A microcomputer-controlled spark advance system

A. D. Robbi | J. W. Tuska

A microcomputer can calculate and control the exact time of spark firing as a function of speed and load to give better engine timing accuracy and dynamic response than a mechanical advance-retard system. Microcomputer control also allows the engineer to build in additional features, such as automatic misfire protection, and has noticeably improved "driveability" in road tests.

DURING the 1950's solid-state devices capable of switching the primary current of an automobile ignition coil became available. Ignition systems using these transistors, normally with a specially designed ignition coil, were built by enthusiasts and offered on the after-market in either kit or finished form by many suppliers. These systems retained the conventional mechanical breaker points, but the breaker points switched transistor base current rather than coil current. Well-designed "transistor ignition systems" increased the amount of energy delivered to the spark plugs and extended the mileage that the vehicle could be operated without significant performance deterioration.

Breakerless electronic ignition systems became available as a factory option during the 1960's,[1] and by late 1973 a significant percentage of the new automobiles produced in North America were assembled with breakerless solid-state ignition systems as standard equipment. It was at this time that we decided to investigate and implement a fully electronic spark timing system. The authors, and their colleagues, are not automotive engineers; and we do not profess to know all the answers to the problem of controlling a modern internal combustion engine so that it provides excellent driveability and performance, certifiably low emissions, and improved fuel economy. We believed that a system in which the exact times of spark firings were calculated and controlled electronically, as a function of engine speed and load, would offer improved timing accuracy and faster response than conventional advance-retard systems with centrifugal weights and mechanically moved sensors in the distributor.

We further believed:

1) that a digital system based on a microprocessor would give us the capability to provide the required spark timing and the flexibility to easily modify the spark timing based on additional sensor inputs or vehicle information;
2) that a microprocessor-controlled spark advance system would allow the automotive engineer new freedom to employ sophisticated control algorithms in a cost-effective way, via software, for ideal ignition timing over a greater range of conditions, both environmental and operational, than is possible with mechanically constrained systems; and,
3) that a true test of the suitability of a CMOS microprocessor, the RCA COSMAC, for engine control, was to build such a system and operate it in the hostile environment of an automobile.

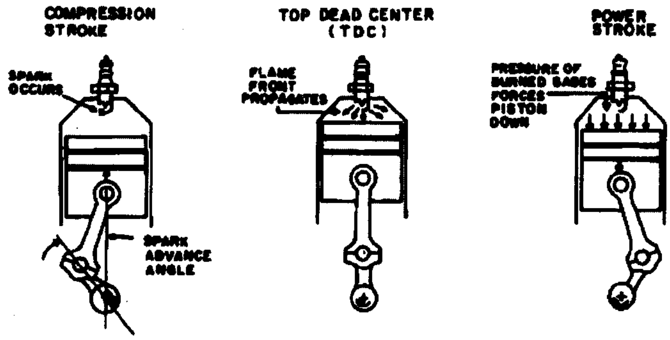

Fig. 1 — Crankshaft vs. piston positions. Spark shown for advanced spark timing (before top dead center).

The system was designed to match the ignition specifications for the 302-cubic-inch displacement, 8-cylinder engine of our instrumented station wagon, and installed on that vehicle. A year of vehicle operation over a variety of driving conditions, specific tests, and demonstrations has confirmed our beliefs.

In the subsequent sections we describe the spark timing problem and its mechanical solution, the approach we have taken, and the performance of our system.

Spark timing

Spark timing is a critical parameter for the modern internal-combustion gasoline-fueled engine because the spark initiates the combustion process. The combustion of the gas-air mixture in the cylinder of an engine should cause the maximum pressure to occur very near the time when the piston has completed the compression stroke and is about to begin the expansion stroke. The relative timing of the spark must be variable because the speed of combustion of the mixture is not the same under all engine operating conditions, and engine operating speeds vary by a factor of approximately 10 from idle to maximum speed. Thus, at a 500-rpm idle speed, 3° of relative spark timing corresponds to 1 millisecond of time; while at 5000 rpm, 1 millisecond of time is equivalent to 30° of relative spark timing.

Factors influencing the combustion process include the air/fuel ratio, the engine load, the throttle opening; and on recent engines, the amount of exhaust gas recirculation (EGR) added.

