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An electronic ignition timing system for automobile engines.

Gary Douglas Huber

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AN ELECTRONIC IGNITION TIMING SYSTEM FOR AUTOMOBILE ENGINES

by

Gary Douglas Huber

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May 2, 1977
(date)

Professor in Charge

Chairman of Department

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ABSTRACT

In recent years, much attention has been given to improving the fuel economy and lowering the exhaust emissions of internal combustion engines. Ignition timing has significant effects on both of these engine characteristics. The conventional timing system has proven to be too inaccurate and inflexible for controlling engine performance and emissions at the increasingly strict levels specified by the Federal Government while maintaining good fuel economy.

The feasibility of using a microprocessor controlled electronic timing system was investigated in an attempt to produce a system with better accuracy and flexibility. A system was developed in which the timing values are derived for a particular engine by experimentation and stored in a memory. The system measures the engine speed, manifold vacuum and temperature and computes the ignition timing from these variables using the programmed values.

Engine performance, as determined by fuel consumption measurements, is nearly equal for both systems under most conditions. The electronic system is more effective in achieving a balance between control of hydrocarbon emissions at low engine temperatures

and minimization of engine idle roughness at full operating temperatures.

The improved emissions control capabilities make the electronic timing system an attractive substitute for the conventional system. However, more precise testing methods are needed to determine the possibility of an improvement in fuel economy significant enough to justify the cost and complexity of the system.

CHAPTER 1

INTRODUCTION

The Importance of Ignition Timing

In recent years, the problems of dwindling fuel supplies and increasing environmental pollution have imposed new requirements on the operating characteristics of internal combustion engines. The major automobile manufacturers have been required by the Federal Government to produce engines which have lower exhaust emissions along with better fuel economy. In order to achieve these goals, much attention has been given to the ignition timing controls on engines.

As discussed in Appendix B, the ignition timing of an internal combustion engine has significant effects on both exhaust emissions and fuel economy. Unfortunately, the timing settings which tend to reduce exhaust emissions also tend to reduce fuel economy. Advancing the ignition timing increases engine performance and fuel economy; but also increases the exhaust emissions. (As shown in Figure 1, hydrocarbon emissions are the most sensitive to ignition timing.[1])

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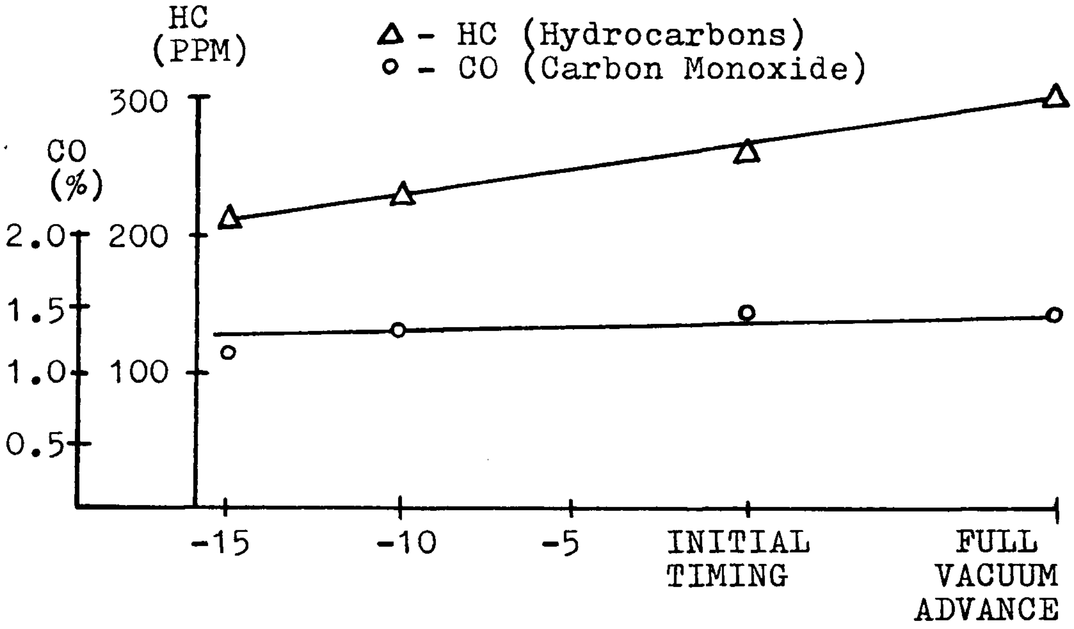
[1] Harold T. Glenn, Glenn's Emission-Control Systems (Chicago: Henry Regnery Co., 1972), p. 23.



IGNITION TIMING
(Crankshaft Degrees)

FIGURE 1

RELATIONSHIP BETWEEN
EXHAUST GAS EMISSIONS AND IGNITION TIMING

Likewise, minimizing emissions by retarding the timing lowers the performance. As a result, the optimum timing setting is a compromise rather than a minimum.

The degree to which optimum engine performance and emissions can be achieved depends on the accuracy of ignition timing control. The timing control system must be capable of adjusting the timing to produce the optimum performance and emissions under the various operating conditions of the engine. These operating conditions include engine speed, loading and temperature. A timing control system which can sense these conditions and adjust the timing to the optimum value is desirable on today's engines and will be mandatory to meet the more stringent regulations of the future.

The Conventional Ignition Timing System

At present, modified versions of the conventional ignition timing system discussed in Appendix A are being used to meet current Federal exhaust emissions standards. These systems control exhaust emissions by making a considerable sacrifice in engine performance.

The conventional control system is mechanical. Two main mechanisms make up the system; these are the centrifugal advance mechanism and the vacuum advance mechanism. Both mechanisms control the opening of the breaker points with respect to the angular position of the crankshaft. The centrifugal advance mechanism senses engine speed and varies the timing accordingly. Engine loading is detected by the vacuum advance mechanism which senses intake manifold vacuum which is inversely proportional to engine loading. Thus, the vacuum advance mechanism adds a load-dependent contribution to the timing set by the centrifugal advance. Figure 2 shows a typical set of timing advance curves.[2] The primary function of the vacuum mechanism is to produce better fuel economy by advancing the timing at light engine loads. The centrifugal mechanism sets the timing required by the varying combustion characteristics of the engine at different speeds.

The mechanical nature of the conventional timing system renders it too inaccurate and inflexible to meet the control requirements for optimum performance. The basic accuracy of the system depends on mechanical tolerances which are subject to wear; furthermore adjusting the advance curves must be done by varying the tension of springs, changing ratios of mechanical linkages and varying surface areas of vacuum diaphragms. These adjustments are inconvenient to say the least and

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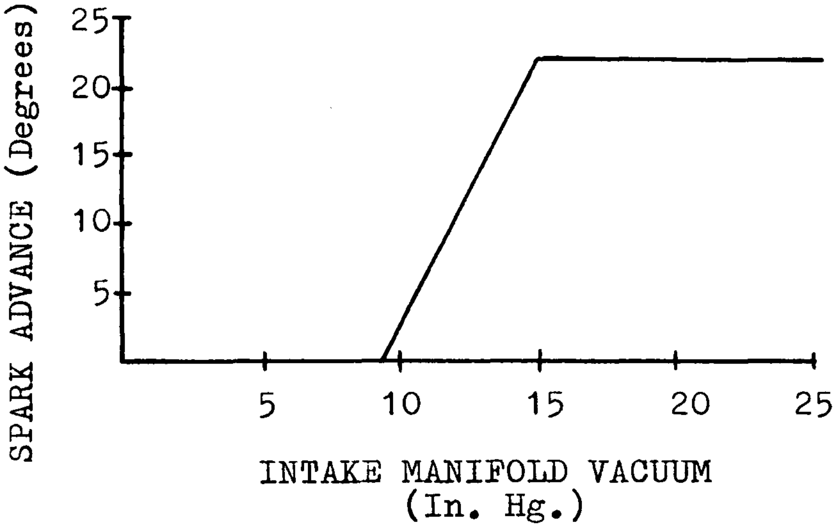
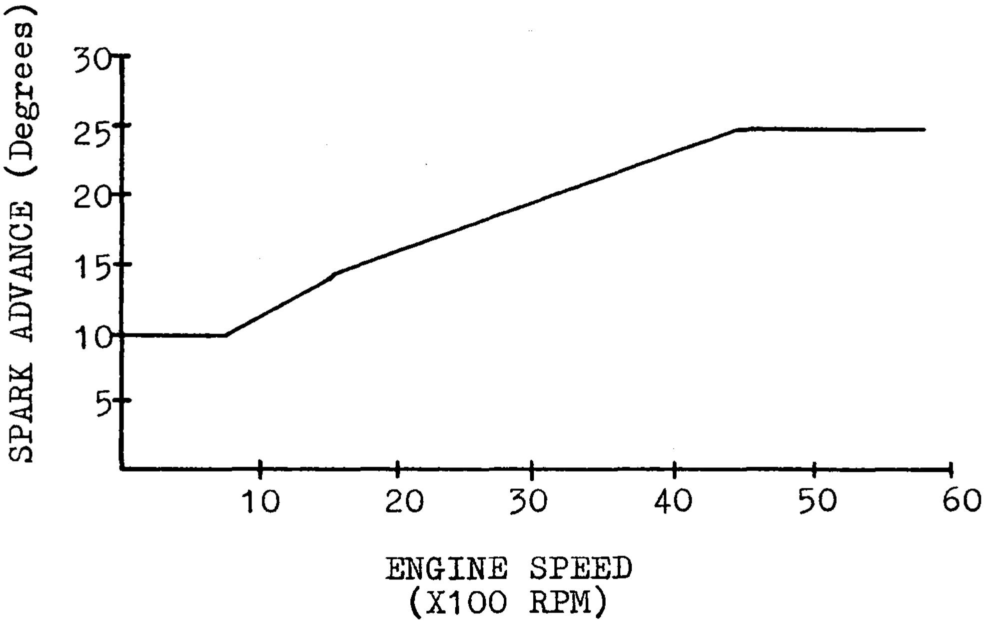
[2] Ibid.



VACUUM ADVANCE CURVE



CENTRIFUGAL ADVANCE CURVE

FIGURE 2

TYPICAL SPARK ADVANCE CURVES

limited in nature. Nor is there any provision for a temperature-based control in the conventional system. Because of these limitations, an alternate system which is more accurate and has more versatility of adjustment must be developed for today's engines.

Electronic Timing Control

An alternate method to control ignition timing is by electronically adjusting the timing according to the engine operating conditions. The purpose of this project is to investigate the feasibility of such a system.

A microprocessor-based digital electronic system is used to replace the conventional system while adding a temperature dependent control. The system measures engine speed, loading and coolant temperature and calculates the ignition timing based on control values programmed into the system memory. These values are generated by observing the ignition timing which produces an optimum condition.

The accuracy of the electronic system is determined by the accuracy of the engine parameter measurement and timing generation parts of the system. It is the object of this project to determine if the accuracy of such a system is greater than that of the conventional system.

Another area, just as important as accuracy, is flexibility of adjustment of timing advance. Because timing is computed from constants stored in the system memory, they can be programmed to any value required. This is a very significant advantage of the electronic system, since it allows a more precise tailoring of the timing curves to the required shape. This greatly enhances the accuracy with which the system can produce optimum timing over the range of operating parameters. A further advantage is that the system may be used to control the experimental determination of the optimum timing constants.

The project consists of three phases. First, the Electronic Ignition Timing System is designed, built and installed on the engine of a test vehicle. Next, test runs are made to determine the ignition timing for optimum fuel economy and exhaust emissions under different operating conditions. The data obtained is then used to generate the optimum timing curves for the electronic system. Finally, fuel economy and emission tests are performed with and without the electronic system on the vehicle and the results with the electronic system compared to those with conventional ignition.

CHAPTER 2

THEORY OF THE ELECTRONIC TIMING SYSTEM

System Operating Cycle

The operating cycle of the Electronic Ignition Timing System consists of three phases. These phases are: engine parameter measurement; ignition timing calculation; and ignition timing generation.

Engine Parameter Measurement

During the first operating phase, the engine speed, intake manifold vacuum and engine temperature are measured and read into the microprocessor.

The engine speed is measured by measuring the time interval between successive closings of the breaker points in the distributor. The interval is measured by gating a digital binary up-counter on and off with successive closings of the breaker points. The counter counts at a fixed frequency during the time interval. The resulting count is inversely related to engine speed.

Assuming that the system is running on an eight cylinder engine, the following relationships are derived. The distributor revolves at one-half the speed of the engine; there are eight breaker point closures per distributor revolution or four closings per engine crankshaft revolution. The equation for the frequency of point closings or firing frequency F_f of the engine is, therefore,

$$F_f = 4 \frac{\text{firings}}{\text{rev}} \times \frac{1}{60} S_e \frac{\text{rev}}{\text{sec}} = .0667 \, S_e \frac{\text{firings}}{\text{sec}} \quad (1)$$

S_e = engine speed in $\frac{\text{rev}}{\text{min}}$

The counter frequency F_c is 25 KHz. This yields a relationship between the count C_s and the engine speed S_e given by the following equation:

$$C_s = \frac{F_c}{F_f} = \frac{2.5 \times 10^4 \text{ Hz}}{.0667 \, S_e \frac{\text{firings}}{\text{sec}}} = \frac{3.748 \times 10^5}{S_e} \quad (2)$$

The value of C_s ranges from 62,467 at 6 RPM to 63 at 6000 RPM. This range yields sufficient resolution at high engine speed while allowing low engine speed to be measured without overflowing the counter.

Intake manifold vacuum is measured using a Bourdon tube gauge with a photo-transistor detector. An operational amplifier is used to calibrate the zero and span of the detector output for a range from 0 volts at a vacuum of 0 inches of mercury to 10 volts at 23 inches of mercury. The voltage is converted to an 8-bit binary word by an analog-to-digital converter.

A similar method is used for temperature measurement. A variable resistance temperature sensor is used with an operational amplifier for zero and span adjustment. The range of output voltage is from 0 volts at infinite sensor resistance to 10 volts at 0 sensor resistance. This translates to a calibrated range from 1.9 volts at 18°F (850 ohms) to 9.2 volts at 212°F (18.5 ohms).

The data words for the three engine parameters are stored in the scratchpad memory in preparation for the calculation phase of the operating cycle.

Ignition Timing Calculation

The new ignition timing value is calculated during the second phase of the operating cycle. In the beginning of this phase, the timing angles corresponding to the three engine parameters are looked up in tables stored in the PROM program memory of the system. The timing angles are then added together and inserted in an equation to compute the timing output value.

The timing values in the look-up tables are addressed using the data values for each of the three engine parameters. The engine speed data in the speed range from 0 to 384 (engine speed from greater than

6000 RPM to approximately 975 RPM) is used to address two 256-word by 8-bit PROM's which comprise the speed look-up table. A fixed timing value is used for speeds corresponding to a count greater than 384 (or less than 975 RPM) to retard the timing for reduction of emissions at idle speeds.

Each look-up table location contains an angle of timing which is the advance angle in degrees of crankshaft rotation required at the particular parameter value. These advance angles are referenced to the top-dead-center (TDC) position of crankshaft rotation. The 8-bit binary value in the location corresponds to a three digit decimal number with an accuracy of one decimal place. The timing contribution for each parameter is, therefore, in the range from 00.0° to 25.6°.

