much smaller stabilization time would be required. At present the stabilization time can be as great as 20-30 minutes.

Another instance in which a faster recording system could save a great deal of tunnel time is when it is desired to take data near the surge line of a compressor. The surge line may be defined as a set of operating conditions beyond which the compressor is unstable. An engine can be operating just below the surge line when the data recording starts but may drift into surge before all the data are recorded. If this happens the run must be started over again.

The two objectives then in the design of the automatic data recording system for a jet engine test stand were accuracy and time. It was felt that the accuracy could be improved because the human element would be removed and the errors of the system would be consistent. To increase the speed, a device was developed to auto-

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matically measure the pressures and temperatures and record them on punched cards at the rate of 200 points/minute.

It was decided to build a versatile device which would measure both pressure and temperature rather than one device for pressure and another for temperature. This can be done because both temperature and pressure can be measured in terms of a voltage in the microvolt or millivolt range. Temperatures are measured with thermocouples and pressures are measured with strain gage type pickups with direct-current excitation. Strain gage pressure pickups are particularly desirable because they are commercially available in a great variety of ranges all having about the same full scale output. Pickups can be selected so that the pressures to be measured are near full scale of the pickup and high accuracy can be obtained.

### *Quantizer*

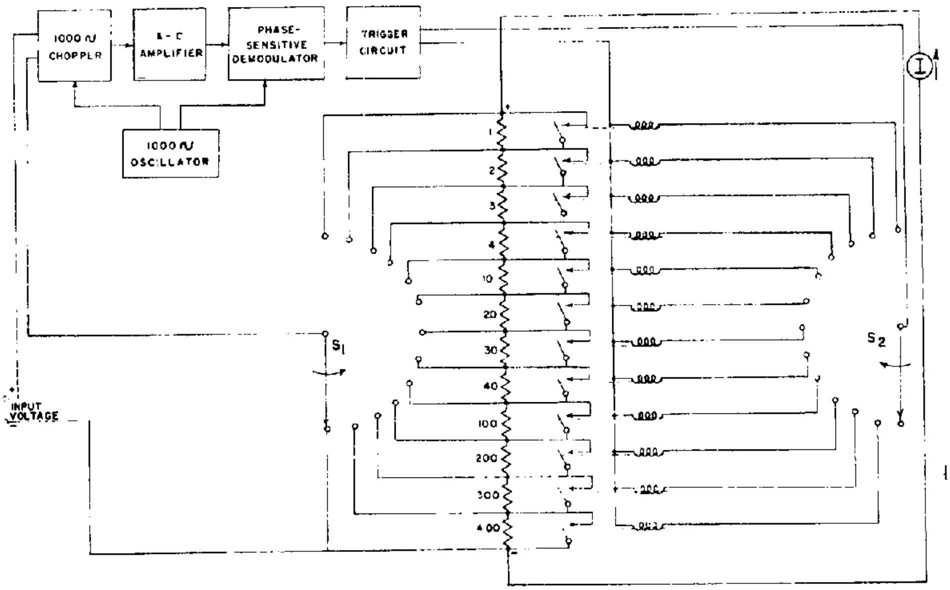
The important element in the system is the device which measures the strain gage or thermocouple voltage and converts it to a suitable input for a card punching machine. The device is an analogue-to-digital converter or "quantizer" since it takes the d-c voltage (analogue quantity) and converts it to a numerical input to the card punch (digital quantity).

One method of measuring or quantizing a voltage is to determine how many times a standard unit of voltage can be subtracted from it before the remainder goes to zero. The resolution required of the system determines the size of the unit of voltage to be used since the system can not resolve any variation in input less than one unit. This simple system is time consuming because the number of operations that might be required is the reciprocal of the resolution. Thus, if measurements are to be made to 0.1% of full scale, 1000 subtractions would have to be allowed for.

In order to decrease the time required, several standard voltages in known ratios are used. The largest voltage that leaves a positive remainder is subtracted from the input and the remainder is treated as a new input and the next smaller voltages are subtracted from it. The process continues until the remainder is less than the smallest unit. If a binary system of standard voltages is used, first it is determined whether the input is greater or less than half scale, then whether the remainder is greater or less than quarter scale, then whether the second remainder is greater or less than eighth scale, etc. This system would require 10 steps to resolve the input to 0.1% of full scale.

