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Modular Instrumentation System for Real-Time Measurements and Control on Reciprocating Engines

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William J. Rice and Arthur G. Birchenough
Lewis Research Center
Cleveland, Ohio

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and Space Administration

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Summary

An instrumentation system has been developed for reciprocating engines. Among the parameters measured are the indicated mean effective pressure, or theoretical work per cycle, and the mass-fraction burn rate, a measure of the combustion rate in the cylinder. These computations are performed from measured cylinder pressure and crankshaft angle and are available in real time for the experimenter. A 100- or 200-consecutive-cycle sample is analyzed to reduce the effect of cyclic variations in the engine. Data are displayed in bargraph form and the mean and the standard deviation are computed. Other instruments are also described.

Introduction

The NASA Lewis Research Center is investigating the combustion process in reciprocating engines. A goal of the research program is to develop a computer model for the Otto cycle that will predict the combustion process. A modular engine instrumentation system (ref. 1) has been developed primarily to provide input data to generate empirical equations for the model and to verify its results. The instrumentation system provides a real-time measurement or computation of key combustion parameters and displays the results in a meaningful, easily understood format.

Two of the major parameters are the indicated mean effective pressure (IMEP) and the mass fraction burn rate (MFBR). IMEP is the work per unit of displacement volume performed during an engine cycle. MFBR is a measurement of the rate of combustion during the cycle. From it the delay between ignition (or injection) and combustion and the combustion time or flame front speed are determined.

Both these parameters have been recognized as important indicators of combustion. They have typically been determined by postrun reduction of pressure-volume and pressure–crankshaft-angle oscilloscope photographs. The reduction of photographed data has not been automated and does not allow the analysis of a sufficient number of consecutive cycles to accurately portray the combustion process especially during lean operation. In addition, high-speed recording with postrun computer reduction is also being used. Neither of these techniques provides real-time analysis to assist the experimenter during the data run. The advantages of this modular instrumentation system are the real-time computation of parameters and the presentation of the data for a large number of consecutive cycles in a meaningful display.

In addition to the IMEP and MFBR, other instruments have been developed to provide the following functions:

(1) Provide analog signals proportional to cylinder volume and crankshaft angle to sweep the oscilloscope horizontal axis and generate pressure-volume diagrams.

(2) Display data in the form of a 100- or 200-sample bargraph, with a computation of the mean and the standard deviation of the sample.

(3) Measure the crankshaft angle where an event such as ignition, injection, or peak pressure point occurs.

(4) Measure the peak-per-cycle value of a parameter such as cylinder or injection pressure.

(5) Generate the average curve of a parameter of 100 consecutive cycles, such as average pressure or average MFBR curves.

(6) Generate output commands of controlled timing and duration to control ignition, injection, or other parameters affecting engine operation.

A modular plug-in concept was adopted to increase the flexibility of the instruments and to allow easy expansion as new measurements are added.

Measurement Concepts

All the parameters are computed and displayed as a function of crankshaft position instead of time. Time-domain analysis is complicated by the variations in engine operating speed, both steady state and transient. Time-domain displays show considerable jitter as a result of transient engine speed variations, and the time sweep must be changed with different engine operating speeds. Angular position analysis eliminates engine speed variation effects from the computations, through a change of variables if necessary, and results in very stable displays.

Crankshaft angle is measured with an absolute position optical shaft encoder directly coupled to the crankshaft. The encoder digitally resolves the crankshaft angle into approximately 0.35° increments at engine speeds up to 6000 rpm.

A major problem with analyzing engine

performance is the cyclic variations in the parameters. Particularly during lean operation, there is considerable variation in a parameter from one cycle to another under equal engine operating conditions. Thus display of a parameter for a single cycle cannot be assumed to be representative of the data. Therefore data in this system are presented in a 100- or 200-consecutive-sample bargraph with the statistical mean, the standard deviation, the sample maximum, and the sample minimum computed. Data collected from all the various modules are from the same set of engine cycles. The display is illustrated later in this report.

A modular packaging concept was adopted to increase the flexibility of the system and to provide for easy system expansion. Commercially available blank plug-in modules and module racks were adapted for use in the system. The module rack contains major power supply components (i.e., transformers, rectifiers, and filter capacitors). A partially regulated direct-current bus structure is available at the edge card connector at the rear of each plug-in position. Final power supply regulation is accomplished in each module to reduce interaction between modules. Additionally, the binary crankshaft-angle signal is bused across the module rack; thus, each module has access to the crankshaft position data.

Most of the modules contain a digital display of the parameter that is measured or computed. Because of the cycle-to-cycle parameter variations, the digital display is of the continuous-averaging type with a time constant of 50 engine cycles and is used primarily as an indicator for establishing an engine operating point. This averaged signal is made available at the rear of the module rack for easy connection into an auxiliary data system. Additionally, at the end of every engine cycle a serial digital output is produced by each module for use by the statistical signal processor. It is this output that is used to produce the bargraphs and to compute the statistical mean and the standard deviation. The module rack with some of the modules installed is shown in figure 1.

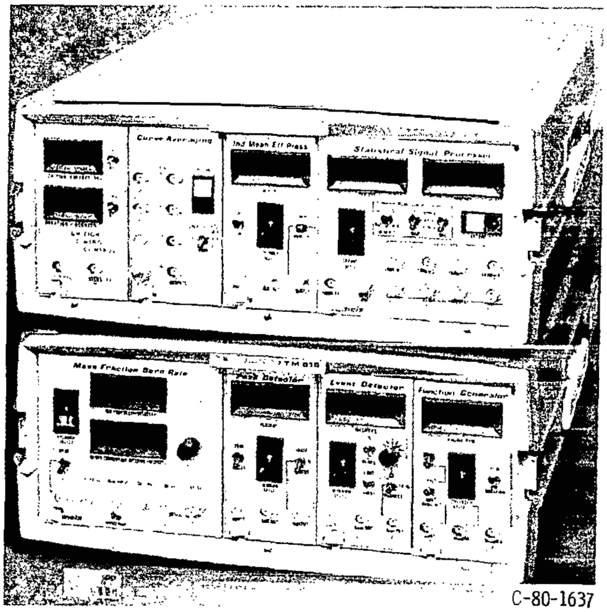
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Figure 1. - Typical modular engine instrumentation system (MEIS).