The timing values for each of the three engine parameters are added to form the total timing advance angle. Once the total advance angle θ_a has been calculated, the timing output data word is then calculated. The timing output is referenced to the point when the breaker points close. The equation used to calculate the output is derived from the relationship of the output to the initial ignition timing setting, point dwell (closed time) and top-dead-center (TDC) firing point shown in Figure 3. The output timing data word C_o required for a certain advance angle is a fraction of the engine speed count C_s. From Figure 3, the following ratio between the output angle θ_o and the angle between points closings θ_s is derived:

$$\frac{\theta_o}{\theta_s} = \frac{\theta_d + \theta_i - \theta_a}{\theta_s} \tag{3}$$

θ_d and θ_i may be combined to form one constant:

$$\theta_c = \theta_d + \theta_i \tag{4}$$

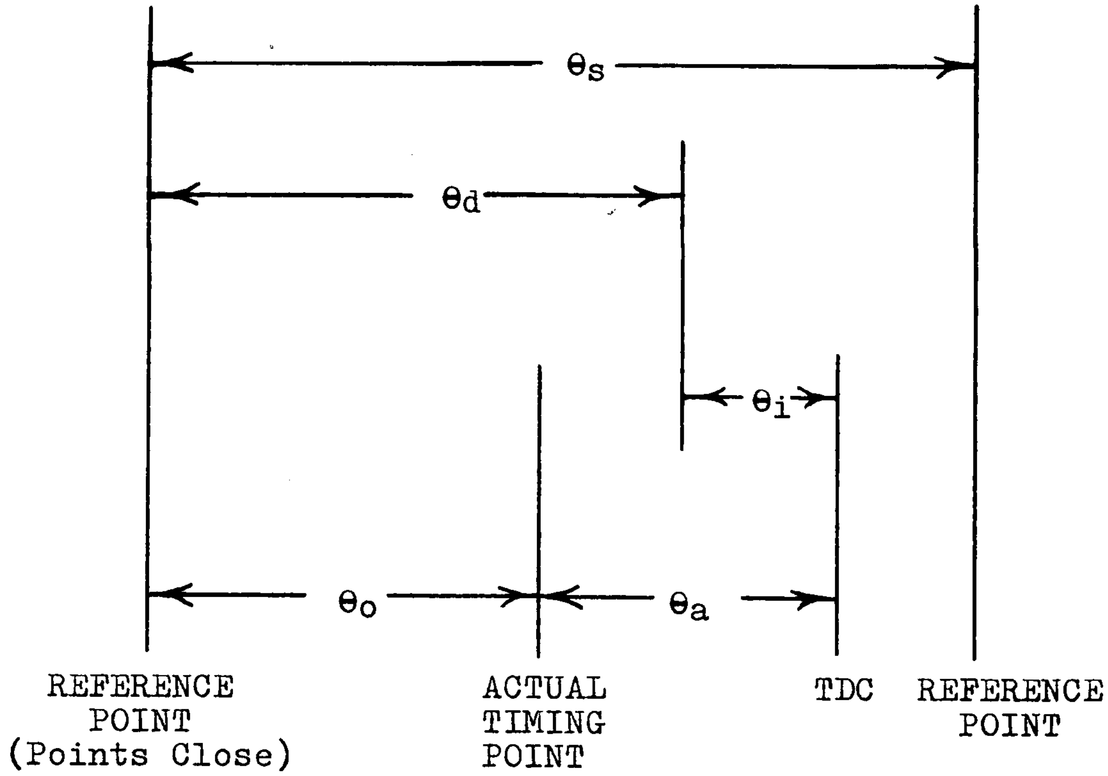
The final ratio between the output angle and the inter-points-closing angle is then,

$$\frac{\theta_o}{\theta_s} = \frac{\theta_c - \theta_a}{\theta_s} \tag{5}$$

The Ignition Timing Counter and the Engine Speed Counter both count at the same 25 KHz frequency; therefore, the output count C_o and the engine speed count C_s represent times which are directly proportional to the output angle θ_o and inter-points-closing angle θ_s respectively. The ratio of output count to speed count is, therefore,

$$\frac{C_o}{C_s} = \frac{\theta_o}{\theta_s} = \frac{\theta_c - \theta_a}{\theta_s} \tag{6}$$

The equation for computing the output count is,



θ_s = Angle between points closings
θ_d = Dwell Angle
θ_i = Initial Timing Angle
θ_a = Total Timing Angle calculated by system
θ_o = Output Angle required to generate timing

Note: For an 8-cylinder engine, $\theta_s = 90^\circ$ and $\theta_d = 60^\circ$.
All angles are in crankshaft degrees.

FIGURE 3

RELATIONSHIP OF TIMING ANGLES

therefore,

$$C_o = \frac{(\theta_c - \theta_a)\ C_s}{\theta_s} \tag{7}$$

After the microprocessor calculates the output count, it is stored in the scratchpad memory in preparation for the timing generation phase of the operating cycle.

Ignition Timing Generation

The output count is used to generate the trigger to fire the spark plug. The output angle is generated by a digital binary down-counter. The counter is gated on each time the points close and counts down at the same 25 KHz frequency as the Engine Speed Counter. When the counter reaches zero, the coil driver is triggered to generate the spark and the counter is loaded with the current value of C_o.

Operating Cycle Time

The rate at which the ignition timing is updated is determined by the time required by one operating cycle of the system. The cycle time must be short enough to provide an update rate fast enough to maintain accurate timing over the engine speed range.

Three factors determine the operating cycle time; these are: program execution time; parameter measurement time; and Ignition Timing Counter update time.

The program execution time is the time it takes the microprocessor to execute the instruction sequence in the Main Operating Program. Measured execution time is 55 milliseconds.

Among the three engine parameters, engine speed measurement time is the most significant. To insure that the Engine Speed Counter is not being read while it is counting, the processor waits through one counting cycle until the counter stops. This delay can be as much as two engine firing cycles if the processor tries to read the counter just after it stops counting. In this case, the processor waits through the next count cycle which takes two firing cycles. This measurement delay is, therefore, engine speed dependent and can add as much as 74 milliseconds to the operating cycle time at 400 RPM and as little as 5 milliseconds at 6000 RPM.

Measurement time for the intake manifold vacuum and engine temperature is determined by the conversion time of the analog-to-digital converter (135 microseconds) which is insignificant with respect to the other time factors in the operating cycle.

The third factor which contributes to cycle time is the update time for the Ignition Timing Counter. In this case, the processor waits as much as one firing cycle to update the counter. This is to insure that the counter is updated when it has just begun counting to prevent the possibility of updating when it is reloading as it counts through zero. The resultant time added to the operating cycle, again, is engine speed dependent and is a maximum of 37 milliseconds at 400 RPM and 2.5 milliseconds at 6000 RPM.

The total operating cycle time is the sum of the program execution, measurement and Ignition Timing Counter update times. Adding the figures above yields a maximum cycle time of 166 milliseconds at 400 RPM and 62.5 milliseconds at 6000 RPM.

The timing update rate is calculated from operating cycle time and engine firing cycle time by the following equation:

$$R_t = \frac{T_f}{T_o} \frac{\text{updates}}{\text{firing}} \qquad (8)$$

T_f = engine firing cycle time in $\frac{\text{sec}}{\text{firing}}$

T_o = operating cycle time in $\frac{\text{sec}}{\text{update}}$

This yields a minimum update rate of once every 6.6

engine firings at 400 RPM and once every 25 firings at 6000 RPM.

The rate at which timing is updated is sufficient for the timing accuracy required over normal engine speed fluctuations. As long as the engine speed does not change rapidly, the timing error due to the update lag time will be small during the transition. After the speed change is finished and the engine speed is in a steady state condition, the timing will be at maximum accuracy after one operating cycle time period.

CHAPTER 3

SYSTEM DESCRIPTION

Basic System Units

The Electronic Ignition Timing System contains four main functional units as shown in the block diagram in Figure 4. These are: engine speed measurement and timing generation; vacuum and temperature measurement; central control and memory; and operator control.

Engine Speed Measurement and Timing Generation

Four circuits comprise the speed measurement and timing generation part of the system. These are: 25 KHz Clock Generator; Engine Speed Measuring Counter; Ignition Timing Counter; and Timing Output Driver.

The 25 KHz clock signal used to drive the Engine Speed Measuring Counter and Ignition Timing Counter is derived from the 5 MHz microprocessor master clock. This is done in a 200-to-1 frequency divider circuit (Figure 5) which is configured as two divide-by-10's followed by a divide-by-2 to give a symmetric 25 KHz output.

The Engine Speed Measuring Counter (Figure 5) measures the time between successive breaker points closings. The timing relationship of various parts of

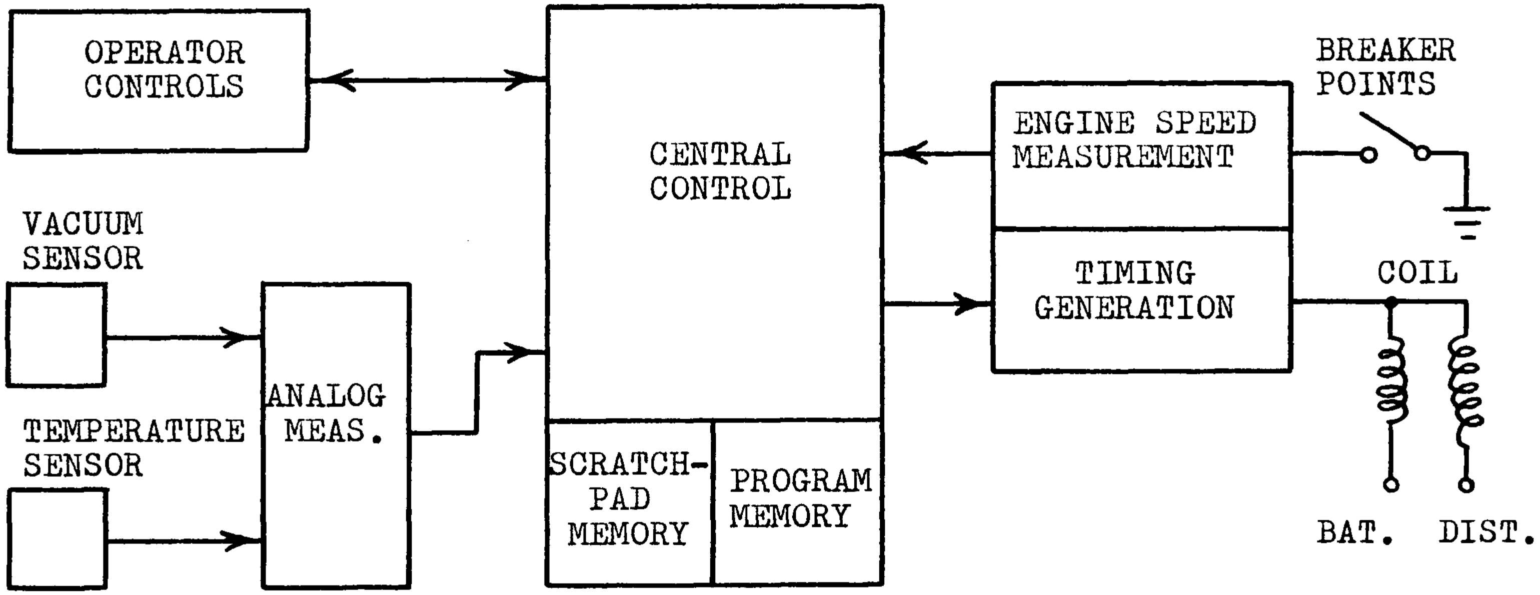


FIGURE 4

SYSTEM BLOCK DIAGRAM

the counter is shown in Figure 6. A 16-bit up-counter is gated on at one points closing and off at the next. This allows for speed measurement and data reading during alternate breaker points closings. The gating control is performed by toggling a J-K flip flop which enables or disables the counter. The flip flop is triggered by the points signal which comes through two one shots. The first one shot (O.S.1) provides a 2 millisecond non-retriggerable pulse to filter points bounce. The second one shot (O.S.2) generates a 5 microsecond pulse which triggers the J-K flip flop on its trailing edge. If the counter is stopped, this pulse resets the counter on its leading edge. A "Ready" signal, which is low while the counter is stopped and high while it is being reset or counting, is provided to the microprocessor. When the counter is stopped, the microprocessor may read the data. If the count range of the counter is exceeded, the "Overflow" line goes high to indicate this to the microprocessor.

The Ignition Timing Counter (Figure 7) determines the time, with respect to the reference point, at which the coil is triggered to fire the spark plug. Timing diagrams for parts of the counter are shown in the