The binary system is not very handy if decimal information is desired because the voltages are in the ratio of 1, 2, 4, 8, 16, 32, 64, 128, etc. and it is difficult to convert the information to decimal numbers. The decoding operation is much simpler if voltages in the ratio of 1, 2, 3, 4, 10, 20, 30, 40, 100, 200, 300, and 400 are used. These voltages require 12 steps for a resolution of 0.1%, however, in groups of 4 they can be treated as decades in the decimal system.

The operation of the quantizer can be seen from FIGURE 1. The standard voltages are developed across the voltage divider made up of resistors in the ratios shown. A constant current flows through the resistors. Switch $S_1$, which moves in synchronism with $S_2$, adds various voltages from the voltage divider in series with the input voltage so that the difference between the input and divider voltages appears at the 1000 cycle chopper. The difference is amplified and produces a signal at the output of the trigger circuit such that, if the voltage from the divider is larger than the input, the relay selected by $S_2$ is energized and shorts out the last resistor added to the string by $S_1$. All of the relays have a holding circuit to keep them energized once they have been energized by the trigger circuit.




QUANTIZER

FIGURE 1

The sequence of operations is as follows: Assume the input voltage is 638.5 units. $S_1$ and $S_2$ move to the first position so that the input is compared to the "400" voltage and the 400 relay is connected to the trigger circuit. The input is greater than the divider voltage, so the 400 relay remains deenergized. $S_1$and $S_2$ move to the next position. The input is now compared with the total voltage across the 300 and 400 resistors. Since this is greater than the input, the 300 relay is energized by the trigger circuit and the 300 resistor is shorted. $S_1$ and $S_2$ move to the next position and the voltage compared to the input is 400 plus 200 or 600, the 300 resistor being shorted. This is less than the input so the 200 relay is not energized. In the next position of $S_1$ and $S_2$, the 100 resistor is shorted because it produces a voltage of 700. Likewise the 40 resistor is shorted. The 30 resistor remains, but the 20 and 10 resistors are shorted leaving a voltage of 630. In the units decade the 4 and 3 resistors remain unshorted, the 2 resistor is shorted, and the 1 resistor remains unshorted. Thus, when $S_1$ and $S_2$ have completed their cycle, the deenergized relays are 400, 200, 30, 4, 3, and 1 relays. The total of these numbers is 638, which is correct within the resolution of 0.1% full scale.

$S_1$ and $S_2$ are advanced in synchronism automatically, dwelling 16 milliseconds on each point. About 80 milliseconds is allowed between cycles to read out of the quantizer and switch the input. The total time for a cycle is just under 0.3 seconds.

The amplifier and demodulator do not have to be linear over the range of input voltages. It is only necessary to determine the polarity of the voltage at the input to the chopper. The sensitivities are such that the trigger circuit is activated by a voltage change of 5 microvolts at the input to the chopper.

Stray pickup is naturally quite a problem with an amplifier used at such low levels. Pickup at 60 cycles is reduced by using d-c filament voltage and small coupling capacitors in the amplifier which has maximum gain around 1000 cycles. The demodulator is insensitive to 1000 cycle pickup which is 90° out of phase with the signal from the chopper. In phase 1000 cycle pickup simply has the effect of a zero shift on the input voltages. If it is constant, it is taken care of in the calibration procedure. Higher frequency noise is eliminated by a 500 cycle low-pass, sharp-cut-off filter after the demodulator. The amplifier must be linear over a large enough range so that it is not saturated by these noise signals. Since the output impedance of thermocouples and strain gages is rather low, an input transformer with a high turns ratio can be used to reduce the effects of microphonics in the first amplifier stage.

Since large negative and positive signals applied to the chopper saturate the amplifier, precautions had to be taken so that it did not become blocked and unable to pass the small signals that might result on the following position of $S_1$. This was accomplished by using push-pull triode amplifier stages with a large common cathode resistor so that plate voltages and thus coupling capacitor voltages do not vary with signal level. Also cathode followers were placed after each amplifier stage and were direct-coupled to the following amplifier stage so that grid current could not charge the coupling capacitors. The time response of the amplifier is such that, when the input to the chopper is reduced from 5 millivolts to 5 microvolts, the output is at its proper value within 2 milliseconds.