Function Generator

The function generator is primarily an interface between the shaft encoder and the instrumentation systems. This module performs several other operations, as illustrated in the block diagram (fig. 2). The digital code produced by the shaft encoder is a Gray code, which has only one bit change for each incremental angle change. This code is desirable in that synchronization between the bits is easily obtained but is not directly usable in the computations. The function generator converts the Gray code to a natural binary code. An extra bit is added to convert the 360° information from the shaft encoder to 720° information for four-cycle engine computations. This binary code is applied to a digital-to-analog converter to generate an analog signal proportional to the crackshaft angle. This analog signal is used as the X-axis oscilloscope sweep, replacing the conventional time base, and converts the display to the crankshaft angle θ domain. A parameter such as cylinder pressure can be applied to the vertical axis and produces a pressure-θ display that is independent of engine speed and speed fluctuations. The display is actually 2048 discrete dots, a dot for each increment, but it appears as a continuous trace.

The instantaneous cylinder volume, a known function of θ, is computed from the engine geometry and the crankshaft position. The cylinder volume, as a function of θ, is then stored in a nonvolatile read-only memory. In the function generator this memory is used as a look-up table, addressed by θ. The memory output is converted to an analog signal, which is used to generate pressure-volume diagram displays. A switch can select which cylinder of an engine the volume signal is generated for in multicylinder applications.

The other operations performed by the function generator are displaying engine speed and generating reference marks. Engine speed is determined by counting the θ increment changes per unit of time. Reference marks are generated every 10°, with larger

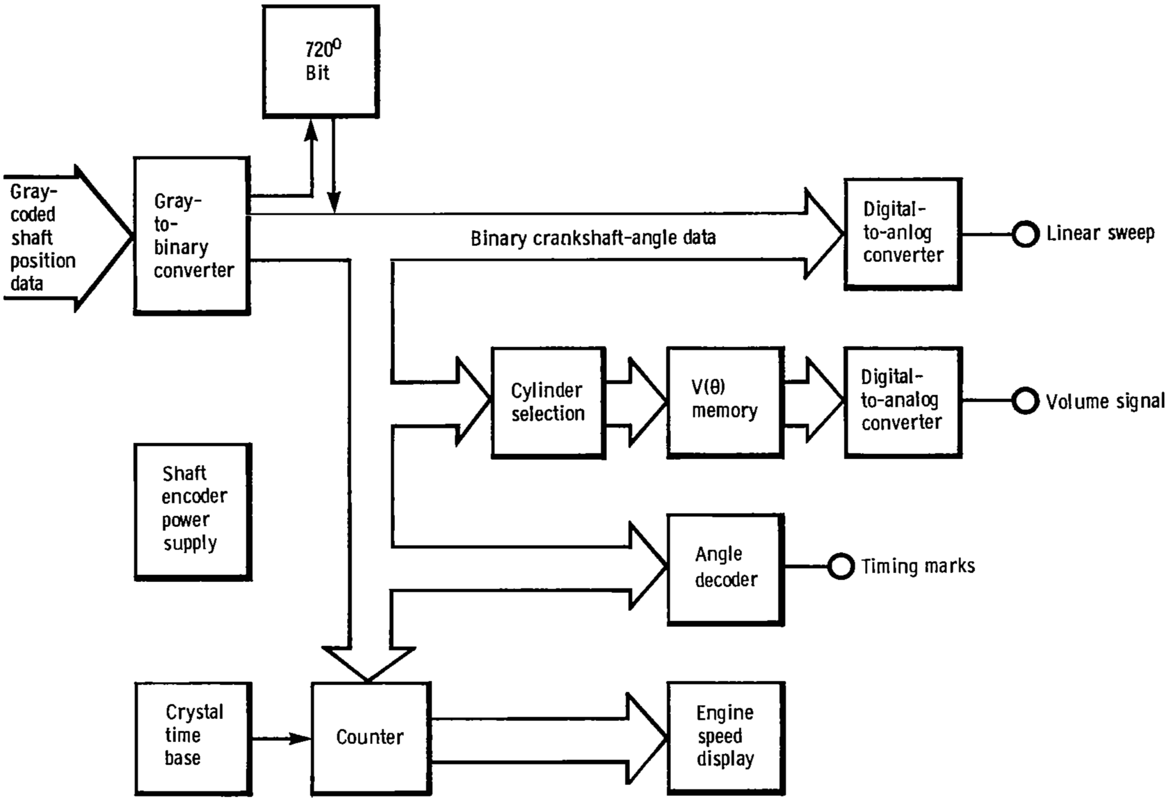


Figure 2. - Block diagram of function generator.

marks at 90° and once per 720° to generate θ reference points for the oscilloscope displays. The 720° and 90° marks are derived directly from the binary θ signal. The 10° marks are obtained from part of the memory used to store the volume signal. The sweep, volume signal, and reference marks are shown in figure 3. Power of the shaft encoder is also obtained from a power supply in the function generator. The function generation module is shown in figure 4.