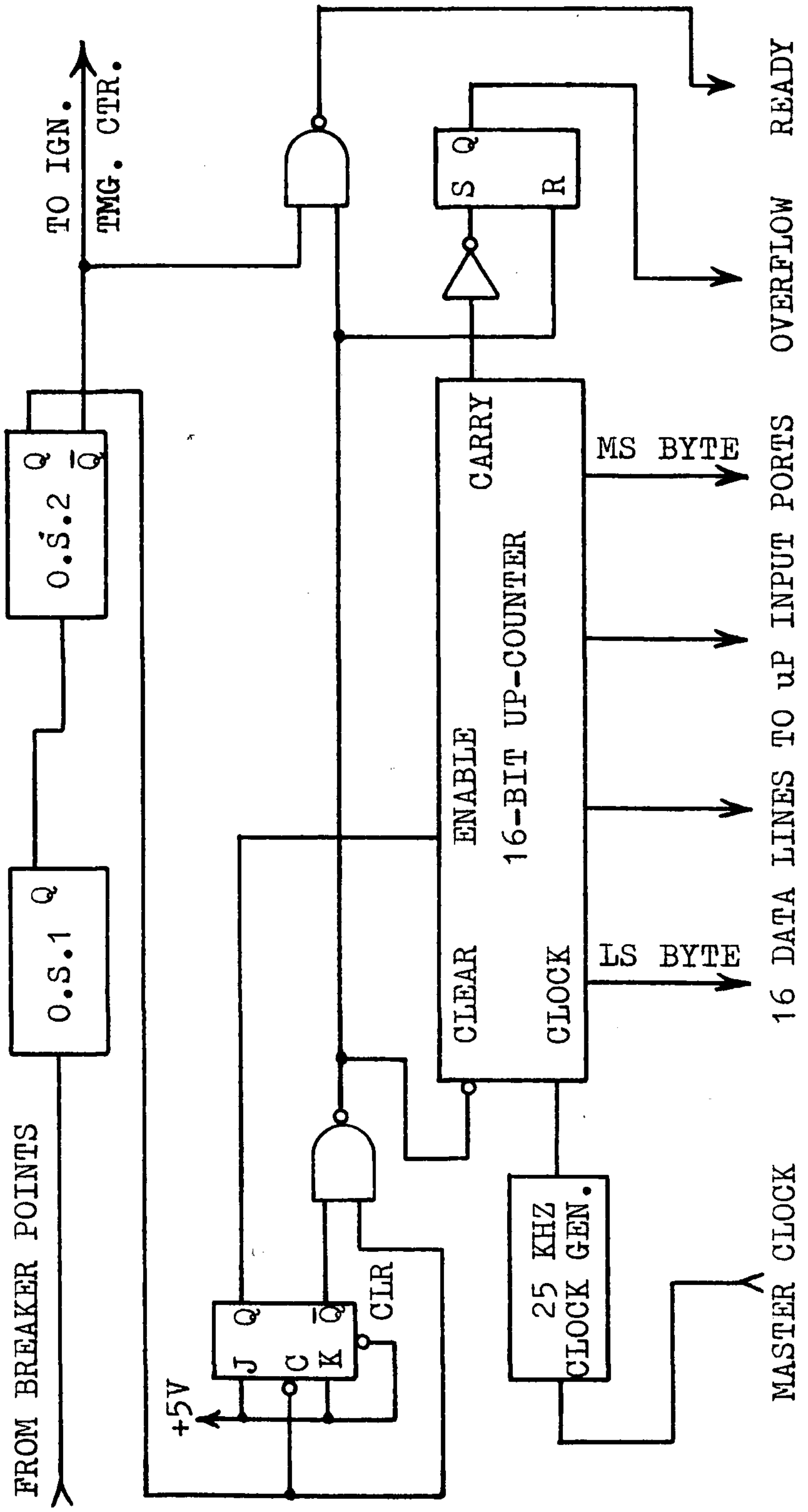


FIGURE 5

ENGINE SPEED MEASURING COUNTER

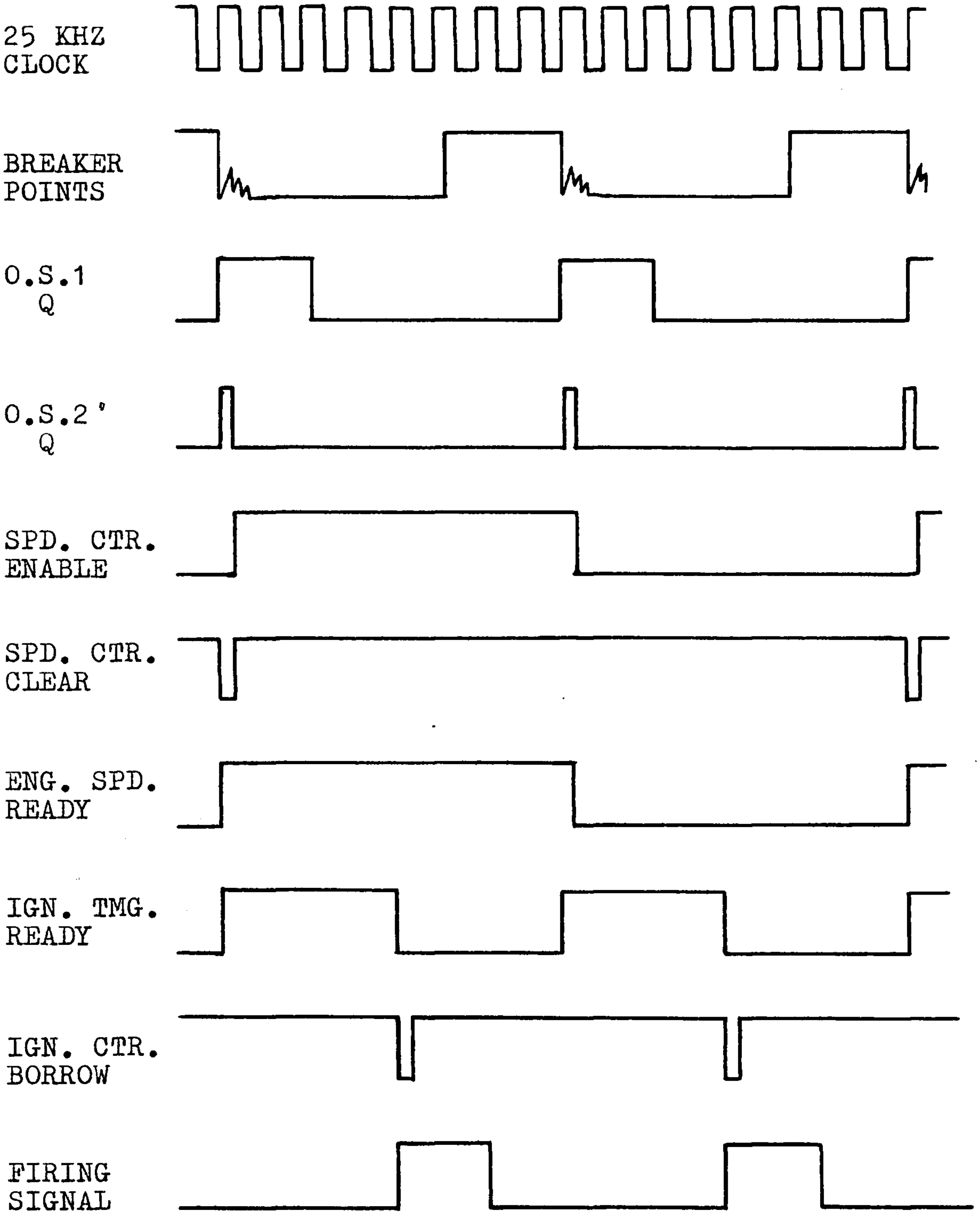


FIGURE 6

COUNTER TIMING DIAGRAM

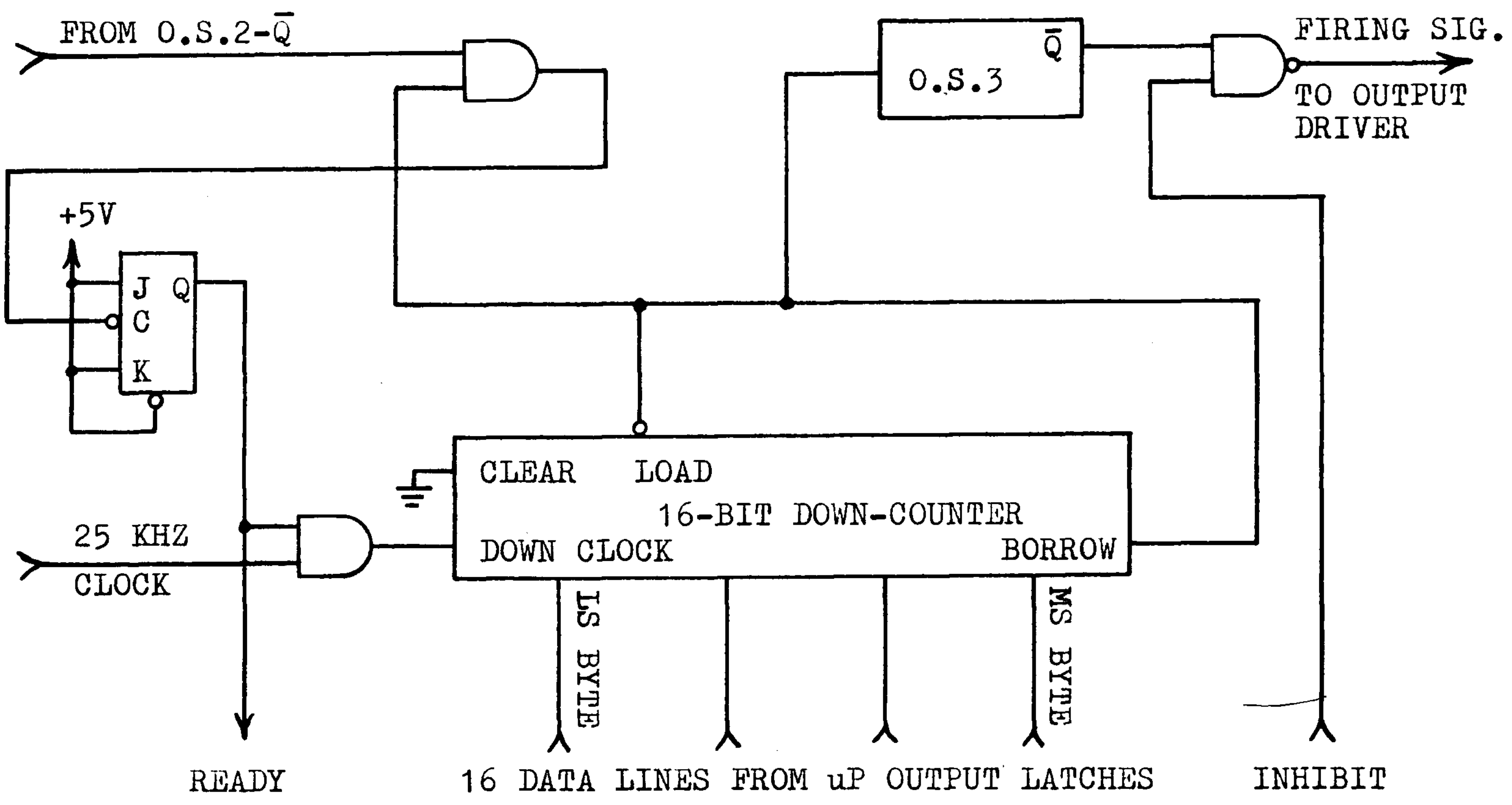


FIGURE 7

IGNITION TIMING COUNTER

lower half of Figure 6. At every points closing, a 16-bit down-counter is started by the 5 microsecond pulse from O.S.2. The counter counts down to zero. When it reaches zero, a one shot (O.S.3) is triggered to generate a 2 millisecond output coil trigger pulse. At the same time, the J-K flip flop is toggled to turn the counter off and the "Load" line is asserted to load the data from the microprocessor output latches. A "Ready" signal is provided to tell the microprocessor when the output latches may be updated. This signal is high while the counter is counting and low when it is stopped. Data may be latched while the counter is counting.

The worst case accuracy of speed measurement and timing generation is ±1.6% of timing setting. Accuracy is dependent upon the resolution of the counters and is the lowest at 6000 RPM when the counts are smallest.

A power driver (Figure 8) is provided to amplify the 2 millisecond timing output pulse to a level suitable for driving the ignition coil or a capacitive discharge ignition system. The input stage of the driver is electrically isolated from the output by an optically coupled isolator. This is done to protect the low level digital logic in the system from high

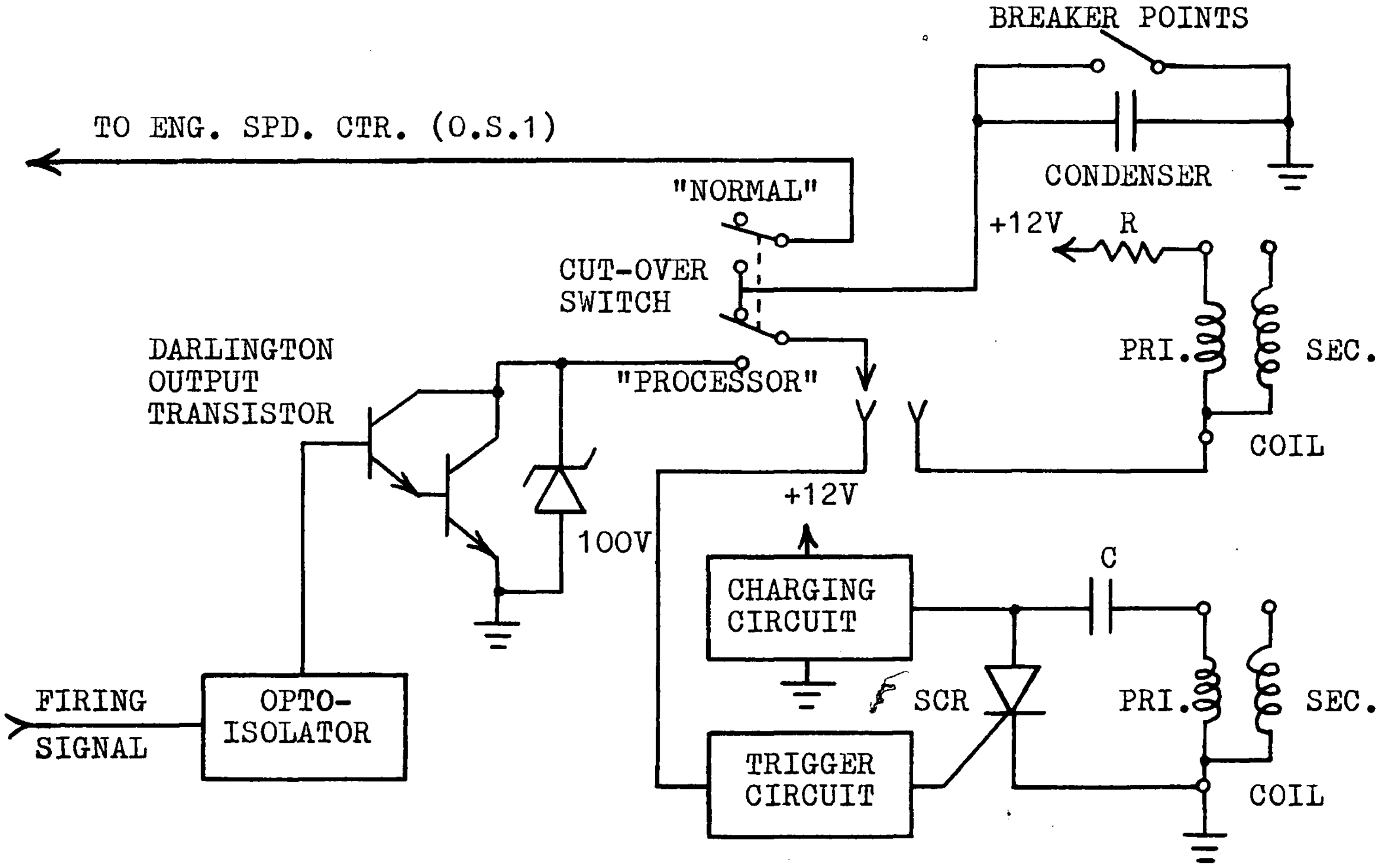


FIGURE 8

TIMING OUTPUT DRIVER

voltage spikes which may be generated by arc-over from the ignition coil. A power Darlington transistor is used for the output because of its low input current requirements for operation. A manually operated cut-over switch is used to switch the ignition system from conventional to electronic operation. In the "Normal" position the switch connects the breaker points directly to the coil primary. With the switch in the "Processor" position, the coil is connected to the collector of the Darlington output transistor and the points are connected to the input of the Engine Speed Measuring Counter.

In a conventional breaker point coil driver circuit, the primary voltage rises to about 250 volts. The conventional coil has a turns ratio of approximately 100 to 1 which amplifies the voltage to 25,000 volts in the secondary.

The transistor coil driver has a different operating characteristic from the conventional circuit. The primary voltage generated in the coil is clamped to a safe level by the zener diode to protect the transistor from damage due to high voltage second breakdown. This voltage is limited to about 100 volts in most available transistors. The resulting secondary voltage generated in the coil is, therefore, only about 10,000 volts which is not sufficient for good spark plug firing. To solve this problem, a special coil with a turns ratio of about 250 to 1 is required to boost the secondary voltage to 25,000 volts.

An alternative method is to use the Darlington output transistor to drive a capacitive-discharge ignition coil driver circuit. The timing output pulse triggers the C-D circuit which drives the coil. Between timing pulses the C-D circuit charges a capacitor to approximately 400 volts. During the timing pulse, the capacitor is discharged through the coil creating a very fast rise in primary voltage. Using a conventional coil, a secondary voltage of about 40,000 volts is generated which provides an excellent spark.

Manifold Vacuum and Engine Temperature Measurement

Intake manifold vacuum and engine temperature are sensed with analog transducers. The outputs of the transducers are converted to digital data by an analog-to-digital converter. The circuitry is divided into three areas: vacuum measurement; temperature measurement; and the analog-to-digital converter.

Intake manifold vacuum is measured using a transducer attached to the intake manifold by a rubber tube. The output of the transducer is amplified by an operational amplifier (Figure 9) to a suitable level for input to the analog-to-digital converter.

The vacuum transducer consists of a curved Bourdon tube gauge with a circular array of 24 photo-transistors to detect the movement of the gauge. As shown in Figure 10, the photo-transistors are mounted around the dial of the gauge spaced at intervals equal to one inch of mercury. A semi-circular disk of opaque paper is mounted on the gauge needle. The disk rotates with the needle and passes between the photo-transistors and the light source. As the gauge rotates clockwise, the transistors are progressively exposed to the light.

The amplifier is adjusted so that the output of A2 varies from 0 volts at 0 inches of mercury to +10 volts at 23 inches of mercury. The output of the transducer depends on the characteristics of the photo-transistors. Since the photo-transistors are not perfectly matched, the output is not linear with vacuum as shown in Figure 11. This non-linearity is, however, compensated for by the vacuum timing values stored in