### *Complete System Operation*

The quantizer can make a measurement in just less than 0.3 seconds and the card punch operates at 100 cards/minute or 0.6 seconds/card. Therefore, it was decided to

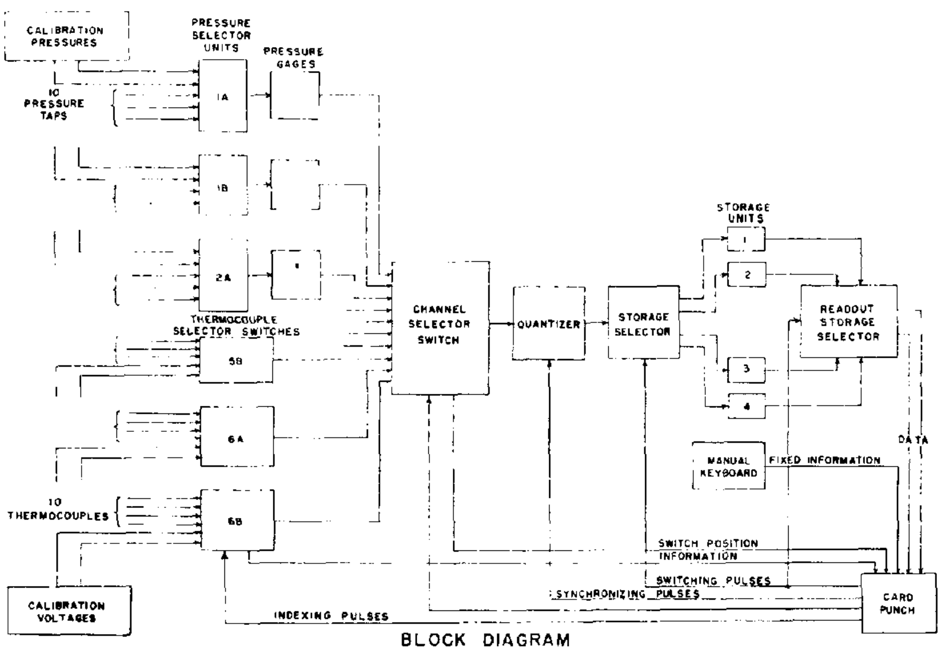



FIGURE 2

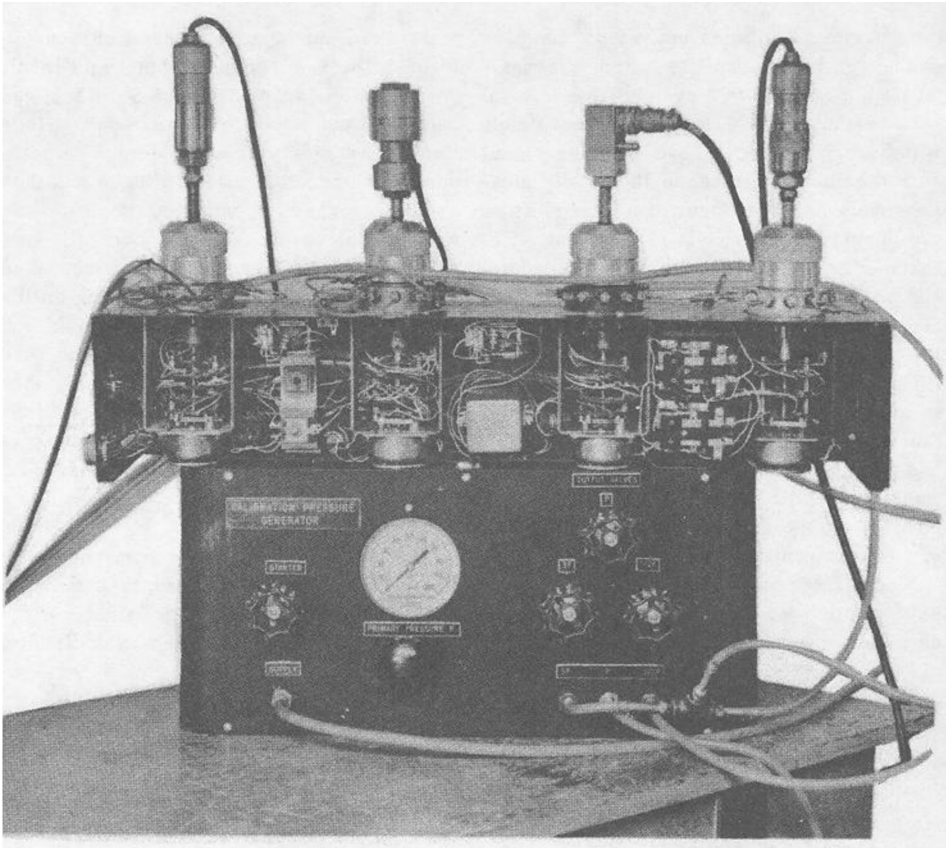


FIGURE 3

allow the punch to free run and synchronize the quantizer to the punch so that two measurements are made on each card cycle. The punch takes its input in parallel (all columns or decades at the same time) and requires 0.5 seconds to read out. Four storage units are provided so that the quantizer can be loading two, one after the other, while the punch is reading out of the other two in parallel. This is shown in FIGURE 2. Each storage unit is composed of twelve relays which repeat the condition of the twelve quantizer relays. The contacts on the four relays in each of the three decades are interwired to permit a decimal readout by the card punch.