Spark timing is normally referred to as the angle in degrees of crankshaft rotation between the angular position of the crankshaft when spark occurs and its position when the piston passes from the compression stroke to the power stroke (top dead center, or TDC). Spark occurring on the compression stroke is referred to as "advanced" as it occurs before top dead center (BTDC); while a "retarded" spark occurs on the power stroke and is after top dead center (ATDC). Fig. 1 illustrates these relative piston-crankshaft positions.

Nearly all automotive ignition systems, whether conventional breaker-point/coil or variable-reluctance-triggered solid-state types, change the spark advance angle by mechanical means. Changes that are proportional to engine speed (or depart from that relationship as needed) are usually obtained by a centrifugal device that rotates the reluctor (or breaker-point cam) with respect to the distributor shaft in the direction of shaft rotation. This relative rotation increases with speed and generates a trigger (or opens the points) sooner than otherwise, resulting in an earlier (advanced) spark firing.

Changes to the spark advance angle to adjust for torque load or throttle angle are generally accomplished by sensing one or more pressures, (e.g., the intake manifold or carburetor venturi pressure). The differential between the sensed pressures, or sensed pressure and atmospheric pressure, is applied via a flexible diaphragm and rod to control the partial rotation of the nominally stationary plate in the distributor that supports the trigger coil (or breaker points). Rotating this plate opposite to the shaft rotation increases the spark advance angle, and since the sensed pressure is less than atmospheric for normal engines, this component of spark timing is frequently referred to as "vacuum spark advance."

The "vacuum spark advance" and "centrifugal" (or rpm) advance components are combined in the distributor to produce the desired spark timing. Since these components are mechanically generated, their operation is subject to wear, friction, and fatigue of the restoring springs.

Thus far we have defined advanced spark, retarded spark, TDC, and have identified the rpm and vacuum components of specific spark timing. These and two additional terms—timed maximum advance (TMA), and REF, the minimum spark advance—are shown in Fig. 2. REF is the position of spark firing when no rpm or vacuum advance components of spark timing are considered; an engine is usually timed for this spark to occur at the designated crankshaft position by rotating the distributor housing relative to the engine block. TMA represents the most advanced time of spark firing and is the sum of the maximum values of rpm and vacuum advance.

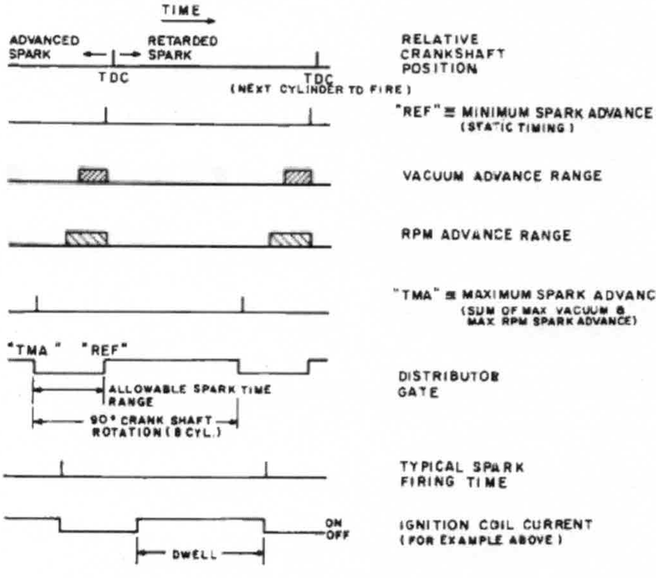

Fig. 2 — Spark timing.

James W. Tuska, LSI Systems Design, RCA Laboratories, Princeton, N. J., received the BS in Electrical Engineering from the University of Pennsylvania in 1956. In 1959 he joined RCA Laboratories, where he has been engaged in memory switching circuit research, permalloy magnetic sheet and plated magnetic wire memory developments, the integration of MOS devices for use with monolithic ferrite memories, and the development of fast, high-voltage switching circuits for computer terminal alphanumeric color displays. In 1967 he was awarded an RCA Laboratories Achievement Award for his work on high-speed laminated-ferrite memory systems. More recently, his research involved the application of the MNOS memory transistor as the storage element in an integrated non-volatile electrically alterable random-access read-only memory. He is presently engaged in the application of integrated circuit technology and digital information processing to automotive electronics systems. Mr. Tuska holds two U.S. patents and has co-authored several papers.