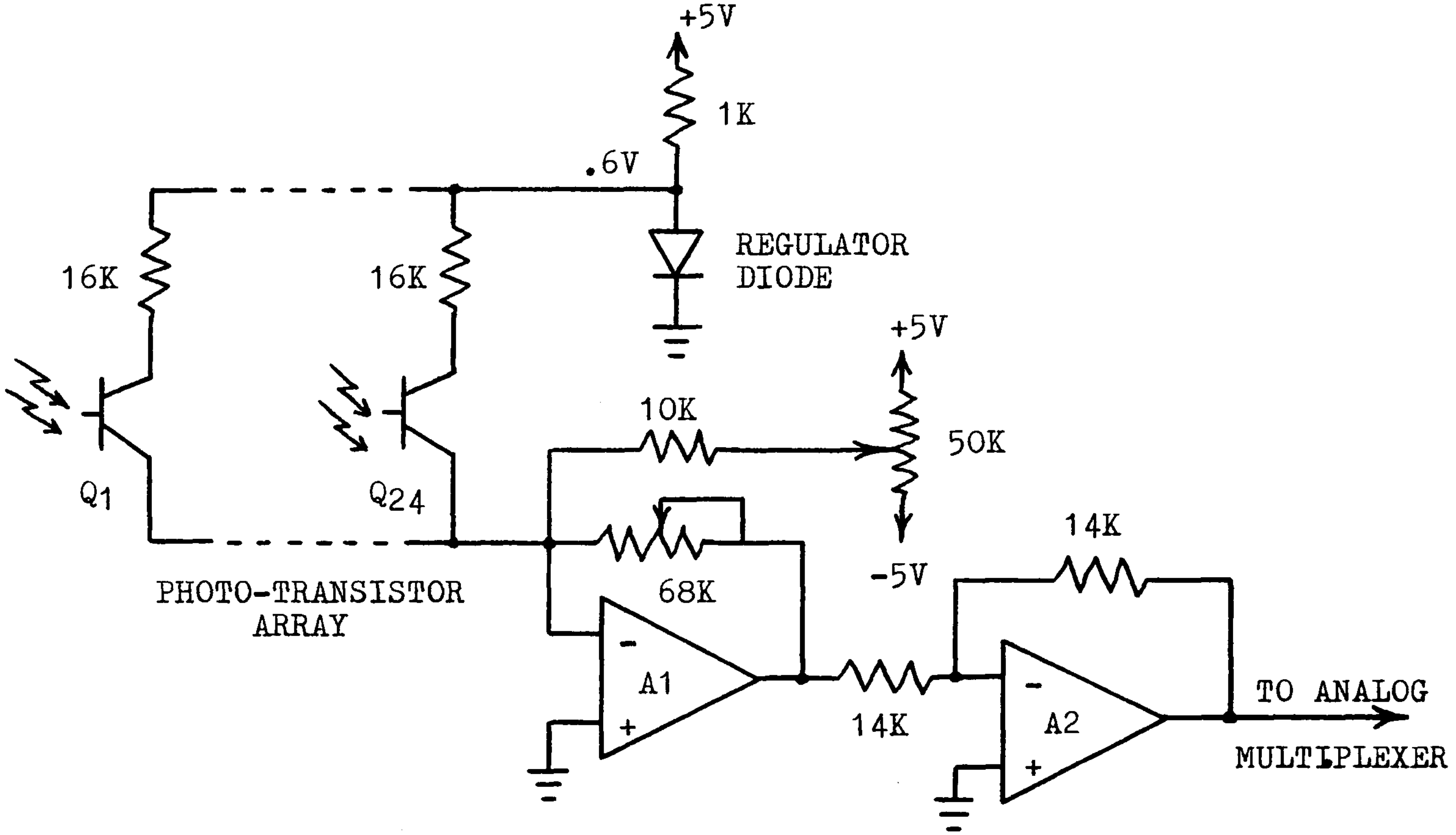


FIGURE 9

VACUUM TRANSDUCER AMPLIFIER

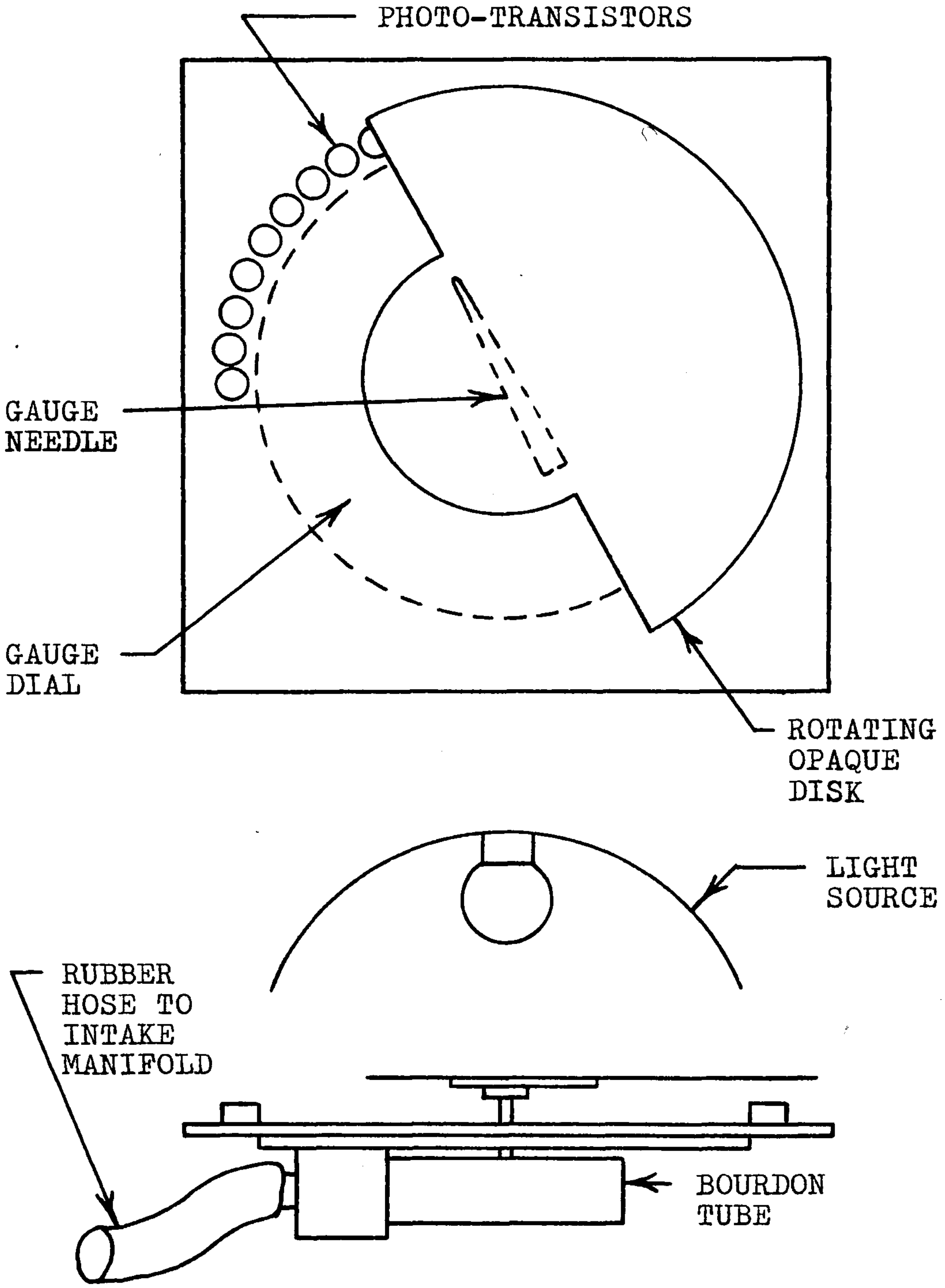


FIGURE 10

VACUUM TRANSDUCER

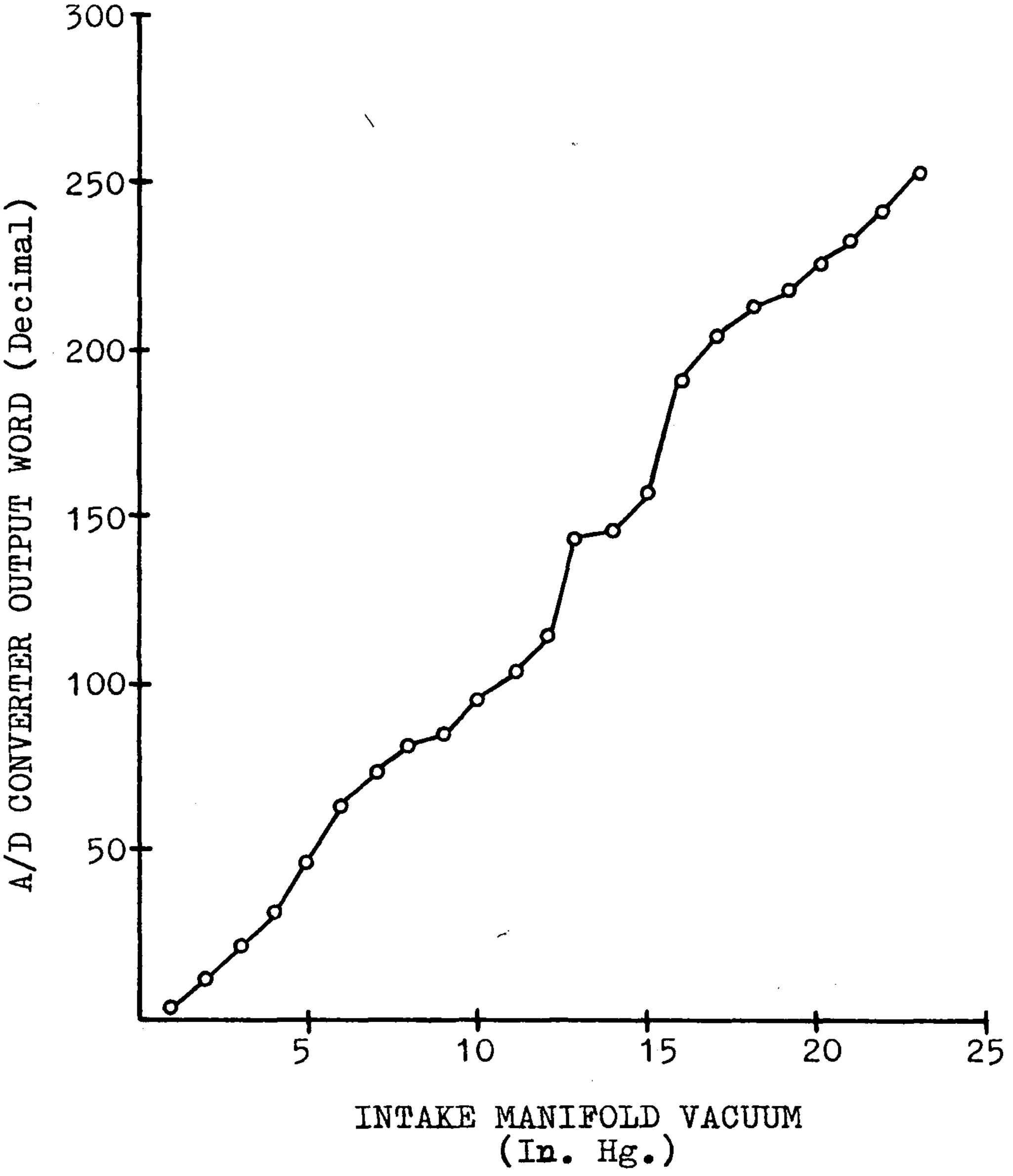


FIGURE 11

A/D CONVERTER OUTPUT VERSUS
INTAKE MANIFOLD VACUUM

the program memory. The accuracy of vacuum measurement is ±.1 inches of mercury and depends on the accuracy of the analog-to-digital converter and the voltage drift of the operational amplifier.

The engine temperature is measured using a standard variable resistance sensor in the engine block. The output of the sensor is amplified by an operational amplifier (Figure 12) to the correct level for input to the analog-to-digital converter.

The amplifier is adjusted so that the output voltage varies from 0 volts to +10 volts over the temperature range of approximately 18°F to 212°F. This voltage variation is subject to the non-linearity in the variation of temperature sensor resistance with temperature. The relationship is shown in the graph in Figure 13. As with the vacuum transducer, this non-linearity is compensated for by the temperature timing values stored in the program memory. Temperature measurement accuracy is ±.7°F and is dependent on the same factors as vacuum measurement accuracy.

Vacuum or temperature is selected by an analog multiplexer under control of the microprocessor. The analog-to-digital converter (Figure 14) provides an 8-bit binary output and utilizes the successive