For convenience in cycling, the input data has been divided into twelve channels. Each channel reads either a group of pressures that are applied to one pressure gage or a group of thermocouples that are in the same temperature range. Provisions have been made to measure ten data inputs on each channel. In addition two calibrations, full-scale and low scale respectively, are made.

In the case of the pressure channels, two known pressures are applied to the gage. The relation between the calibration pressures and the numbers they produce in the card punch give a calibration for the complete system including changes in gage calibration factor, zero of the gage, current through the quantizer resistors, and any stray voltage that might be added to the signal. In the case of the temperature channels, two calibration voltages are used which correspond to the output of thermocouples of the type being used at two convenient temperatures. Therefore, the complete system is calibrated when each set of data is taken.

Pressures are selected by means of a solenoid-operated switch that connects the pressure gage to any one of twelve pressure taps. FIGURE 3 shows four pressure selector switches and pickups and the Calibration Pressure Generator. Other solenoid-operated switches select the proper thermocouple leads for each channel. These are shown in FIGURE 4 with the unit that produces the calibration voltages. The cycling is arranged so that each selector switch is advanced as soon as the channel has been read. This channel is not read again until all of the other 5 pairs of channels have been read, a period of 3 seconds. Therefore, in the case of the pressure channels a period of 3 seconds is allowed for the pressure channels a period of 3 seconds is allowed for the pressure in the pressure pickup to settle out to the applied pressure. Pulses are taken from the card punch to index the channel selector switch just before the quantizer starts its cycle and index the selector switches for each channel just after the channel has been read.

The information fed to the card punch includes the data from two of the four storage units and information which tells the position of the selector switches when the data from the storage units was taken. In addition, a manual keyboard is provided for such information as date, run number, conditions, etc.

A complete run consists of 72 card cycles of the card punch or 144 readings of the quantizer. Of these readings, 24 are calibration points (2 for each channel) and 120 are data points (10 for each channel). The first 12 of the 72 cards contain the calibration points. The cards are taken from the punch and run through a tabulating machine at the test stand to give the test operator an indication of the results of the test. The numbers that appear on the tabulator are not in real units, but are proportional to the data being measured. They are