Indicated Mean Effective Pressure

Indicated mean effective pressure can be used as a measure of combustion efficiency. IMEP is a measurement of the net work delivered at the piston face during a single thermodynamic cycle, normalized by the cylinder displacement. But it is a computed parameter and has not generally been available as a real-time measurement. IMEP can be readily determined from a pressure-volume (P–V) diagram, as shown in figure 5. The area enclosed by the P–V diagram is a measurement of the work done by the engine. Area A1 represents negative work, or work done on the engine. The algebraic difference A2 – A1 divided by the displaced volume is equal to the IMEP and has units of pressure (psi). Planimeter measurements can readily obtain the area, or IMEP can alternatively be computed from an analysis of pressure–crankshaft-angle data. This has often been done by postrun computer analysis but does not provide real-time data. Computer analysis can provide data for a large number of consecutive cycles that are not readily available from P–V diagram analysis.

In this instrument (refs. 2 and 3) IMEP is computed continuously in real time by analysis of the pressure–crankshaft-angle data. IMEP is defined as the closed integral of the pressure-volume relationship in the cylinder divided by the cylinder displacement volume:

$$\mathrm{IMEP} \triangleq \frac{1}{V_D} \oint P \, \mathrm{d}v \qquad (1)$$

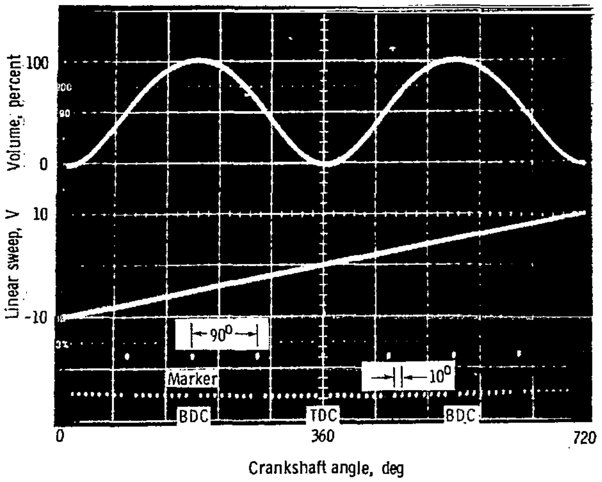


Figure 3. - Function generator outputs.

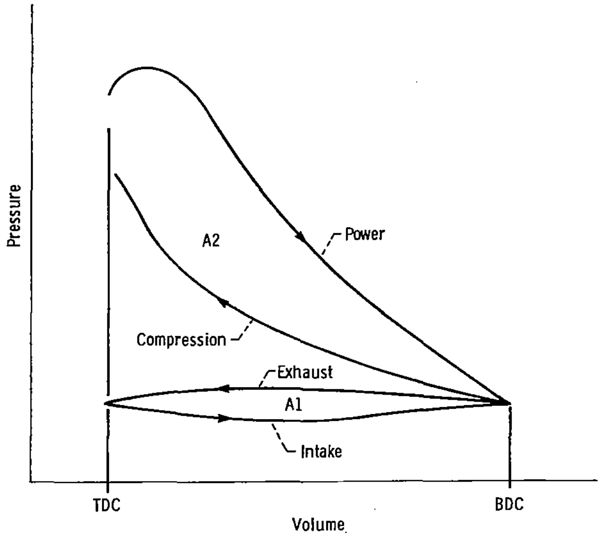


Figure 5. - Pressure -volume diagram. IMEP = Net work/Displaced volume = (A2 - A1)/V_D.

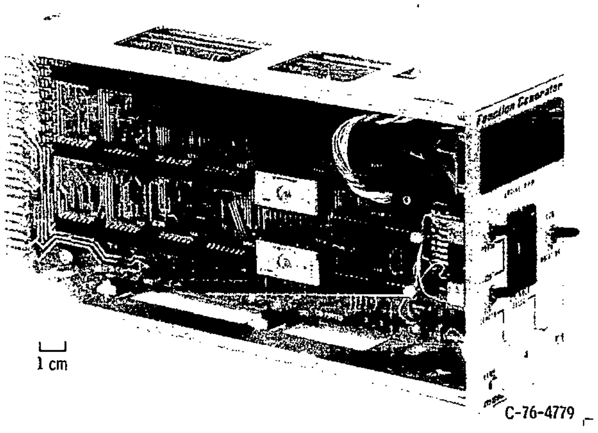


Figure 4. - Function generator.

where V_D is the displacement volume. This integral can be performed in the θ domain by a change of variables:

$$\text{IMEP} = \frac{1}{V_D} \int_{\theta=0}^{720^\circ} P\left(\frac{dv}{d\theta}\right) d\theta \qquad (2)$$

In the instrument this integral is approximated by a summation of finite difference products:

$$\text{IMEP} \simeq \frac{1}{V_D} \sum_{i=1}^{n} P\left(\frac{\Delta V}{\Delta\theta}\right)\Bigg|_{\theta = i\Delta\theta} \Delta\theta \qquad (3)$$

where $\Delta\theta = 720^\circ/n$ and $n = 1024$. The term $\Delta V/\Delta\theta$ is a function only of engine geometry and θ:

$$V(\theta) = A\left[R + r(1 + \cos\theta) - (R^2 - r^2 \sin^2\theta)^{1/2}\right] + V_c \qquad (4)$$

where

V	volume
A	cylinder area
R	rod length
r	1/2 stroke
θ	crankshaft postion (measured from bottom dead center (BDC))
V_c	clearance volume

$$\frac{\Delta V}{\Delta\theta} \cong \frac{d}{d\theta} V(\theta) \qquad (5)$$

$$\frac{\Delta V}{\Delta\theta} = A\Big[-r\sin\theta + r^2 \sin\theta\cos\theta(R^2 - r^2\sin^2\theta)^{-1/2}\Big] \qquad (6)$$

This function is computed and stored in a memory as is the function-generator volume signal. The computation of IMEP is then reduced to multiplying the cylinder pressure by the stored function and summing the products. The computation is performed 1024 times during each engine cycle or at approximately 0.7° increments of θ.