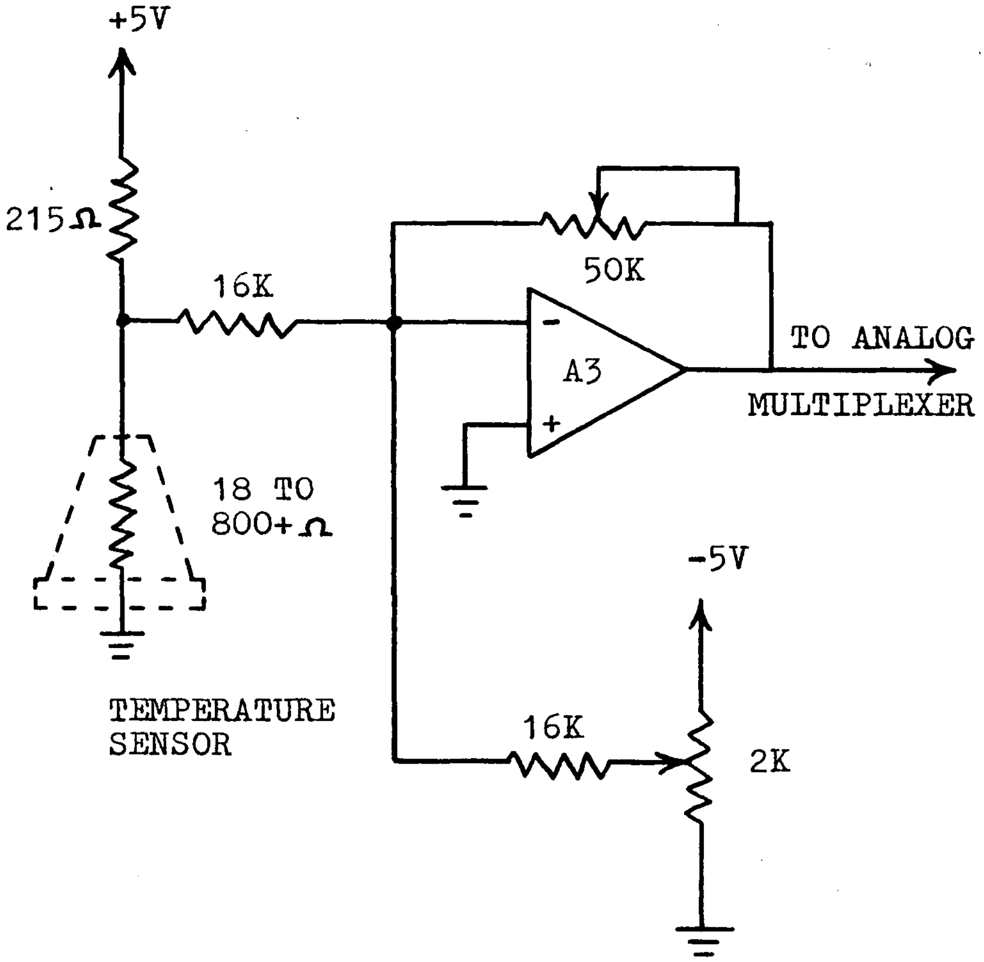


FIGURE 12

TEMPERATURE TRANSDUCER AMPLIFIER

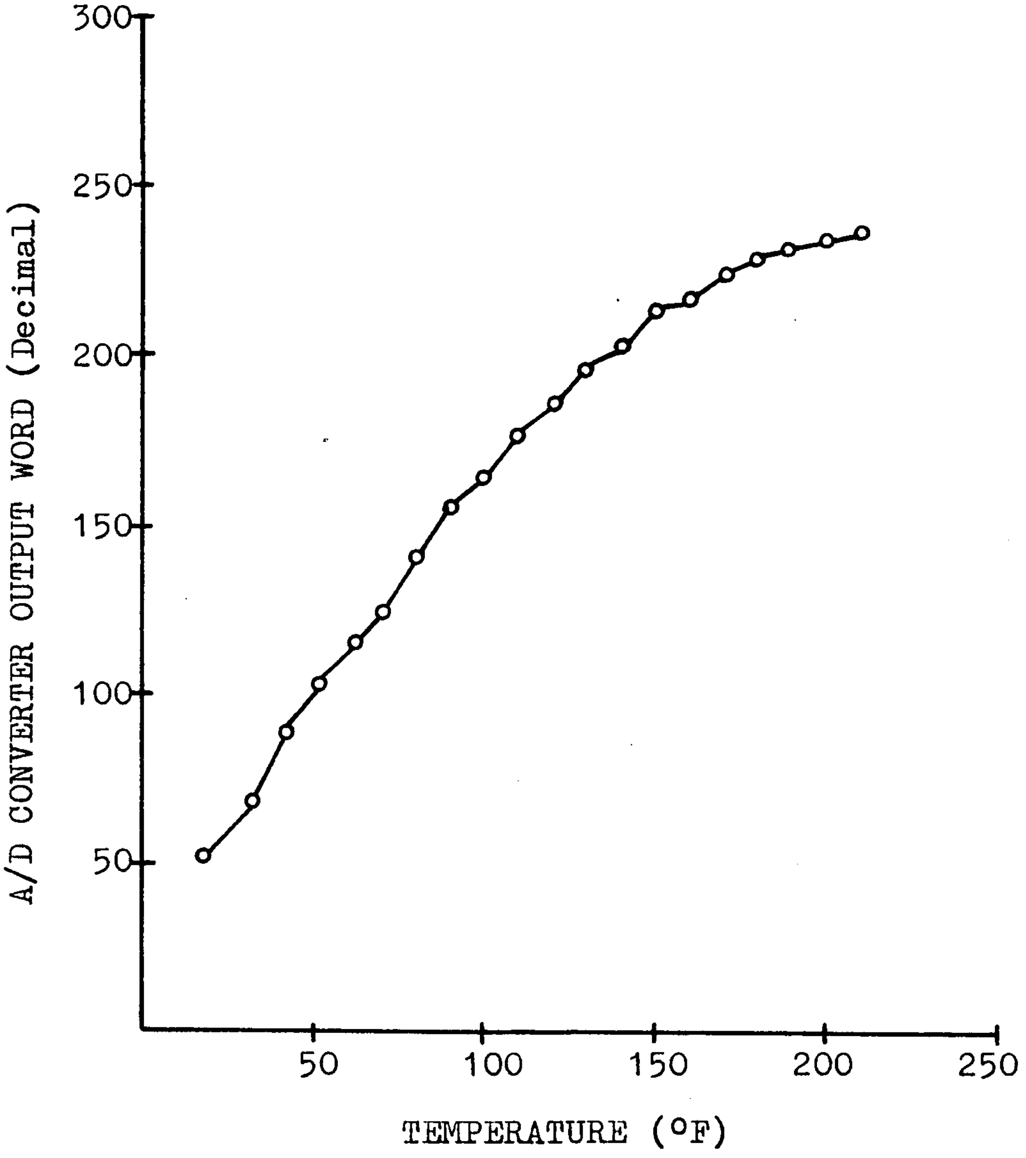


FIGURE 13

A/D CONVERTER OUTPUT
VERSUS TEMPERATURE

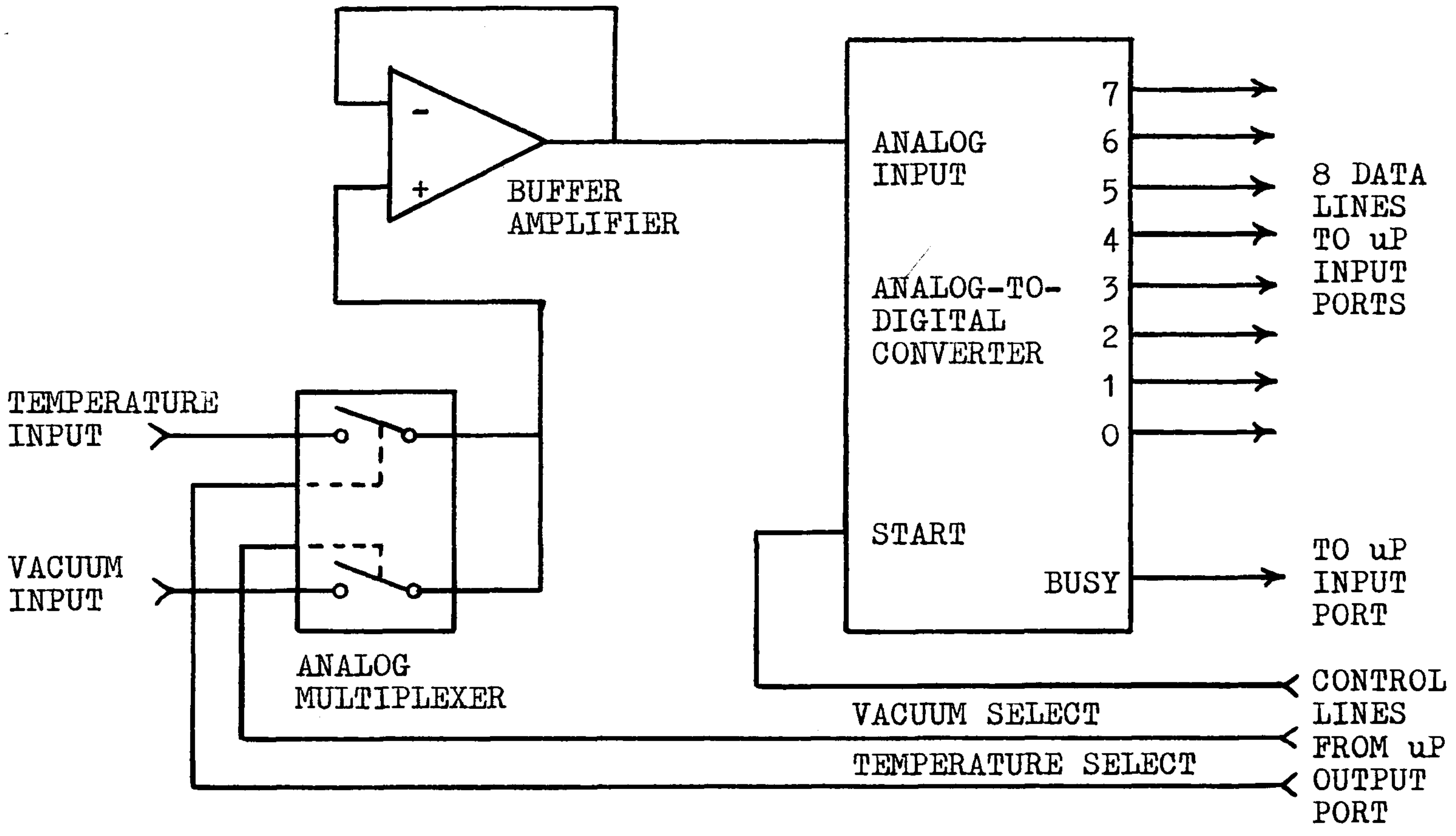


FIGURE 14

ANALOG MULTIPLEXER AND A/D CONVERTER

approximation method of conversion. It is connected to the microprocessor through the eight data lines and two control lines. The control lines are a "Start" line and a "Busy" line. Conversion is initiated on the negative transition of a positive pulse on the "Start" line. While the conversion is in progress, the "Busy" line is a logic zero. A logic one on the "Busy" line indicates that the conversion is completed.

Microprocessor Hardware

A microprocessor is used for control and data manipulation in the system. The microprocessor executes the operating program stored in a program memory. Data is exchanged with the various peripherals through an input/output interface. A scratchpad memory is used by the processor for temporarily storing data and performing mathematical operations on it.

The microprocessor hardware is divided into four main areas: microprocessor CPU and clock; scratchpad memory; program memory; and input/output interface. The first three areas are shown in the diagram in Figure 15 while the fourth is shown in Figure 16.

A fifth area, operator controls and indicators, is provided for communication between the microprocessor and a human operator. This includes a set of data entry switches and an alpha-numeric display, both of which are shown in Figure 16.

The microprocessor CPU is an Intel 4040 contained in one 24 pin integrated circuit package. It is a 4-bit parallel structured device containing 1 accumulator, 24 index registers and a 7-level address storage stack. Nominal instruction cycle time is 10.8 microseconds. The CPU also contains peripheral control and timing circuits for interfacing with RAM and ROM memory and external devices. Interrupt capability is provided; however, the interrupt is not used in this system.

Timing in the system is controlled by the 5 MHz master clock. The 25 KHz clock for the Engine Speed and Ignition Timing counters is derived from the master clock. The two processor clocks ϕ_1 and ϕ_2 are also derived from the master clock by the divider and phase shifter. ϕ_1 and ϕ_2 are 750 KHz in frequency and are shifted 180 degrees with respect to each other. A Sync signal is derived within the CPU for peripheral sequence timing. Sync pulses occur at the instruction cycle rate of once every 10.8 microseconds.

The scratchpad memory is a 1K-word by 4-bit

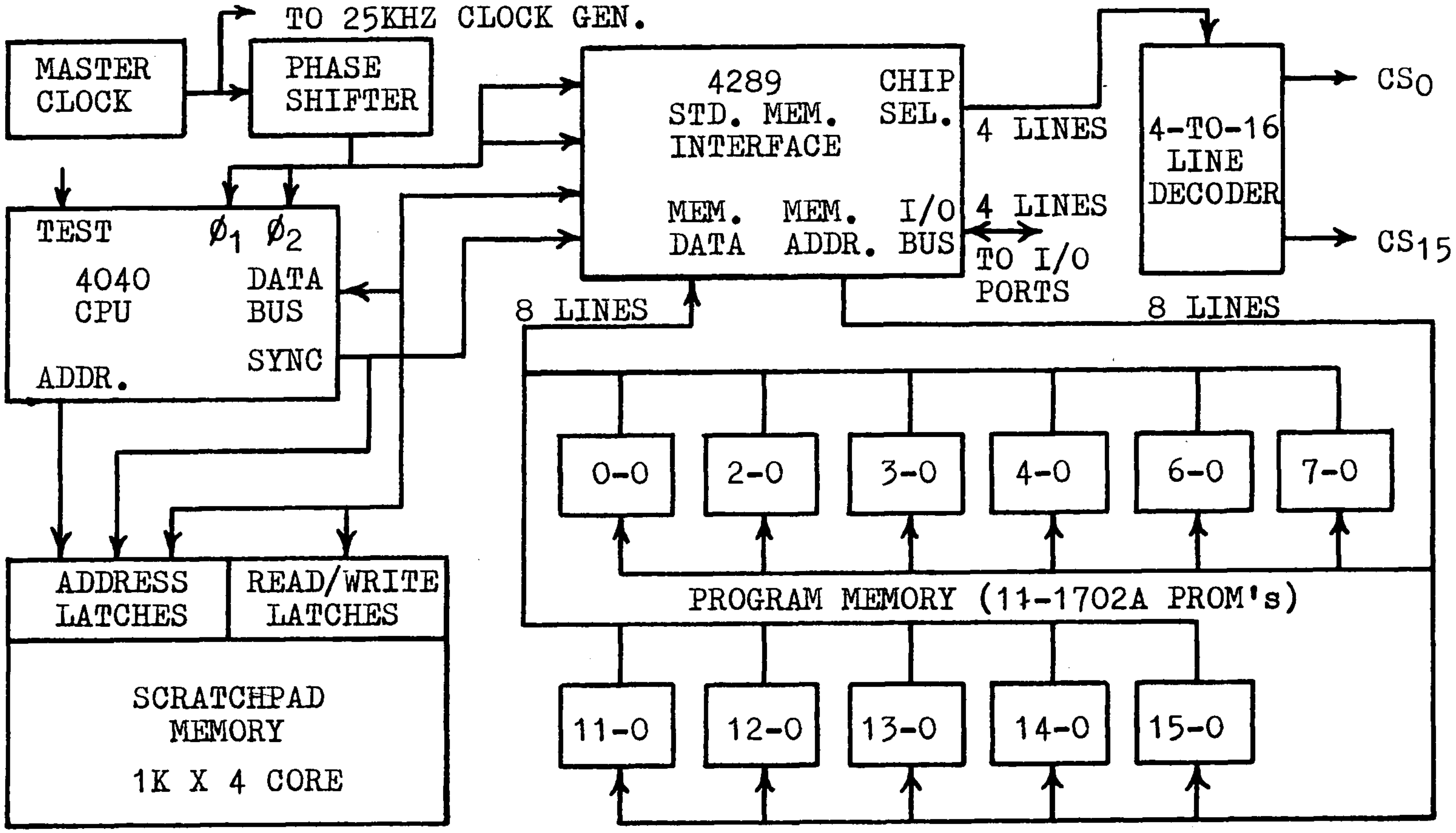


FIGURE 15

MICROPROCESSOR AND MEMORY

core read/write random access memory. The memory is divided into four 256-word pages. Only the first page is used in this system.

The program memory contains the operating programs and timing advance curve tables for the system. Eleven Intel 1702A programmable read only memorys (PROM's) make up the program memory. Each 1702A PROM contains 256 8-bit storage locations which are addressed by 8 bits. The PROM's are erasable so that programs or data tables may be changed conveniently. An Intel 4289 Standard Memory Interface and a 4-to-16-line decoder perform the addressing and data exchange functions between the CPU and the program memory.

Control and data exchange functions are performed by the CPU with the external peripherals through the input/output interface. The interface shown in Figure 16 consists of sixteen 4-bit ports. Eight of the ports are inputs and are used for reading operating status and data from the peripherals. The other eight ports are output latches which send control information and data to the peripherals. The input/output port selection is controlled by the same 4289 interface and 4-to-16-line decoder as is used for the program memory. Data is transmitted between the CPU and the ports

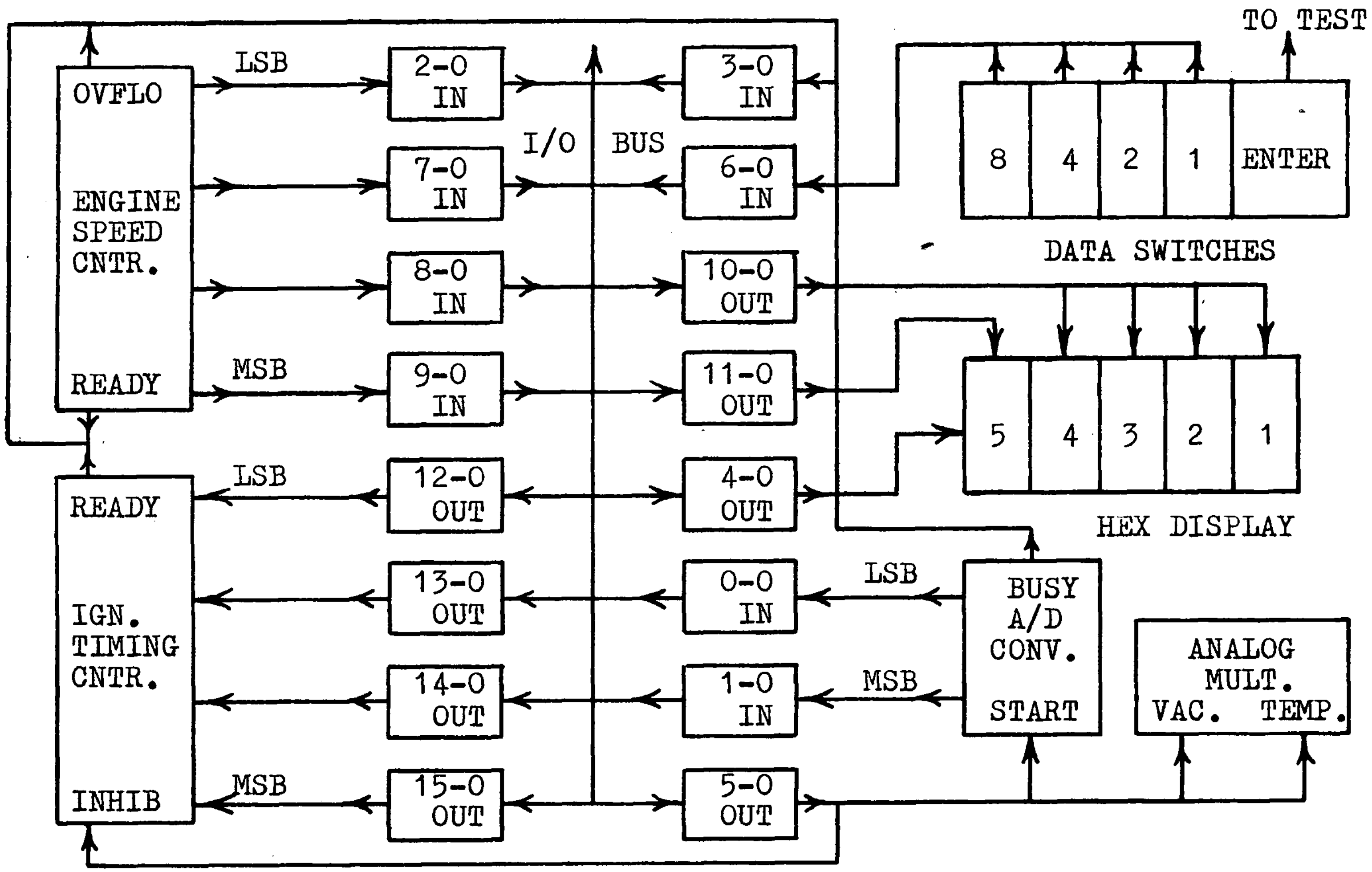


FIGURE 16

INPUT/OUTPUT INTERFACE

through the 4289 via the I/O bus and the processor data bus.

The connection of the I/O ports to their associated peripherals is shown in Figure 16. Input ports 2-0 and 7-0 through 9-0 read data, LSB through MSB respectively, from the Engine Speed Measuring Counter. Output ports 12-0 through 15-0 latch data, LSB through MSB, respectively for the Ignition Timing Counter. Data LSB and MSB are read from the A/D converter by input ports 0-0 and 1-0. Output port 4-0 provides data for the display while output ports 10-0 and 11-0 latch the data. Input port 6-0 receives data from the data switches. Counter and A/D converter status is read in by input port 3-0. Spark inhibit, analog measurement selection and A/D converter start are performed by output port 5-0.

The data switches (Figure 16), in conjunction with the "Enter" switch, are used for entering HEX digits into the processor to program the system initial timing constant. The data is entered on the data switches and the "Enter" switch is set to assert the "Test" line in the CPU to read in the data. The display contains 5 HEX digits and is used to display various operating parameters in the system. The parameters displayed are selected by setting various combinations on the data switches as the system operates. The operating parameters include: engine speed count; ignition timing count; vacuum reading; temperature reading; and initial timing constant.