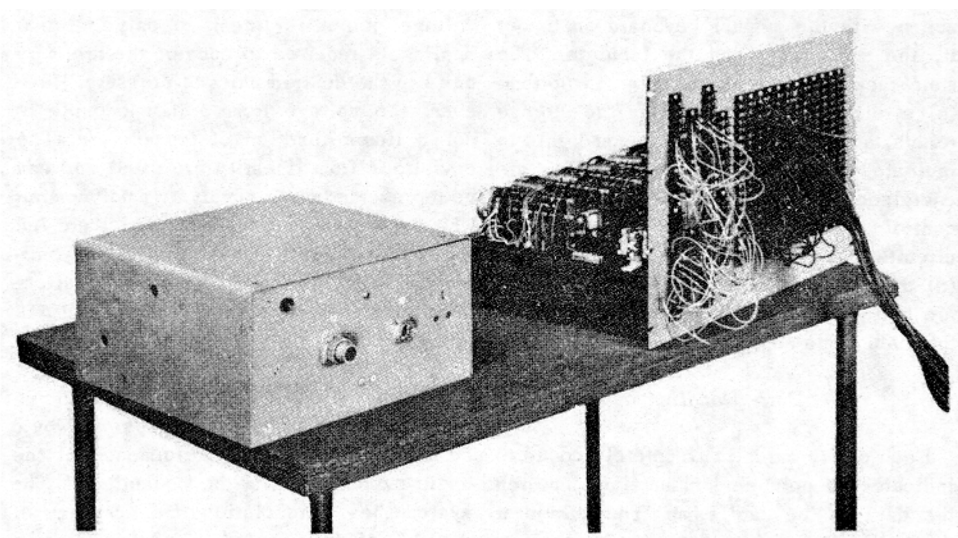


FIGURE 4

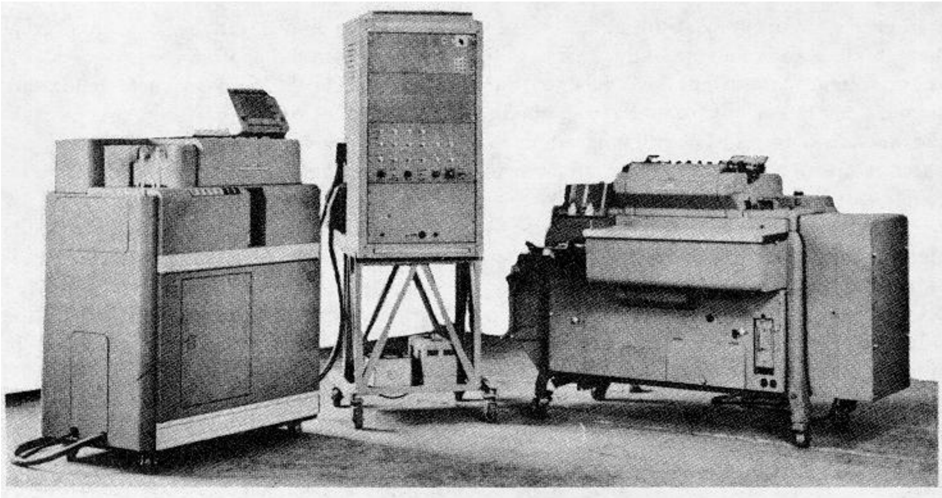


FIGURE 5

in an arbitrary set of units varying between 0 and 999. In addition, zero and scale factor corrections must be made before the data is exact.

The thermocouple and pressure selector switches are located in the test cell to keep the length of the leads from the test rig to a minimum. FIGURE 5 shows the remainder of the equipment which is located in the control room. This includes the card punch with the manual keyboard on top of it, the main rack, and the tabulator. The main rack consists of, from top to bottom: (a) a relay chassis containing the storage relays, quantizer relays, and neon lights to indicate which of the quantizer relays are energized; (b) the amplifier chassis; (c) the control chassis containing the start-stop circuits and zero and scale factor controls; (d) the power supply. Underneath the rack are batteries for strain gage excitation and the 1000 cycle supply.

### *Data Handling*

Each of the cards is completely coded to indicate the point and channel from which the data on the card came. The values of the calibration points (i.e. fixed pressures and voltages) on each channel are known in advance. Therefore a computing machine can be given all the information needed to transform the data in arbitrary units to corrected data in what ever units are desired, e.g., degrees centigrade, degrees Fahrenheit, pounds per square inch, inches of mercury, etc.

The relationship between the pressure applied to a strain gage pickup and the voltage output is linear so only a linear scaling is required to convert the arbitrary units to the desired units of pressure. However, the voltage from a thermocouple is not a linear function of temperature. The deviations from linearity are small and can be represented quite simply by a polynomial. The coefficients of the polynomial are fed into the computing machine with the calibration point information and the corrections are made after the linear scaling has taken place.

### *General Uses*

Before discussing other uses, it would be well to repeat the performance of the basic system, that is, the "quantizer." The system has a resolution and accuracy of ± 0.1% of full scale. In addition, noise limits the resolution to about 10 microvolts. Full scale can be set to any value desired by adjusting the current through the quantizer resistors. It is possible to have a different full scale voltage on each of the 12 channels.

The time required to actually measure a voltage is 0.2 seconds. If the input voltage varies during the 0.2 second measuring period, the quantizer will measure and indicate a voltage somewhere between the maximum and minimum value, but not necessarily the average. The indicated value is correct for some instant of time between the start and finish of the measuring period. Therefore the quantizer is most useful for measuring quasistatic voltages, as opposed to measuring rapidly varying voltages "on the fly." Measurements are made at the rate of 200/minute.

The quantizer is not limited to measuring the output of strain gages and thermocouples. Any voltage producing element can be used as long as its internal impedance is a few hundred ohms or less. A-C voltages can also be measured if the same frequency is available to provide current for the quantizer resistors and phase sensitive demodulator. When a-c voltages are measured the chopper is not used.

The system is most useful when many repetitive measurements must be made at many points. The system can also be used to continuously measure a few points if the data is not varying too fast. The reason for applying several pressures to one gage is to reduce the number of gages required and also reduce the amount of calibration that must be done.