A block diagram of the instrument is shown in figure 6. Digital and analog signal processing is used to attain the high speed required. The pressure signal is multiplied by $\Delta V/\Delta\theta$ for each $\Delta\theta$ interval. The $P(\Delta V/\Delta\theta)$ signal is digitized and then summed with an adder-accumulator. At the end of each engine cycle the accumulator value, as an analog signal, is stored as the IMEP for that cycle, and the accumulator is reset for the next cycle. The signals during the computation are shown in figure 7. Figure 7(a) is the absolute value, as an analog signal, of $\Delta V/\Delta\theta$. These traces are shown for one 720° engine

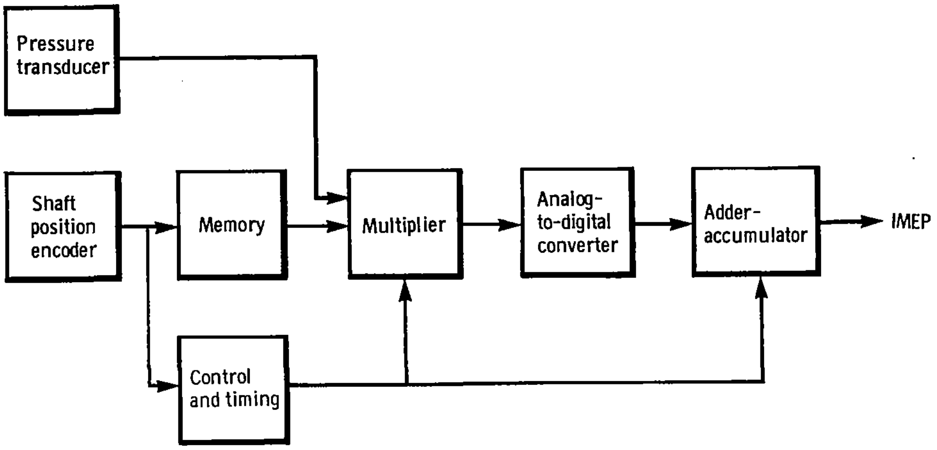
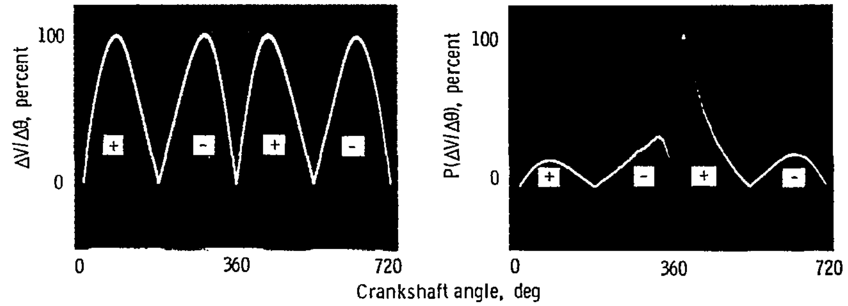
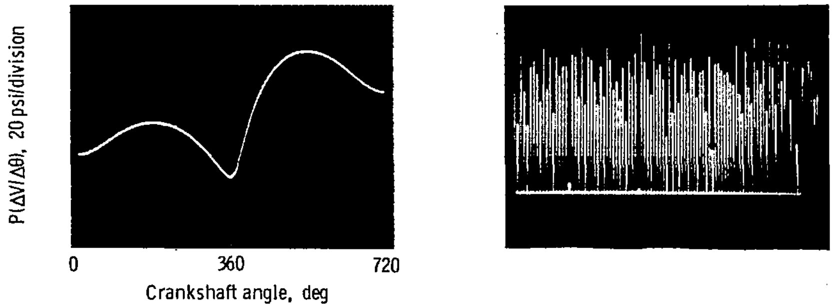


Figure 6. - Block diagram of IMEP instrument.



(a) Absolute value of ΔV/Δθ versus crankshaft angle.

(b) Absolute value of P(ΔV/Δθ) versus crankshaft angle.



(c) Running summation of P(ΔV/Δθ) versus crankshaft angle.

(d) Bargraph of 100 consecutive IMEP values. 10 psi/division.

Figure 7. - Signals during computation.

cycle, with top dead center (TDC) of the combustion stroke in the center. The actual value of $\Delta V/\Delta\theta$ is negative during the second and fourth quadrants of the trace. The absolute value of $P(\Delta V/\Delta\theta)$ is shown in figure 7(b). Again, the actual value would be negative during the second and fourth cycles.

Figure 7(c) is the running summation of the $P(\Delta V/\Delta\theta)$ products. This trace indicates positive work produced during the intake stroke. This instrument computes with absolute pressure and does not compensate for crankcase pressure acting on the other side of the piston. Including crankcase pressure would effectively subtract a constant from the cylinder pressure at all times, assuming constant crankcase pressure, and would not affect the final IMEP calculation. It would, however, cause the traces in figures 7(b) and (c) to indicate negative work during the intake stroke. Figure 7(d) is a bargraph of 100 consecutive cycles of IMEP. The bargraph is not produced directly by the IMEP module but is formatted by the statistical signal processor module. The amplitude of each bar represents the IMEP for a single cycle. This sample was taken near the lean limit (equivalence ratio, 0.7) and shows considerable variation in IMEP: The standard deviation was 22 percent of the mean.

The IMEP data have been verified by extensive P-V diagram analysis. (Agreement of the data has been ±1 percent of reading at 20 percent of full scale.) The module can be adapted to a wide variety of engines by changing only the memory (a plug-in component) and the calibration setting. The IMEP module is shown in figure 8.