Microprocessor Software

The ignition system functions are performed under control of the microprocessor as it executes the programs stored in program memory. The software consists of a Main Operating Program (Figure 17) which is composed of many subroutines for performing the specific tasks in the system. The subroutines are divided into three major categories: peripheral drivers; arithmetic routines; and service routines. Also included as part of the Main Operating Program are the timing lookup tables for engine speed, manifold vacuum, and engine temperature.

The peripheral driver subroutines control the flow of data between the microprocessor CPU and the external devices in the system. These programs include: Engine Speed Counter Driver; Ignition Timing Counter Driver; A/D Converter Driver; Display Driver; and Data Switch Input Driver.

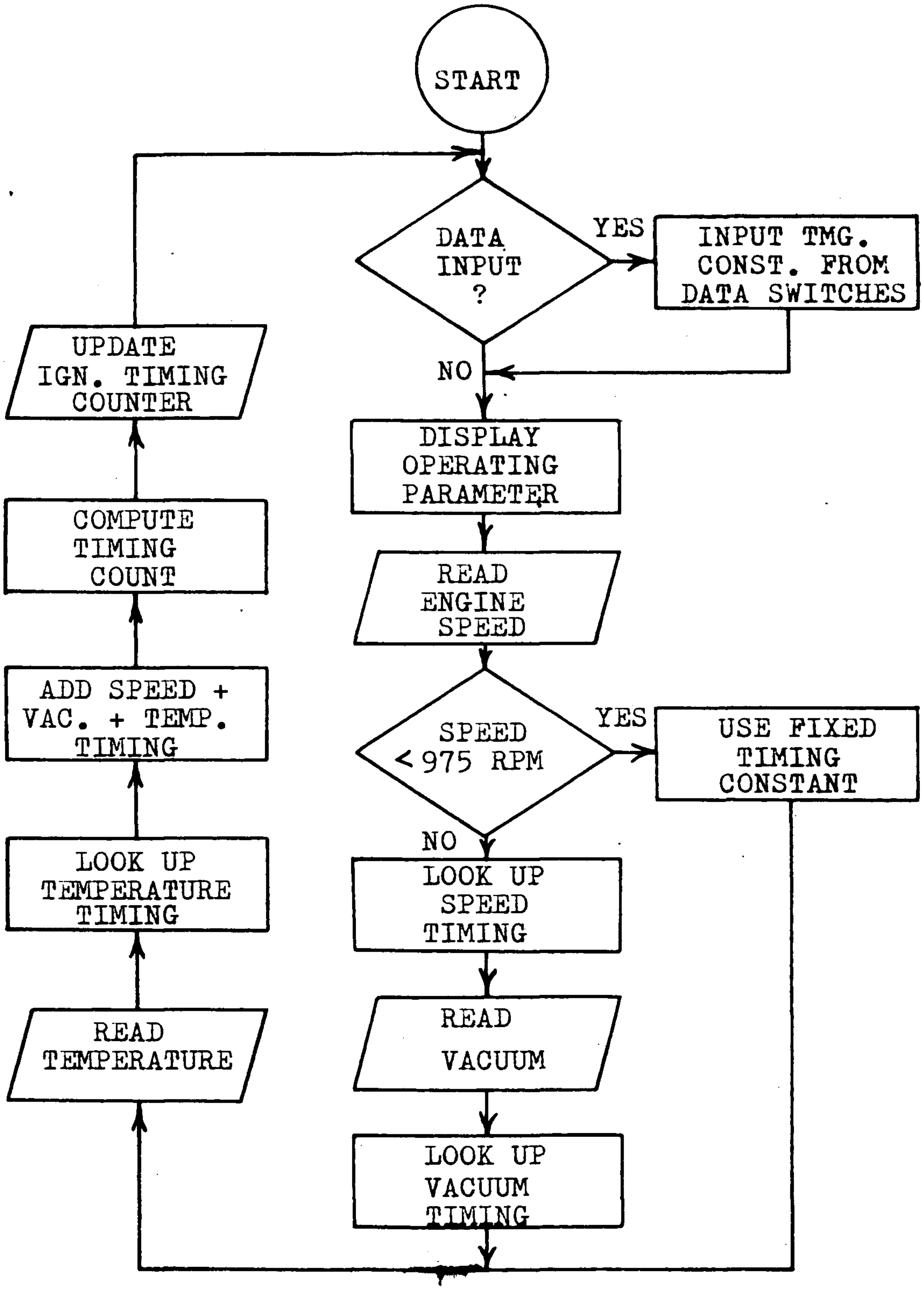


FIGURE 17

MAIN OPERATING PROGRAM

Four types of arithmetic subroutines are provided for performing addition, subtraction, multiplication, and division of binary numbers. Included in this group are the Binary Adder, Binary Subtracter, Binary Multiplier, and a special division subroutine. Addition and subtraction are performed on words up to 64 bits long, while multiplication is done on words up to 32 bits long. The division subroutine divides a 20-bit number by a fixed multiple of 2 (8192) using a shift process. The routine introduces 1% error, but minimizes execution time greatly.

A variety of service functions are performed by the third group of subroutines. These functions include scratchpad memory register clearing and transfer operations and other special data word shifting and checking functions. The routines in this group are the Register Clear, Display Clear, Register Transfer, Shift-Right-One-Bit, and Address-Less-Than-Three subroutines.

The lookup tables contain the timing values corresponding to values of the operating parameters of engine speed, manifold vacuum and engine temperature. The Main Operating Program branches to and from these tables to retrieve the timing values at appropriate times during the timing computation phase of system operation.

System Accuracy

The overall timing generation accuracy of the system depends mainly on the vacuum and temperature measurement accuracies and the calculation error introduced by the division subroutine. Errors introduced by the speed measurement and timing generation hardware are insignificant. Using the maximum slopes of the respective timing curves (Figures 19 and 20) to translate the measurement accuracy to worst case timing accuracy, the vacuum dependent accuracy is ±.12° and the temperature dependent accuracy is ±.08°. The maximum error introduced by the division calculation is .34° at maximum timing advance. The sum of these accuracies yields an overall timing accuracy of ±.54°.

CHAPTER 4

TEST RESULTS AND CONCLUSIONS

Testing The System

The Electronic Ignition Timing System was built and installed on a 1972 Ford Torino with a 351 cubic inch V8 engine, equipped with a four speed manual transmission and a digital fuel consumption meter.

Initially, an estimated set of timing values was programmed into the system. A series of test runs were then made to determine the timing values for optimum performance on both level roads and hills. The initial values and the data collected from these tests were then used to derive a final set of optimum timing values for the system. The speed advance curve (Figure 18) was determined by adjusting the timing with a manual control on the processor so that preignition knock just began under full load, wide open throttle conditions at different vehicle speeds. The resulting values were then plotted against engine speed. The vacuum advance curve (Figure 19) was derived using the manual control to adjust the timing for maximum fuel economy under a variety of conditions. The difference between the resulting timing values and those on the