Anthony D. Robbi, Sr. Member, Technical Staff, LSI Systems Design, SSTC, Somerville, received the Ph.D. from Carnegie Institute of Technology in 1961. He has also received much on-the-job education in computers since joining RCA in 1961. Since 1971 Dr. Robbi has worked in microprocessor research, and has participated in CEE-55, a video-tape training course on microprocessors. During his career with RCA he has received three RCA Laboratories Outstanding Achievement Awards, has published many technical papers, and has submitted numerous patent disclosures. Dr. Robbi is active in IEEE, especially in the social implications of working as an engineer. Away from work he serves as a school board member and enjoys the outdoors.

Reprint RE-22-2-8
Final manuscript received January 9, 1976.

Jim Tuska (left) and Toni Robbi check the timing on their 'electronic car.'

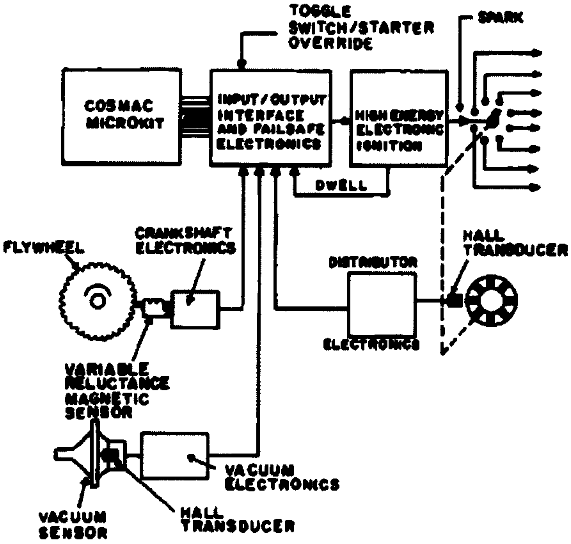

Fig. 3 — COSMAC-controlled ignition electronics.

Up to now we have defined our spark timing in terms of crankshaft degrees. The term *dwell* is generally referred to in ignition system discussions as an angular measure of the time during which current flows in the primary winding of the ignition coil. This term, however, is measured in degrees of *distributor* shaft rotation, which is half the crankshaft speed in a 4-cycle engine. The formula below indicates that for a typical 8-cylinder dwell of 30°, current flows in the ignition coil primary for 2/3 of the available time.

$$\text{Duty cycle} = \frac{\text{indicated dwell}}{\text{available time per cylinder}} = \frac{\text{indicated dwell}}{360^\circ \div \text{no. of cylinders}}$$

System overview

The hardware constituents of the experimental spark control system are shown in Fig. 3. The digital system output is a trigger signal to a commercial high-energy electronic ignition.[2] The ignition electronics determine the spark duration and initiate dwell, and this information is fed back to the digital system. Following the manufacturer's specifications,[1] the spark advance is computed as the sum of two components, vacuum advance and rpm advance. Vacuum is determined by measuring a Hall-effect voltage, which is a function of diaphragm position. Rpm is determined by measuring the duration of a synchronizing signal derived from the distributor. This signal also serves as a reference point for counting degrees to the desired firing angle and as a timer for default firing.

The flywheel, with 164 teeth on its circumference, is an excellent source of crankshaft angular rotation and position, as it is rigidly attached to the crankshaft. The crankshaft electronics converts the tooth count to a 328-cycle-per-crank-revolution wave. Each pulse may be considered to correspond to a "tooth degree", which is thus 360/328 actual crank degrees. To fire an advanced spark the computational system performs two primary tasks: computing the advance (rpm + vacuum) in tooth degrees, and counting tooth degrees from a reference point, TMA, to the desired firing point. The computation is rapid enough to allow a fresh computation for each spark. This, and the fact that spark is synchronized with the crankshaft, which may accelerate as much as 20% per spark firing (1/4 revolution), gives rise to an excellent dynamic response.