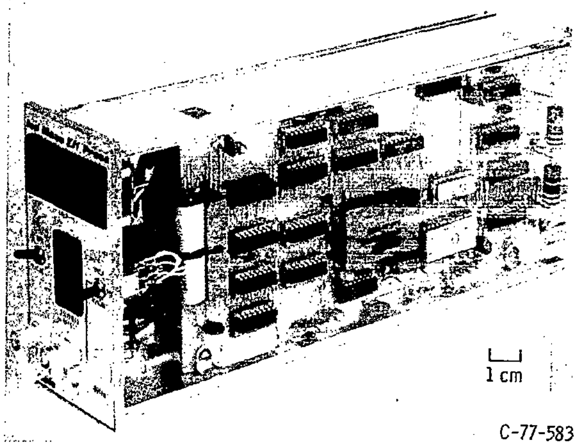


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Figure 8. - IMEP module.

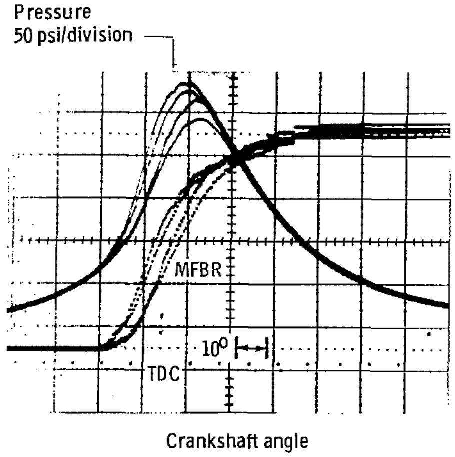

Figure 9. - Pressure and mass-fraction burn rate curves.

Mass Fraction Burn Rate

Although IMEP is an excellent indication of combustion efficiency, it gives little insight into the combustion process. Even studying the $P(\Delta V/\Delta\theta)$ and running sum curves does not add much insight. But the mass fraction burn rate (MFBR) will indicate several characteristics of the combustion. The MFBR curve displays the percentage of the fuel burned in the cylinder at any crankshaft angle. The MFBR curve is shown in figure 9 for four engine cycles. Ignition delay is the interval between ignition and the crankshaft angle where 10 percent of the mass is burned. The burn interval is defined as the interval between crankshaft angles where 10 and 90 percent of the mass is burned. The maximum amplitude of each curve is proportional to the total amount of mass burned during that engine cycle. Although some variation in the total mass burned is expected because of fuel distribution and transient conditions, some cycles never finish combustion by the end of the cycle.

MFBR is computed by using many of the principles developed for the IMEP instrument and also by using only pressure and crankshaft-angle information. The calculation is based on the thermodynamic analysis advanced by Rasweiler and Withrow (ref.4). Basically, the pressure rise, or decrease, in a cylinder is caused by two components. Piston motion will compress, or expand, the volume and cause a pressure increase or decrease. There is also an additional pressure rise if any of the fuel mass was burned during the interval. Therefore

$$\Delta P = \Delta P_p + \Delta P_b \tag{7}$$

where

ΔP total pressure change during interval

ΔP_p	pressure change due to compression or expansion
ΔP_b	pressure change due to mass burning

Let P_i be the actual pressure at the end of the interval and P_{i-1} be the pressure at the beginning of the interval. We can define a pressure P_i^* that would be the pressure at the end of the interval if the only pressure change was due to expansion or compression. Then it follows that

$$\Delta P_b = P_i - P_i^* \tag{8}$$

Assuming a quasi-static adiabatic process,

$$PV^\gamma = \text{Constant} \tag{9}$$

where

γ	polytropic gas constant, C_p/C_v
V	gas volume

or specifically

$$P_i^* V_i^\gamma = P_{i-1} V_{i-1}^\gamma \tag{10}$$

Solving for P_i^* gives

$$P_i^* = \frac{(P_{i-1} V_{i-1}^\gamma)}{V_i^\gamma} \tag{11}$$

Then by backsubstitution

$$\Delta P_b = \frac{P_i - P_{i-1} V_{i-1}^\gamma}{V_i^\gamma} \tag{12}$$

or

$$\Delta P_b = \frac{P_i V_i^\gamma - P_{i-1} V_{i-1}^\gamma}{V_i^\gamma} \tag{13}$$

The mass burned during the interval ΔM is proportional to the product $\Delta P_b \times V_i$, where V_i is the instantaneous cylinder volume at the end of the interval. Therefore

$$\Delta M = k V_i (\Delta P_b) \tag{14}$$

where k is the constant of proportionality, or

$$\Delta M = k\left(\frac{V_i}{V_i^\gamma}\right)(P_i V_i^\gamma - P_{i-1} V_{i-1}^\gamma) \tag{15}$$

This last equation is the equation solved by the instrument. (For notation purposes, the last term will be abbreviated to $\Delta(PV^\gamma)$ in the following discussion.)

The mass fraction burned at any time is the sum of the ΔM's. In the instrument (block diagram of figure 10), the pressure during each θ increment (0.35°) is multiplied by $[V(\theta_i)]^\gamma$ and compared to PV^γ for the previous interval. Any deviation is due to mass burning. The $\Delta(PV^\gamma)$ terms are multiplied by V/V^γ and summed to generate the mass fraction curve. The computation is only valid when all valves are closed and is therefore performed over a -45° to 135° interval about top dead center.