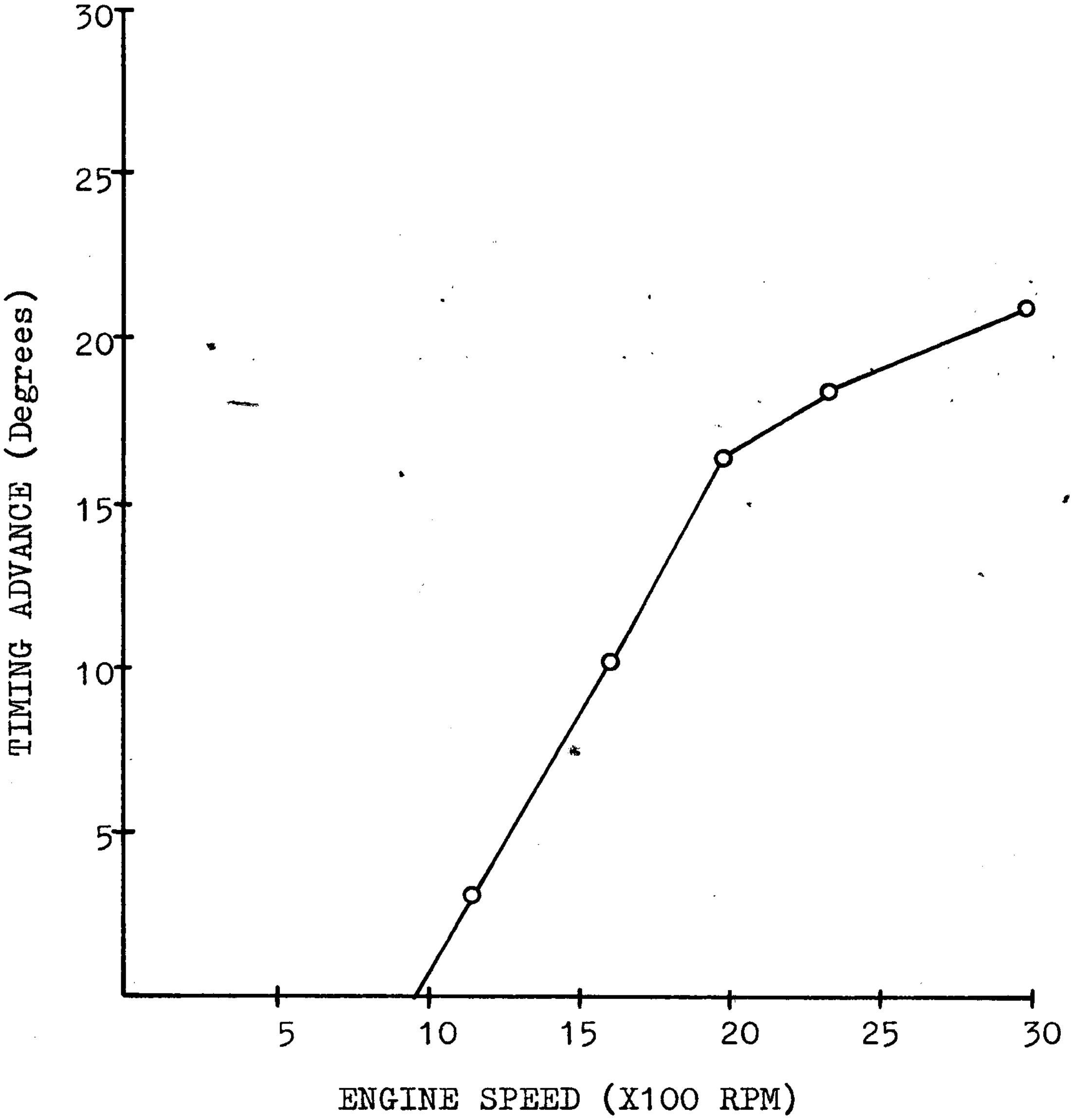


FIGURE 18

SPEED ADVANCE CURVE

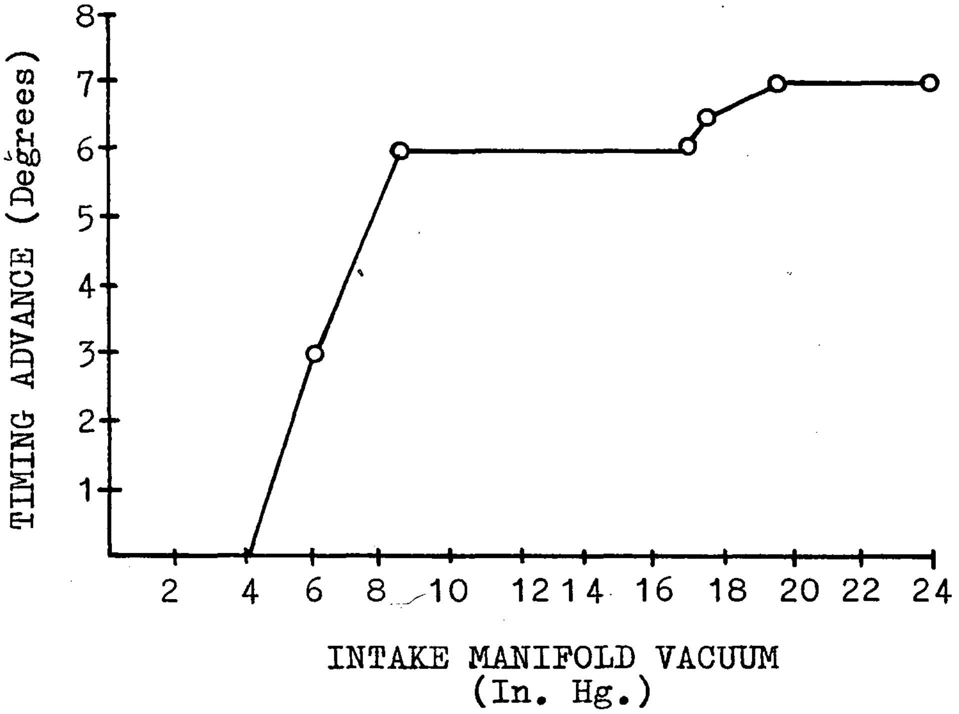


FIGURE 19

VACUUM ADVANCE CURVE

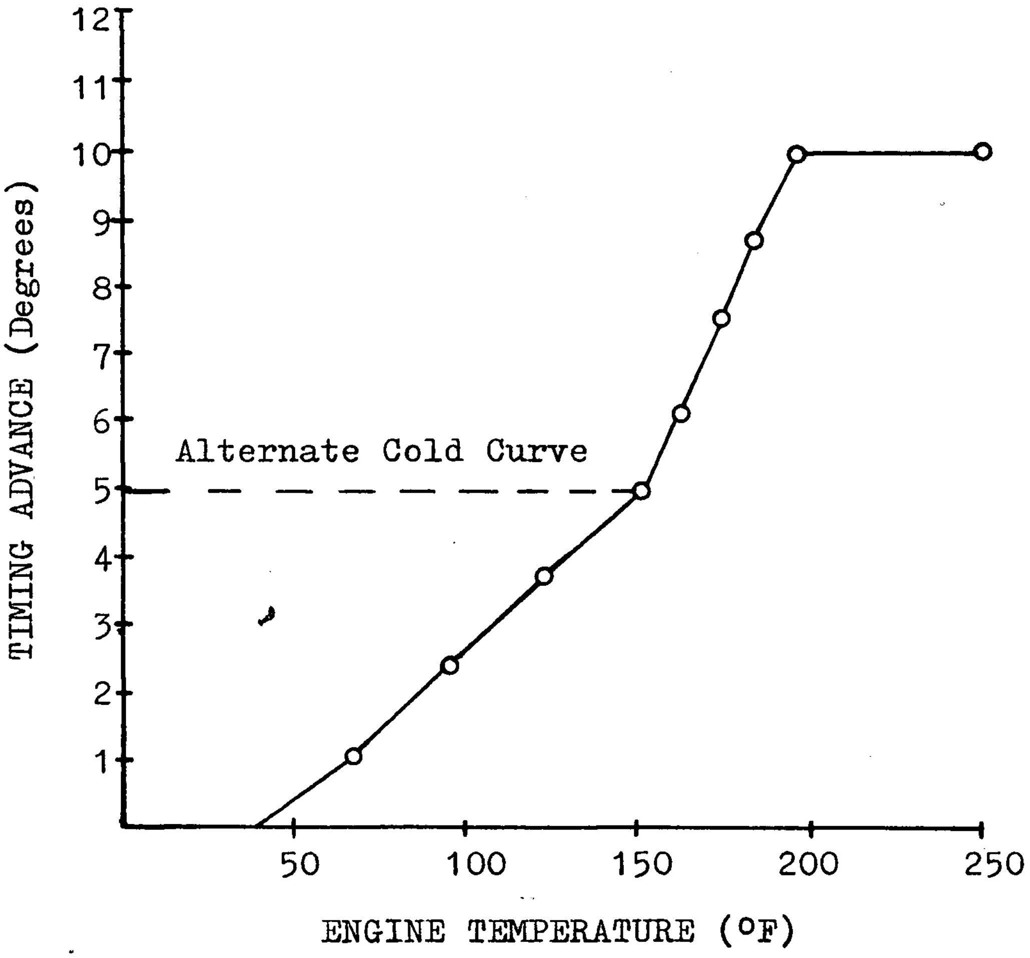


FIGURE 20

TEMPERATURE ADVANCE CURVE

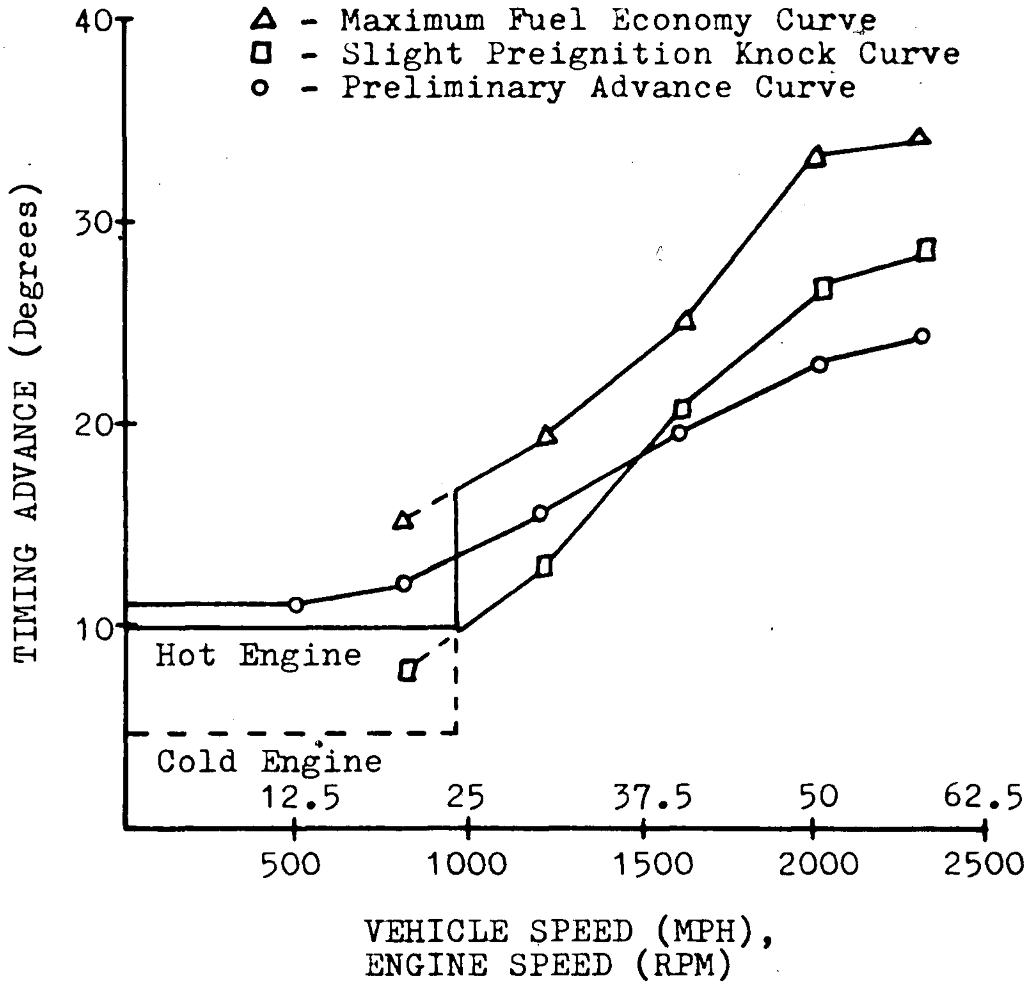


FIGURE 21

COMPOSITE ADVANCE CURVE

speed curve (Figure 21) was then plotted against the measured manifold vacuum. The initial temperature advance curve (Figure 20) was verified by emission tests and was not altered.

The performance of the electronic timing system with optimum curves was compared to that of the conventional timing system. Identical test runs were made with each system, during which fuel consumption was measured under varying road conditions and vehicle speeds. Tests were performed to measure the effectiveness of each system in controlling hydrocarbon and carbon monoxide emissions at engine idle speeds during warm up and at full temperature operation.

Test Results

The data from the performance tests (Table 1) indicates that there is very little difference between fuel consumption with and without the electronic timing system. Fuel consumption with both systems differs by less than one mile-per-gallon under all conditions. The performance with the electronic system is slightly better at lower speeds on level roads but is about equal to or slightly worse compared to the conventional system under all other conditions.

CONDITIONS	VEHICLE SPEED(MPH)	ENGINE SPEED(RPM)	FUEL CONSUMPTION (MPG)	
			CONVENTIONAL IGNITION	ELECTRONIC IGNITION
Level Road	20	824	8.5	8.7
"	30	1209	10.2	11.6
"	40	1616	15.0	14.7
"	50	2004	17.3	16.5
"	55	2166	17.0	16.9
"	60	2328	15.8	15.0
Light Hill	30	1209	10.0	9.3
"	40	1616	10.0	9.1
"	50	2004	8.0	8.5
Medium Hill	40	1616	9.7	8.7
"	50	2004	8.9	9.0
"	60	2328	8.2	8.1

Weather Conditions: Clear, Approx. 65°F

TABLE 1

PERFORMANCE TEST DATA

The emission test data (Table 2) shows nearly equal performance of the two systems for controlling hydrocarbons at full engine temperature. During warm-up (150°F) the timing for minimum hydrocarbons was found to be 5 to 6 degrees advance as set by the temperature curve in the electronic system. Manually increasing or decreasing the timing from this point increased the hydrocarbon emissions. The conventional system fixes the timing at 2 degrees advance at idle which would result in higher hydrocarbon emissions during warm-up. The hot idle setting of 10 degrees advance by the electronic system produces smoother engine running while controlling the emissions within the specified limits (400 PPM) of New Jersey state laws. Because of the limited time during which the emission test equipment was available, the effect of timing on hydrocarbon emissions at absolute cold start conditions could not be measured. The temperature curve, therefore, could not be verified below about 150°F. Assuming that the 150°F behavior of hydrocarbons applies at colder temperatures, a temperature curve which provides a minimum of 5 degrees advance below 150°F may be more suitable.

Carbon monoxide emissions remained constant under

ENGINE SPEED(RPM)	IGNITION TIMING (Degrees BTDC)	HYDROCARBONS (PPM)		
		CONVENTIONAL IGNITION	ELECTRONIC IGNITION	
		ENGINE TEMP. = 190°F	ENGINE TEMP. = 150°F	ENGINE TEMP. = 190°F
750	-4	-	-	150
"	0	-	-	170
"	2	150	350	155
"	3	-	450	180
"	4	-	500	167
"	5	-	300	165
"	6	-	250	170
"	7	-	300	175
"	8	-	475	195
"	9	-	500	200
"	10	-	500	200
"	16	200	-	-
2000	25	50	-	-
"	34	-	-	50

CARBON MONOXIDE: 4.0% at 750 RPM; 1.1% at 2000 RPM (Independent of engine temperature, timing, and ignition type)

TABLE 2

EMISSION TEST DATA

all conditions of ignition timing and engine temperature above $150^{\circ}F$. The carbon monoxide emissions could not be measured at cold start for the same reason as stated above. Carbon monoxide emissions were, however, within state limits (4%) above $150^{\circ}F$ for both timing systems.

During the tests, the absolute timing accuracy of the two systems was measured by observing the timing marks on the engine vibration damper with a timing light. The variation of timing with the conventional system was ± 1 degree from 750 to 2000 RPM as compared to ± 1 degree at 750 RPM and ± ½ degree from 1400 to 2000 RPM for the electronic system. The electronic system is, therefore, slightly more accurate than the conventional system at higher engine speeds.

Conclusions

This project has demonstrated the feasibility of controlling ignition timing electronically. The ability to optimize the timing curves in the electronic system for maximum engine performance and minimum exhaust emissions has been shown. The final timing curve (Figure 21) is considerably different from the initial one and was achieved with only one iteration of testing.

Although the performance is optimized with the electronic system, it is not significantly better than with the conventional system. However, with more iterations of testing and better testing methods such as dynamometer tests, a greater improvement may be attainable. If this can be done, the electronic system would be more attractive for increasing fuel economy in spite of its higher cost and complexity.

The electronic system is better for controlling hydrocarbon emissions under engine warm-up conditions. The system provides a better balance between control of emissions at cooler engine temperatures and smooth engine operation at full operating temperature. This advantage alone could justify the use of such a system, especially in the light of tighter Federal emissions regulations for automobiles.

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APPENDIX A

OPERATION OF THE CONVENTIONAL IGNITION TIMING SYSTEM

Major Parts of the Conventional System

The ignition system used on most internal combustion engines is the high voltage spark-type ignition system developed by Charles Kettering about 65 years ago.[1] Timing of the spark in this system is performed by two mechanical systems: the centrifugal advance mechanism; and the vacuum advance mechanism. The centrifugal advance mechanism adjusts the spark timing according to engine speed while the vacuum advance mechanism controls the timing based on engine loading.

Basic Components of the Ignition System

The conventional ignition system (Figure 22) consists of a battery, an ignition switch, an induction coil with series resistor, a distributor which houses the breaker points, condenser, cam, rotor and timing advance mechanisms, spark plugs, and high and low voltage wiring.[2]

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[1] Ronald K. Jurgen, "Ignition Systems Go Solid State," IEEE Spectrum, September 1975, p. 49.

[2] Edward F. Obert, Internal Combustion Engines (Scranton, Pa.: International Textbook Co., 1968), p. 532.

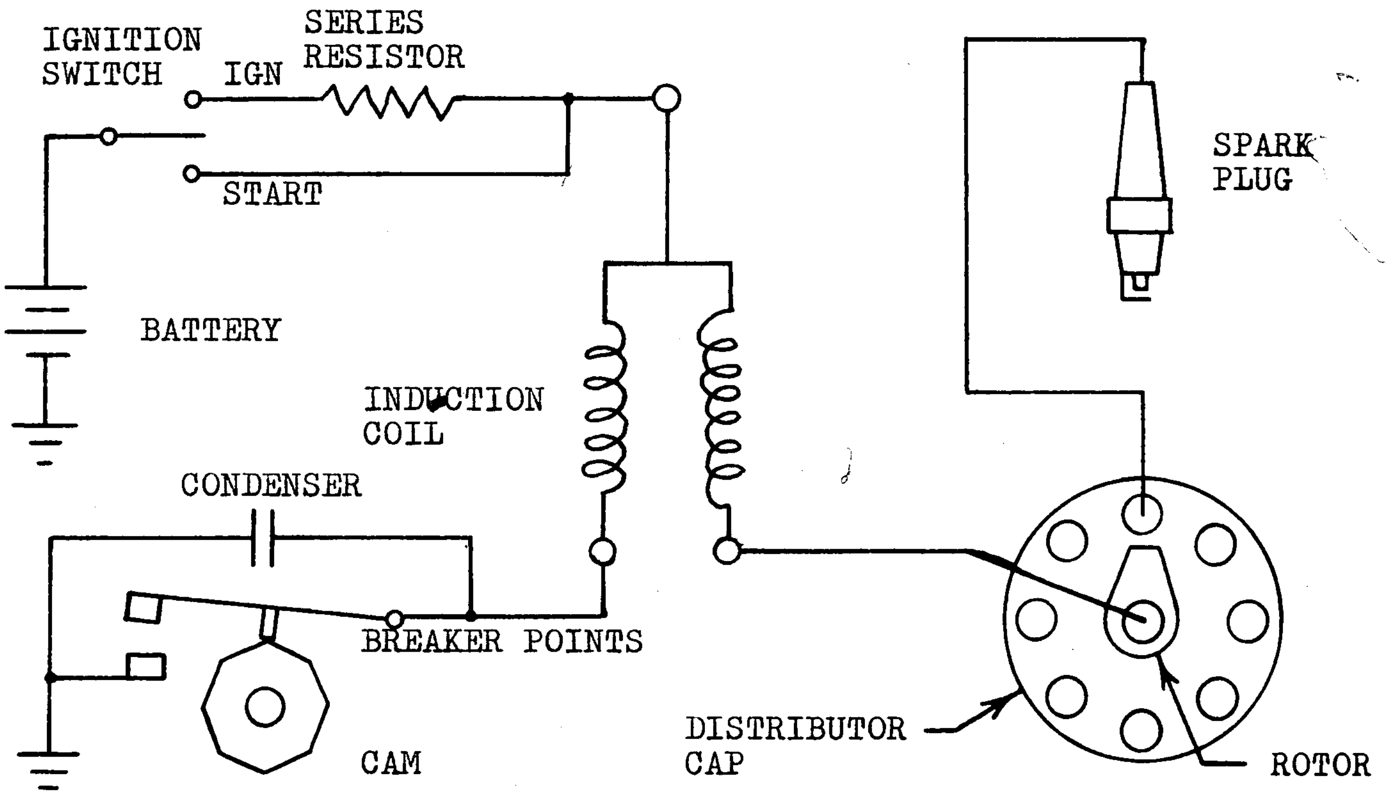

FIGURE 22

CONVENTIONAL IGNITION SYSTEM

The battery, ignition switch, series resistor, primary winding of the coil and points are connected in series to form the primary ignition circuit. The secondary winding of the coil and spark plugs are connected in series through the distributor rotor and cap to form the secondary circuit. The condenser is connected in parallel with the points to provide rapid collapse of the flux in the coil by reducing the primary current rapidly when the points break. The series resistor limits the coil current. This prevents burning out the coil if the points are closed for long periods of time, when the engine is stopped with the ignition switch on. This resistor is usually by-passed during starting to maintain enough coil current at the lower battery voltage encountered under this condition.

The cam rotates at engine camshaft speed. The rubbing block of the points rides against the cam surface and pushes the points open as each cam lobe passes by. Between cam lobes, when the points are closed, current flows in the coil and builds up a magnetic field. When the points open, the rapid collapse of the field in the primary induces a high voltage in the secondary. This high voltage is conducted to the spark plugs by the rotor and distributor cap. The rotor is keyed to the distributor camshaft; as it rotates under the distributor cap it passes each spark plug wire contact in synchronism with the opening of the points. The spark plug wires are arranged around the distributor cap in the cylinder firing order of the engine.[3]

Centrifugal Spark Advance Control

The centrifugal spark advance mechanism (Figure 23)[4] controls ignition timing by rotating the distributor cam ahead in position with respect to the crankshaft as engine speed increases. Two spring-loaded weights and cam mechanisms are located on the distributor camshaft in the base of the distributor. The distributor camshaft is divided into an upper and lower shaft. As engine speed increases, the weights expand and rotate the upper camshaft ahead of the lower shaft. This causes the points to open ahead of idle speed position in proportion to engine speed and advances the spark.

The amount of centrifugal advance is determined

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[3] Ibid., p. 533.

[4] Ford 1972 Car Shop Manual, 5 vols. (Dearborn, Mi.: Ford Marketing Corporation, 1971), 2:23-10-02.

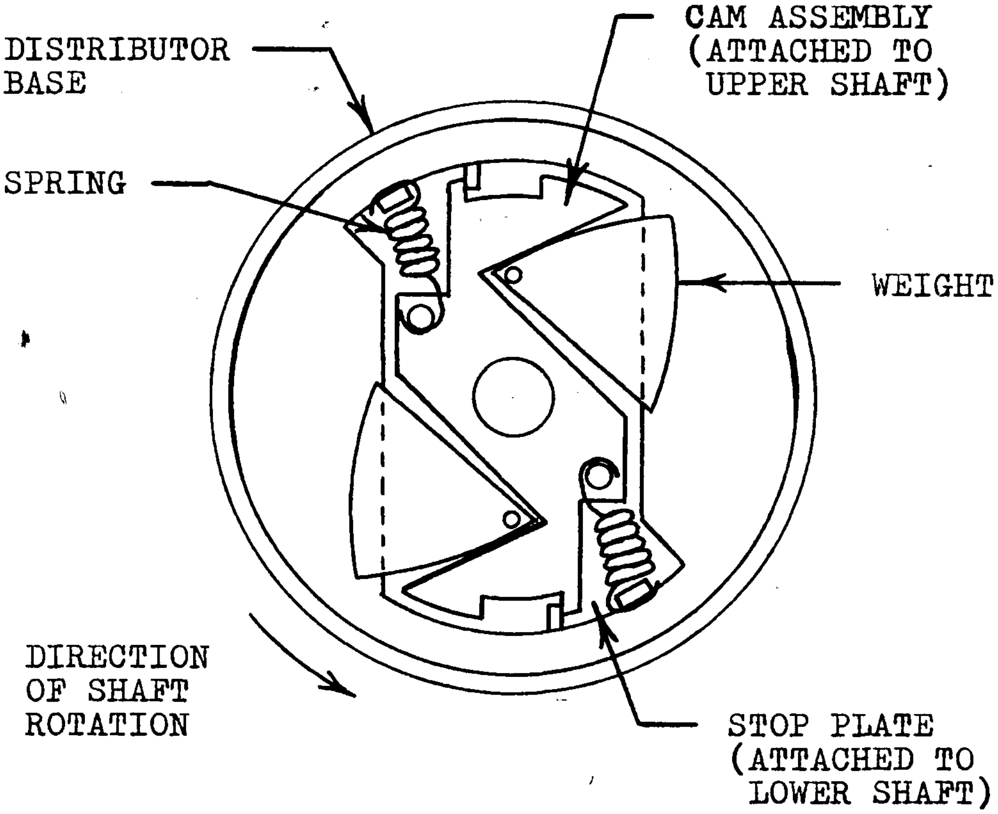

FIGURE 23

CENTRIFUGAL ADVANCE MECHANISM

by the force of the two springs which retain the weights in the mechanism. The more force the springs exert against the expansion of the weights the less the spark advance will be at a particular engine speed. The centrifugal advance curve is adjusted either by changing the springs or bending the tabs to which the springs attach.[5]

Vacuum Spark Advance Control

Ignition timing is controlled according to engine loading by the vacuum spark advance mechanism (Figure 24).[6] This mechanism uses the intake manifold vacuum as an indication of engine loading.