The possibilities of misfiring (too early or too late) or an omitted firing are reduced by a failsafe strategy employed in the interface. Computer-initiated sparks are gated by the TMA-REF signal, thus preventing misfiring. If a computer-initiated spark does not occur in the interval, the interface initiates spark at REF. This mode is intentionally used when the starter is active or if an override toggle switch located in the passenger compartment is closed.

A flow chart for the main program loop accomplishing the spark computation and control is shown in Fig. 4.

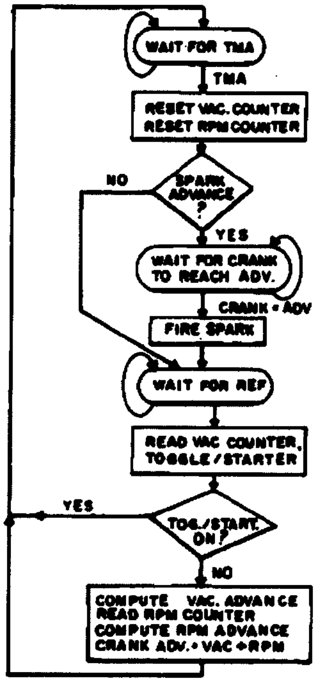

Fig. 4 — Ignition program flow.

Peripheral circuits and sensors

Two of the peripheral sensors shown in Fig. 3, the distributor and the vacuum sensor, are experimental devices fabricated by members of the Laboratories Automotive Systems Group based in Somerville.* While more conventional sensors, representative of the state of the art of the most recent automotive production sensors, could have been used in our system, these experimental types were chosen as part of an ongoing program to investigate and develop effective solid-state sensors fitting the anticipated needs of the automotive industry.

The distributor for this experimental system is greatly simplified when compared to the distributor of a conventional ignition system. The experimental dis-

---

*J. Olmstead, P. Del Priore, and L. Herrod tributor is illustrated in Fig. 5. There is no movable baseplate for vacuum advance changes, and no centrifugal advance mechanism with weights, pivots, and springs. A standard distributor housing was used to facilitate installation and to accommodate a cap and rotor designed for high-energy ignition service. The distributor shaft, conventionally gear-driven from the engine, directly drives an inverted segmented cupped ferrous disc. The eight equally-spaced segments rotate between the magnet structure and the Hall-effect detector of the variable-reluctance sensor attached to the distributor baseplate. The distributor shaft extends above the disc to drive the rotor, which directs the high-energy ignition to the proper spark plug as in conventional systems.

The geometry of the rotating segments is chosen such that the sensor output, after amplification and standardization by the distributor electronics, yields the "distributor gate" waveform shown on Fig. 2. The output from the distributor electronics is digital, with state transitions of high to low at TMA, and low to high at REF. The amplitude ("high" = +5V, "low" = 0V) is independent of speed. This output is capable of driving the high-energy electronic ignition module directly without the input/output interface or failsafe electronics. A firewall toggle switch is included in our installation should the need for the direct connection arise, and as a convenience for moving the vehicle when the COSMAC-controlled system is removed for bench testing or modifications. (Spark firing occurs at REF at all times when the direct connection is used.)

The vacuum sensor connects to the normal "vacuum advance port" on the engine. Pressure (less than atmospheric—hence vacuum) variations cause a flexible diaphragm in the sensor to change position. A Hall transducer converts the diaphragm position to a voltage. This analog voltage controls the pulse width of a triggered monostable, providing two outputs that are a function of vacuum—the continuous analog voltage and the width of the monostable pulse.

Crankshaft rotation is measured by a variable-reluctance magnetic sensor in close proximity to the gear teeth on the outer circumference of the flywheel. The output from the sensor is approximately sinusoidal in shape, and as there are 164 teeth on the test vehicle's flywheel, the frequency is 164 cycles per crankshaft revolution. The sensor output is converted by the crankshaft electronics to a 328-cycle/crankshaft-revolution square wave of constant amplitude (5V). These electronics consist of a full-wave diode bridge, voltage clamping, amplification, and wave-shaping circuits. The frequency is doubled to enable its direct use in the spark calculation to a resolution of approximately 1 degree.

The ignition coil used is a standard high-energy coil, controlled by a high-energy electronic ignition module intended for operation with a breakerless distributor. Our only modification to the ignition module was the addition of an intermediate-stage dwell output. (Dwell is initiated by the ignition module electronics and this information is an input to the digital system.)