The V^γ term is stored in a memory and multiplied by P in a multiplying digital-to-analog converter. A digital differentiator (ref.5) determines $\Delta(PV^\gamma)$. This is digitally multiplied by V/V^γ, also stored in a memory, and summed. The MFBR curve is then normalized to determine the 10- and 90-percent points. The delay between ignition and 10 percent mass burned and the interval between 10 and 90 percent mass burned are determined. The MFBR curve is also available. Heat transfer and leakage are not directly accounted for in the analysis but can be compensated for by changes in γ. Ring and valve leakage also affect the calculation, particularly at low burning rates. Cylinder leakage is also compensated for in the instrument. Results obtained by using the mass fraction burn rate instrument compare very favorably with results obtained by using extensive computerized postrun data analysis of pressure-crackshaft-angle data. The MFBR instrument is shown in figure 11.

Statistical Signal Processor Module

The statistical signal processor module was designed to provide a meaningful real-time display of the engine parameters. Each module in the system typically produces a measurement or computation for every cycle of the engine. However, even at low operating rpm, data are produced too rapidly for the operator to comprehend. For example, at 3000 rpm, 25 measurements or computations are performed by

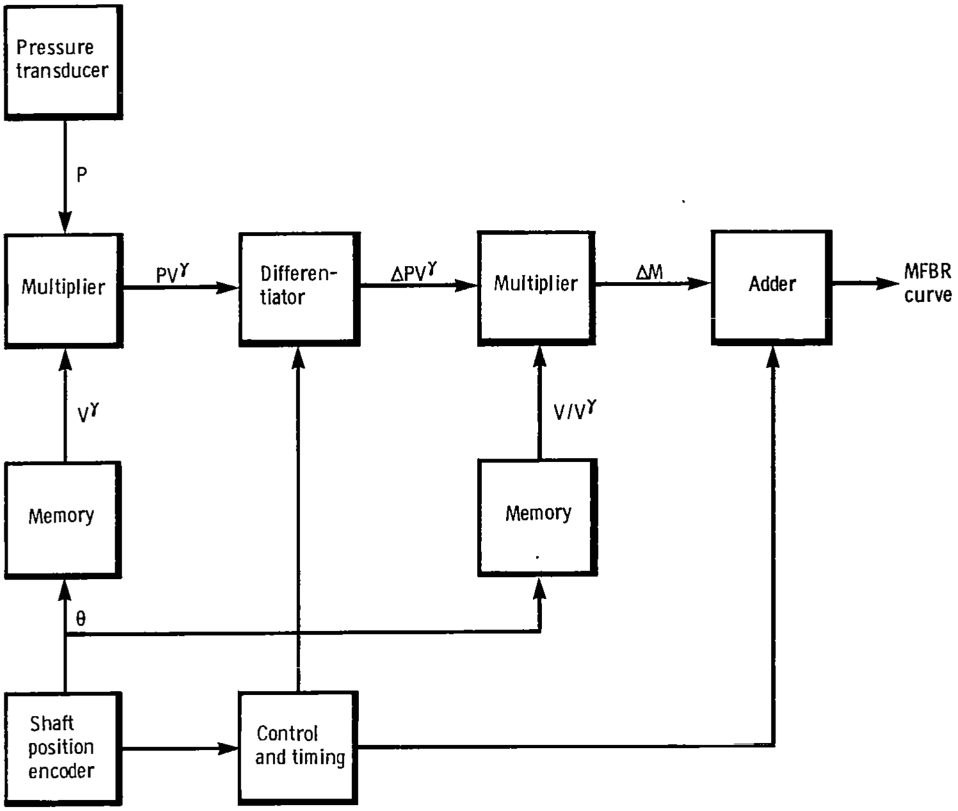

Figure 10. - Block diagram of MFBR instrument.

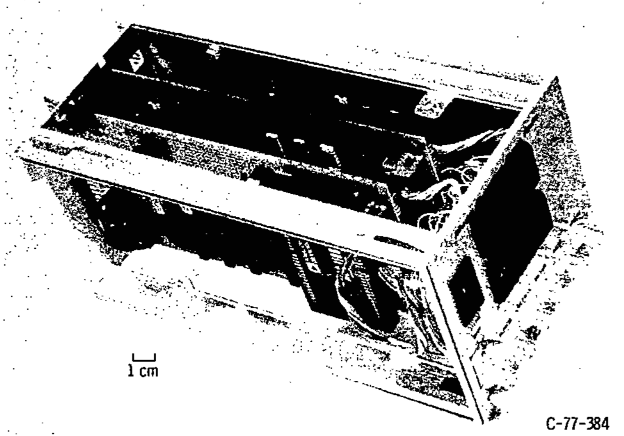

Figure 11. - MFBR instrument.

each module every second. The digital displays on each module do provide an indication of the average value, but not in a statistical sense, and provide no information as to the cyclic variations in the parameters.

The statistical signal processor module records data from the various modules connected to it. Upon initiation of a sample command, the next 100 or 200 values of the data are stored in an internal semiconductor memory. There are four such memories in the module, each divided into an upper and lower partition. Thus data can be collected from four modules as either two separate 100-cycle samples or a 200-cycle sample from each module.

As soon as the sample is completed, the data are recalled from the memory and formatted into a bargraph display for each channel. The bargraph consists of 100 or 200 vertical bars evenly spaced along the horizontal axis. The height of each bar is proportional to the parameter value for a particular engine cycle. The bars are displayed in the order of occurrence, with the first cycle on the left. These bargraphs are displayed on an oscilloscope. A block diagram of the statistical signal processor module is shown in figure 12.