The vacuum advance system operates by rotating the breaker points with respect to the distributor cam. The points are mounted on a plate known as the breaker plate. The breaker plate is rotated by a rod connected to a vacuum diaphragm mounted in a chamber connected by a hose to a port which is open to manifold vacuum. The diaphragm is spring loaded to the full retard position. As manifold vacuum increases with light engine loading, the diaphragm rotates the

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[5] Ibid., 2: 23-10-01.

[6] Ibid., 2: 23-10-02.

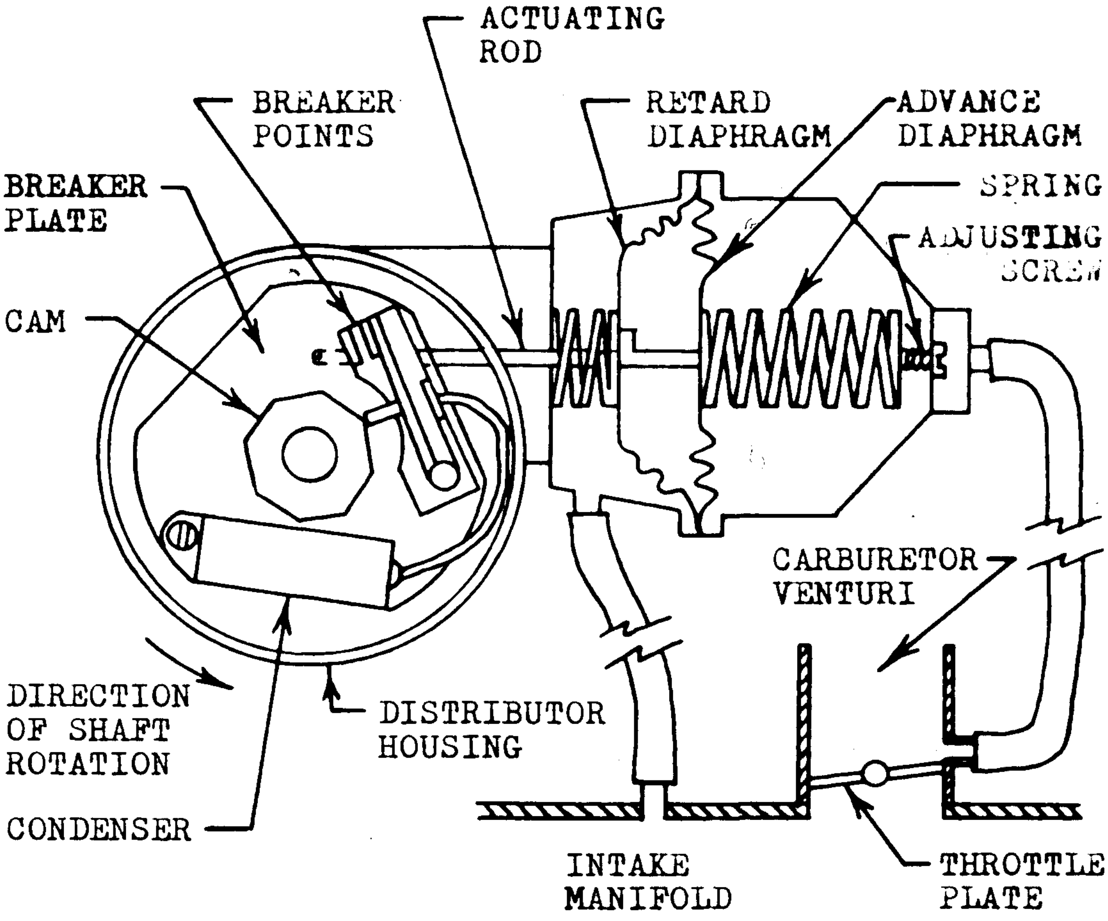

FIGURE 24

VACUUM ADVANCE MECHANISM

breaker points in the opposite direction from the distributor cam rotation. This moves the position at which the points open ahead with respect to the crankshaft position and advances the spark.[7]

On most engines, the vacuum sensing port is located above the throttle plate in the carburetor venturi. When the throttle is open at higher engine speeds than idle, the port is open to manifold vacuum. At closed throttle, the port is closed to manifold vacuum to give the retarded spark required by most engines to obtain a slow idle speed.[8] On many engines, a second diaphragm is incorporated which is hooked directly to manifold vacuum to provide additional retard at idle to reduce exhaust hydrocarbon emissions.[9]

The amount of vacuum advance is controlled by the force of the spring on the diaphragm. The vacuum advance curve is adjusted by varying the compression on the spring by moving the spring stop back and forth.

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[7] Ibid., 2: 23-10-01.

[8] Obert, p. 536.

[9] Ford 1972 Car Shop Manual, 2: 23-10-01.

Interaction of Centrifugal and Vacuum Advance

The effects of the centrifugal advance and vacuum advance mechanisms on ignition timing are additive. The ignition timing at any particular combination of engine speed and load is the sum of the values of the centrifugal and vacuum advance curves at those conditions.

Figure 25 shows a typical centrifugal spark advance curve, plus the resulting curve using vacuum advance, for an engine propelling an automobile at different speeds.[10] At low vehicle speeds, the engine load is light and the throttle is partially open producing high vacuum and increased spark advance. At higher vehicle speeds, the heavy engine load and corresponding wider open throttle produce low vacuum; thus, the spark advance approaches that of the centrifugal advance only.

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[10] Obert, p. 537.

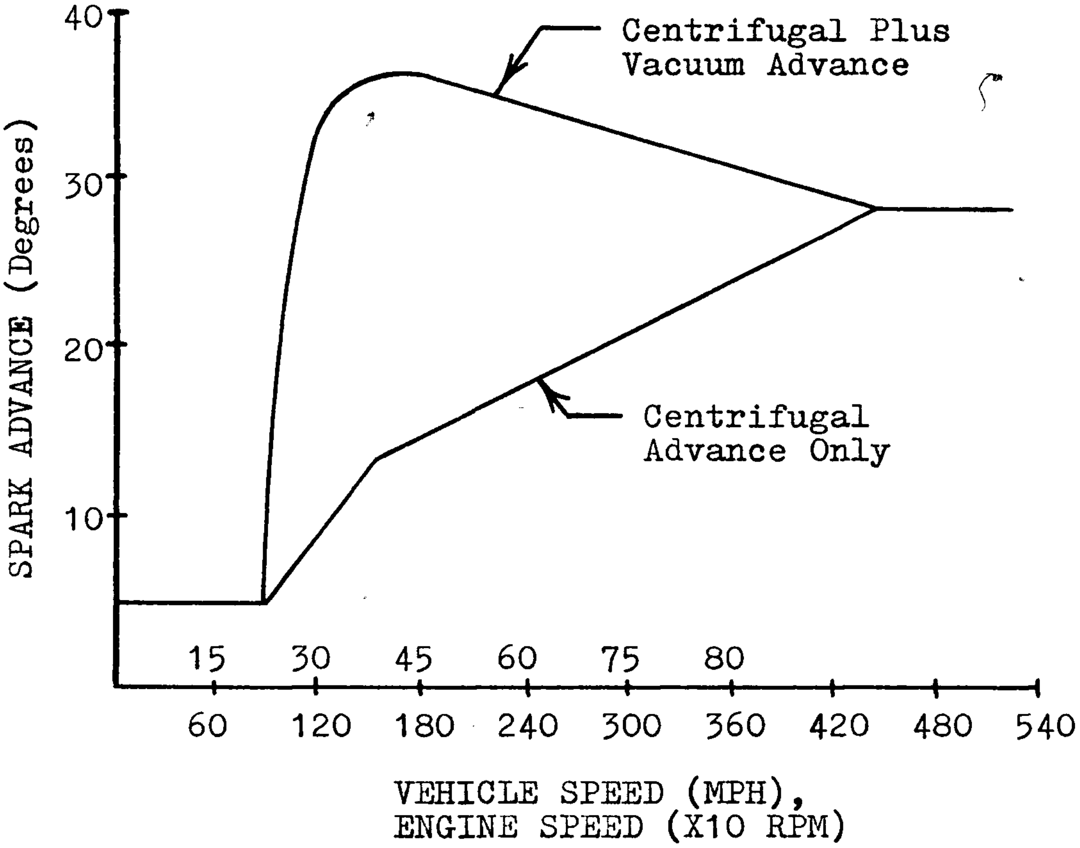

FIGURE 25

TYPICAL COMPOSITE ADVANCE CURVE

APPENDIX B

THE FUNCTION OF IGNITION TIMING IN THE SPARK IGNITION ENGINE

The Significance of Ignition Timing

The time at which the air-fuel mixture is ignited in the cylinder of an internal combustion engine has significant effects on the operation of the engine. Ignition timing affects the efficiency, performance and exhaust gas emissions of an engine. The effects on performance tend to be inverse to those on emissions, resulting in the need for a compromise in the ignition timing setting at a given set of operating conditions. This setting must be precisely maintained in order to keep a satisfactory balance between performance and emissions. It is, therefore, important to accurately control the ignition timing as a function of the operating conditions of the engine.

Factors Which Determine Ignition Timing

Ignition timing depends largely on two parameters: the nature of the air-fuel mixture in the cylinders of the engine; and the speed of the engine. As these parameters change, the timing must change to maintain satisfactory burning of the fuel in the cylinders.

Optimum engine efficiency is achieved when as much of the air-fuel mixture as possible is burned when the piston reaches top-dead-center (TDC) in the compression stroke.[1] When the spark plug is fired, there is a delay period until the mixture actually ignites. The spark must, therefore, be timed ahead (before top-dead-center (BTDC)) to correct for the ignition delay of the mixture.

The mixture ignition delay is constant and independent of engine speed. Therefore, the ignition of the gases requires a greater number of crank degrees as the engine speed increases. As a result, the spark must be advanced farther ahead of TDC as the engine speed increases to make the mixture ignite at the optimum time.[2]

Although the ignition delay is constant with respect to engine speed, it varies with the air-to-fuel ratio of the mixture. The nature of the mixture depends on engine loading and carburetor throttle

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[1] D. J. Patterson and N. A. Henein, Emissions from Combustion Engines and Their Control (Ann Arbor, Mi.: Science Publishers, 1972), pp. 70-71.

[2] Ibid.

position. At light loads and part throttle, the mixture is lean (air/fuel ratio is high) and requires more time to ignite. The spark timing must be advanced under these conditions to provide the extra ignition time required. At wide-open or full-load throttle, the mixture is rich (air/fuel ratio is low) requiring less time to ignite. A reduced or retarded spark timing (closer to TDC) is needed to ignite the rich mixture at the correct time.[3]

It can be seen in this discussion that the ignition timing depends on both engine speed and loading and their relation to the air-fuel mixture. How well the timing is controlled with respect to these parameters determines the level of engine performance and exhaust emissions.

Effect of Ignition Timing on Engine Performance

The performance of an internal combustion engine is measured by its power output versus energy input. One means of expressing this ratio is in terms of thermal efficiency of the engine. Thermal efficien-

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[3] Ibid., pp. 75-76.

cy is expressed by the following equation:[4]

$$\text{Thermal Efficiency} \quad N = \frac{w^*}{J(1-f)FQ_c} \tag{9}$$

Q_c = heat of combustion

F = fuel/air ratio

f = residual gas ratio: $\frac{\text{left over gases}}{\text{new charge}}$

J = Joules law coefficient

w^* = work output

The work output w^* is related to pressure and volume displacement during a stroke of the piston by the following equation:[5]

$$w^* = m_{ep}(V_1^* - V_2^*) \tag{10}$$

m_{ep} = mean effective pressure

V_1^* = expansion volume

V_2^* = compression volume

From Equation 9, it is seen that the thermal efficiency is proportional to the ratio of the work output to the fuel input. Equation 10 states that the work output is proportional to the mean effective pressure (m_{ep}). When the mixture is ignited at TDC, m_{ep} is maximum. The work output and corresponding thermal

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[4] Charles F. Taylor, The Internal Combustion Engine In Theory and Practice (Technology Press of MIT, 1960; New York: John Wiley & Sons, 1960), p. 70.

[5] Ibid., p. 69.

efficiency for any given fuel consumption is a maximum when the mixture ignites at TDC.

The phenomenon described above may be seen in an engine under test. As the ignition timing approaches optimum, at a constant fuel input setting, the engine power output increases. In tests on a particular engine, it has been demonstrated that the power output at a particular speed reaches a maximum peak at a certain spark advance setting; however, thermal efficiency was maximum for 20° advance at all speeds.[6] At any speed, a retarding of the ignition timing below 20° BTDC created a marked drop in thermal efficiency or power output. It was found that the changes in ignition timing had the greatest effect at the higher engine speeds.[7]

Ignition timing has a very significant effect upon engine performance. It is important that ignition timing be controlled to produce maximum efficiency under varying load conditions. This allows the engine to run as economically as possible by minimizing fuel

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[6] S. J. Young and R.W.J. Pryer, The Testing of Internal Combustion Engines (New York: D. Van Nostrand Co., 1937), p. 169.

[7] Ibid.

consumption.

Effect of Ignition Timing on Engine Exhaust Emissions

There are three compounds in the exhaust gas of an internal combustion engine that are considered to be harmful. These are: carbon monoxide (CO); hydrocarbons (HC); and oxides of nitrogen (NO_x). Because of the increasing numbers of motor vehicles on the roads, the concentrations of these compounds in the atmosphere are a major source of concern. It is important, therefore, to control the output of these emissions as much as possible in the internal combustion engine. The ignition timing has significant effects on two of these exhaust emissions: hydrocarbons; and oxides of nitrogen.

The concentration of hydrocarbons in the exhaust gas increases as the ignition timing is advanced. In engine tests it was found that a 10° reduction of the spark timing from the optimum performance level reduced HC emissions by 100 parts per million (ppm). The HC emissions were at a minimum when the timing was set at 5° BTDC.[8]

The same relation to ignition timing is true for

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[8] Patterson and Henein, p. 151.

oxides of nitrogen emissions. Advancing the spark timing at any engine load and speed increases the NO_x output. Under conditions of high loads and lean mixtures (high air/fuel ratio), ignition timing has more effect on NO_x emissions.[9]

Ignition timing has little effect on carbon monoxide emissions until the timing is reduced below 10° BTDC. As the timing is reduced from 10° BTDC the CO emissions increase. At this setting, the mixture does not ignite until after TDC resulting in poor combustion. This makes the engine run poorly and require more fuel input. The poor combustion of fuel produces increased CO concentrations in the exhaust gas.[10]

Another important factor which determines exhaust emission levels is the operating temperature of the engine. Emissions increase as the engine temperature decreases. They are highest under cold-start conditions.

Running an engine with the ignition timing retarded from the optimum performance level under all conditions of engine load and speed will reduce ex-

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[9] Ibid., pp. 168-169.

[10] Ibid., p. 152.

haust gas emissions. The ignition timing may be retarded further when the engine is cold to reduce the increased emissions.

BIOGRAPHY

Gary D. Huber was born in West Chester, Pennsylvania on June 30, 1948. His parents are John C. Huber and Abbie M. Huber. He graduated from The Pennsylvania State University with a BSEE degree in 1970. He is a member of Eta Kappa Nu and the Institute of Electrical and Electronics Engineers. From 1970 to 1975, he worked for Western Electric Company designing automatic testing systems for integrated circuit manufacture. He is presently employed by MKD Corporation where he is involved in the design and programming of microprocessor based point-of-sale terminals.