COSMAC interface

The experimental system was developed on the COSMAC Microkit, a hardware/software development system based on the RCA CDP1801 microprocessor.[4] The interface circuitry unique to the ignition system resides on a 4- by 6-in breadboard that fits into one of the empty slots in the Microkit backplane. A block diagram of this module is shown in Fig. 6. The Microkit provides facilities not required for a final product; the next step in a product design would be to create a minimum-cost system that performs in a functionally identical manner. The interface described here uses the following Microkit facilities: microprocessor, RAM memory, PROM memory, address latch, I/O decode, and a byte I/O input port (interface to RAM memory).

The Microkit operates at the standard V_{DD} = 5V and clock frequency of 1.95 MHz. This gives a machine cycle time, and TPA (CPU timing pulse) period, of a little over 4 µs, and an instruction fetch/execute time of a little over 8 µs. TPA, appropriately gated, drives botn the VAC and RPM counters. The contents of the VAC counter (and the toggle/start switch position) are read into memory by issuing an I/O instruction (IOD) just after REF. The contents of the RPM counter are read into memory by DMA input cycles caused by crank square-wave transitions (82 per firing cycle). Since DMA cycles automatically increment COSMAC register R0, its position serves as a "tooth degree indicator." R0 is reset by program at each occurrence of TMA. The program in-

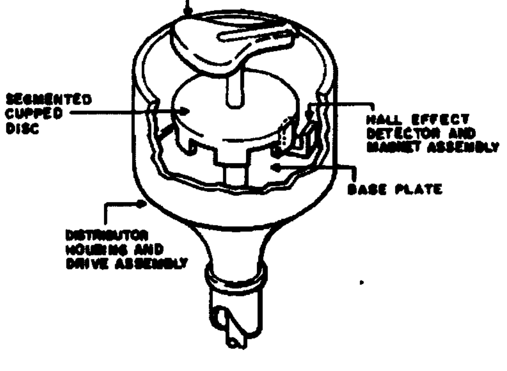

Fig. 5 — Experimental distributor.

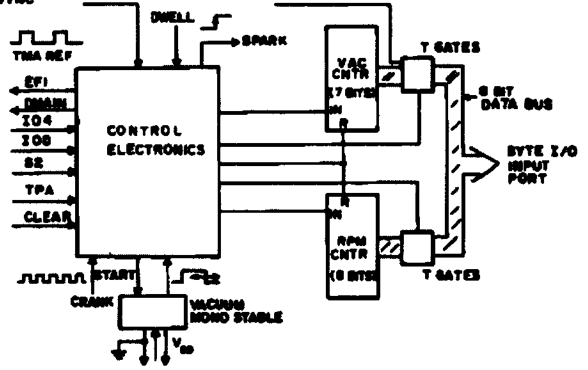

Fig. 6 — Ignition-control electronics module.

itiates spark issuing an I/O instruction (IO4) when the address in R0 matches a pre-calculated value, which is a function of the advance.

Program description

As can be seen in the functional flow chart of Fig. 4, the program operation is synchronized by the distributor waveform, which the program senses by testing an external flag (EF1). At REF, by which time spark has initiated, the VAC and RPM counts are read and the spark advance is computed, in tooth degrees. The program translates this to a count relative to TMA and waits for TMA. At TMA the two counters are reset and the vacuum monostable is started. When the address in R0 reaches the appropriate tooth degree count, spark is initiated and the program execution waits for REF to start the next cycle.

Both the vacuum and rpm advance computations use a table look-up and interpolation subroutine, as both advance components are nonlinear functions of VAC and RPM. The smooth advance curves shown in Fig. 7 are drawn through limit values specified by the manufacturer.[3] Obviously, mechanically-caused advance is not expected to be very precise. The discrete points within the curves correspond to look-up table values stored in the program. Each of the tables actually has 16 entries, but since the abscissas are counts that are not scaled to fit the bounds exactly, some points spill beyond the limits shown (and are never actually used). The table look-up routine linearly interpolates values between the points shown to an accuracy of one part in eight. On average, about 60 instruction executions are required to return an interpolated advance value, given a vacuum or rpm value. Thus the computational portion of program, from TDC to REF, requires roughly 1 ms of processing time. Even at 4000 rpm, roughly 2.5 ms are available in this interval, so the computing load on the microprocessor is light.