As the bargraphs are formed, the data are also processed by analog circuitry to produce the statistical mean and the standard deviation for the 100- or 200-cycle sample. A low-pass filter in

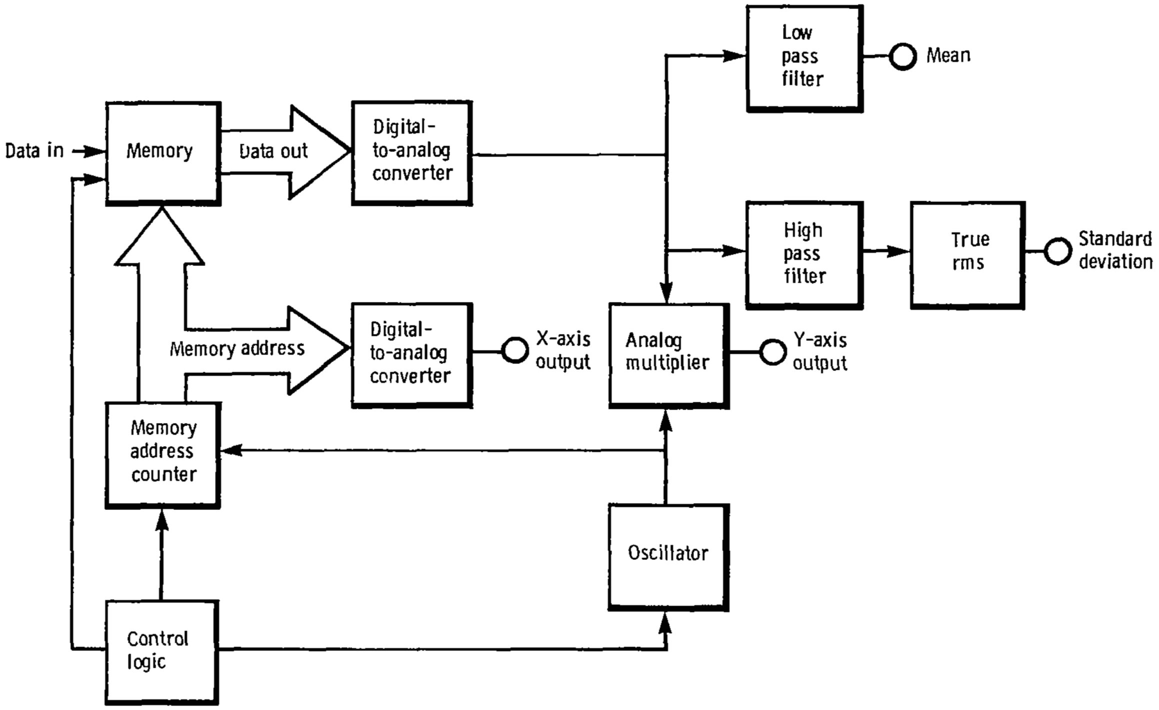

Figure 12. - Block diagram of statistical display module.

conjunction with a true root-mean-square (rms) converter is used to compute the standard deviation. The mean and the standard deviation are displayed on digital readouts. A thumbwheel switch is used to select which input channel is displayed on the readouts. However, all the mean and standard deviation values are available at the rear of the module rack for recording on an auxiliary data system.

In addition to the mean and the standard deviation the statistical signal processor module also measures the maximum and minimum values of the sampled data. These values are displayed on the same digital readout as the mean and the standard deviation by using the same channel selector switch. All the maximum and minimum values are available at the rear of the module for auxiliary recording.

The statistical signal processor module is shown in figure 13.

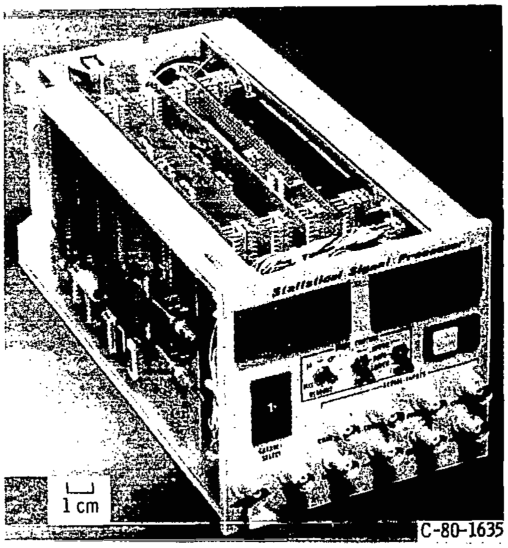

Figure 13. - Statistical signal processor.

Event Detector

An event detector module has been developed to measure the angle of occurrence of significant events. This module was developed primarily to determine the point at which ignition occurs. However, the design was made flexible enough so that other events of significance could be determined such as the fuel injection point on an injected engine, the point at which parameters such as pressures cross a selectable value from either direction, or, in conjunction with the peak detector module (described later), the point at which parameters reach their maximum or minimum value.

The module accepts analog or digital inputs in the range −10 to 10 volts. A level control is provided on the front panel to set the trigger level. A switch is provided to select the slope or direction in which the input signal crosses the trigger level. For inputs that cross the trigger level more than once, a switch is provided to select whether the first or last crossing is detected.

Additionally, a window 180° wide is established to restrict measurement to only a portion of the 720° engine cycle. A thumbwheel switch is provided to move the window in 90° increments through the complete cycle. This allows parameters such as ignition timing to be determined for any one of the cylinders. The module is shown in figure 14.

Peak Detector

The peak detector module is used to determine the maximum or minimum value of an analog input signal. A switch is provided on the front panel to select either the peak or valley mode of operation. In the peak detect mode an internal track-hold amplifier is reset to the most negative value at the beginning of each engine cycle. The amplifier is then placed in the track mode and will follow the input signal analog as it is increasing. As soon as the input signal begins to decrease, the track-hold amplifier switches into the hold mode and retains the peak value at its output. A status output signal is generated at this time to indicate that a peak value has occurred. If the input signal should exceed this peak value at some point later in the cycle, the track-hold amplifier will again track the input until a new (higher) peak is reached. Operation in the valley mode is analogous with the track-hold amplifier reset to the most positive value at the beginning of the cycle and tracking the input until a minimum level is detected.

As with the event detector a selectable window is established that restricts the measurement to portions of the 720° cycle. An additional switch position is used to disable the window function so that the entire cycle can be examined.

The status output signal is compatible with the event detector. When used together, both the peak value and the crackshaft-angle where the peak occurred can be measured. The module is shown in figure 15.

Curve-Averaging Module

Data correlation to computer predictions is of prime concern. However, because of the cyclic variations in combustion, it is difficult to determine a representative curve for a parameter. The curve-averaging module (ref. 2) was developed to provide a 100-cycle average of a 720° curve. The module adds the input value at each increment for 100 successive cycles and divides the output by 100 to obtain the average. The average curve is stored for readout on the oscilloscope.

The module provides a 2048-point approximation to a 720° curve, or it can be used in a two- or four-channel mode, averaging two or four separate curves

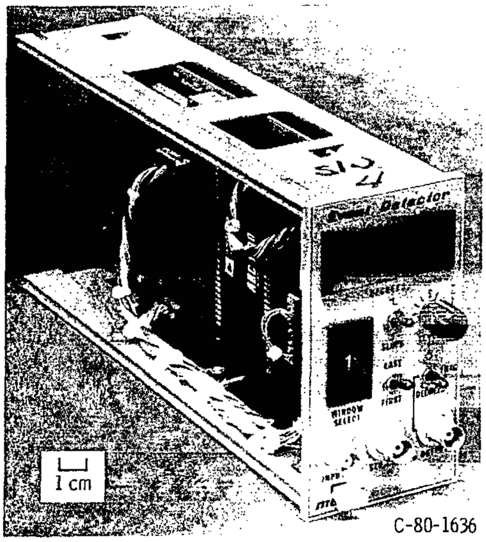

Figure 14. - Event detector module.

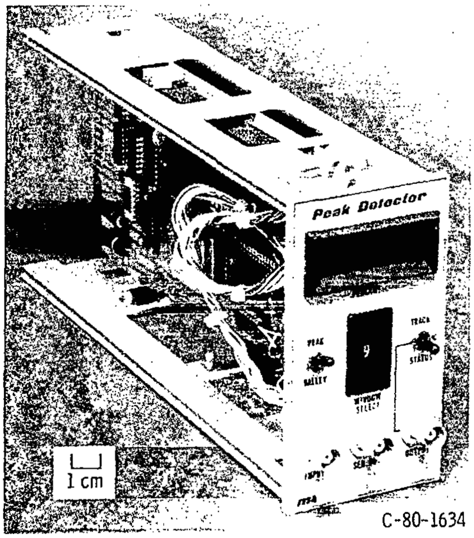

Figure 15. - Peak detector module.

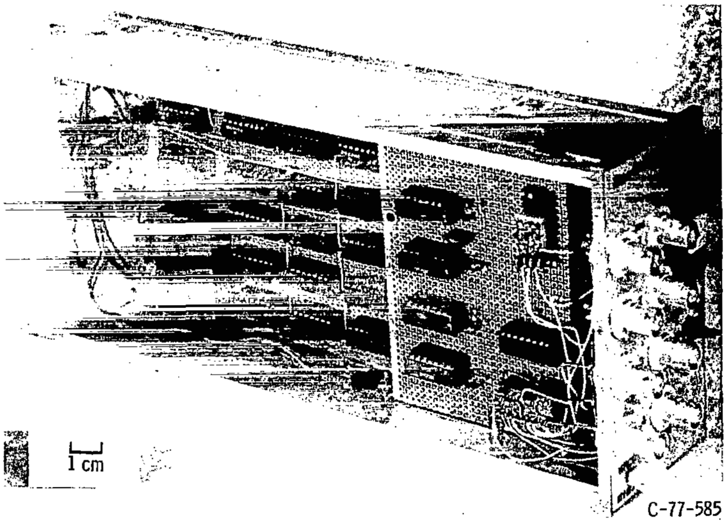

Figure 16. - Curve-averaging module.

in a single module with 1024 or 512 points per curve. The input signal range is ±10 volts. This module is shown in figure 16.

Event Generator Module

An event generator module has been designed to provide control functions at various points in the engine cycle. Switches are provided on the front panel to set the event start point in degrees before TDC (0 to 89) on the compression stroke and the event duration (0 to 89) in degrees. Two output signals are produced by the module: one output for an internally selectable cylinder on its respective compression stroke, and one output that occurs on each compression stroke of the engine. This allows for control of engines with up to eight cylinders.

Various applications for this module include the control of ignition, fuel injection, gas sampling probes, or oscilloscope triggering.

Concluding Remarks

Research intended to improve the performance of internal combustion engines has been hindered by a lack of understanding of the combustion process. Data from the combustion process have been tedious to obtain and analyze. Real-time measurements have not been available, and the large data samples necessary to eliminate the effects of cyclic variations are not generally taken because of the expense of data reduction.

This instrumentation system makes available the real-time calculation and display of such complex parameters as indicated mean effective pressure and mass-fraction burn rate. The results are statistically displayed for 100- or 200-cycle samples.

Computations and displays are performed in the crankshaft angle domain, which simplifies the computations and allows stable displays despite engine speed fluctuations. The modular concept allows flexibility in test system configuration and easy expansion of the system.

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16. Abstract

An instrumentation system has been developed for reciprocating engines. Among the parameters measured are the indicated mean effective pressure, or theoretical work per cycle, and the mass fraction burn rate, a measure of the combustion rate in the cylinder. These computations are performed from measured cylinder pressure and crankshaft angle and are available in real time for the experimenter. A 100- or 200-consecutive-cycle sample is analyzed to reduce the effect of cyclic variations in the engine. Data are displayed in bargraph form, and the mean and the standard deviation are computed. Other instruments are also described.

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