The program itself occupies 192 bytes of memory storage, broken down as follows:

	Bytes	*%*
Main loop	71	37
Look-up subroutine	64	33
Initialization and start-up	25	13
Look-up table data	32	17
	192	100

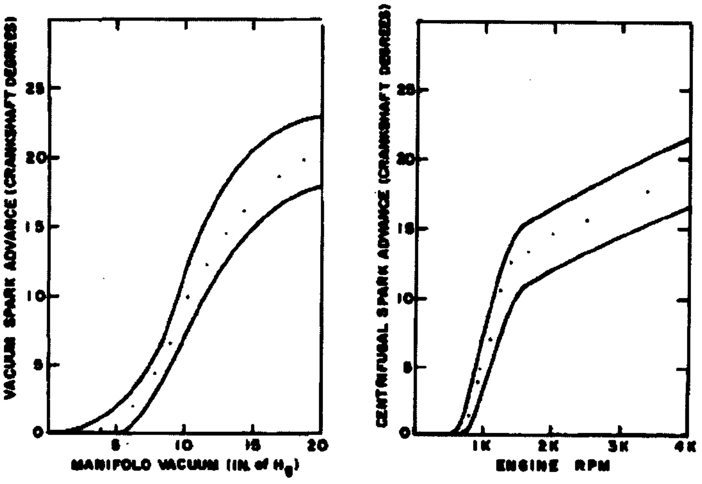

Fig. 7 — Manufacturer's specifications for mechanical control of ignition. Dots indicate stored-program data.

It uses more RAM than it needs to, because it is provided in the Microkit. Since only 7 of the 16 available COSMAC scratch-pad registers (2 bytes each) are used, only a single byte of RAM for arithmetic and input/output would be required.

System performance

When this microcomputer-controlled spark advance system was first installed on our test vehicle we adjusted the distributor position such that default firing, or spark firing without vacuum or RPM advance, would occur at the desired time. We used a high-voltage stroboscopic timing light that we had used on this and other engines many times. This time the timing marks on the rotating damper, illuminated by the timing light, were much sharper and more clearly defined than we had seen before on this or other vehicles. We had expected increased accuracy and improved transient response from our system, and this visible demonstration of more accurate repeatability was the first of many on-the-car confirmations of our expectations. The vacuum and rpm components of spark advance have been measured individually, and in combination, on the operating engine. (The timing light was clamped in position for accuracy, and the standard timing scale (2° graduations) replaced with a temporary scale with accurately marked 1° graduations. The measured advance components were within ±1° of the data points in Fig. 7, with the exception that approximately 2° of spark advance results from manifold vacuums between 3 and 4 inches of Hg.

Our station wagon, with its microcomputer-controlled spark advance system, has been driven in dense traffic and on open interstate roads, and in temperatures varying from summer to winter in New Jersey. The system has been subjected to a variety of intra- and extra-vehicular electrical noise, including the repeated cycling of the vehicle's air-conditioner clutch, normal vehicle controls (e.g., blower, turn signals, etc.), a 550-W inverter, and the car's CB transceiver. The vehicle has been driven in the vicinity of rural electric fences and rf transmission sites, and has been subjected to the radiated noise from SCR-controlled power tools. During all of this testing we have not experienced a failure or detected any irregularities.

The "driveability" of a vehicle is a difficult term to define and impossible to measure in an engineering sense. However, the change in driveability of the test car with the experimental spark advance system, as compared to the same car with a well-maintained, freshly-timed conventional system, is noticeable, with an apparent improvement in smoothness and response. The vehicle's responsiveness, when the 302-cubic-inch engine is operating under microcomputer-controlled spark, is more readily felt than described.

References

1. Norris, J.C.: "Delcotronic breakerless transistor ignition system." SAE paper 617B (Jan 1963).
2. Carlson, D. W.; and Duelp, W. L.: "A successful electronic ignition system through fundamental problem analysis." SAE paper 740154 (Feb 1974).
3. Ford Shop Manual, 1969, Vol. 2.
4. MPM-103, "COSMAC Microkit Operator's Manual," RCA, SSD, Somerville, N.J.