DESIGN, IMPLEMENTATION, AND TESTING OF A REAL-TIME MICROCOMPUTER AIR-FUEL RATIO AND SPEED CONTROLLER FOR AN ELECTRONICALLY FUEL INJECTED INTERNAL COMBUSTION ENGINE

by

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CHAPTER I

INTRODUCTION

1-1 Introduction

Ever since the world's first electronic digital computer was laboriously built nearly three decades ago the growth in usage of the digital computer has had a tremendous impact on the field of engineering. The latest computer revolution has been caused by an electronic data-processing machine so small it very well may have been lost in the socket of one of that first computer's tubes. This device, the microprocessor, was invented eight years ago, but its mass applications are just beginning to explode.

Coinciding with the microprocessor's invention was another event that was to have a pronounced effect on the nation. The advent of governmental emission standards in 1968 resulted in the requirement that the automobile engine have more precision in metering and mixing the fuel and air to maintain an air-fuel ratio that would reduce exhaust emissions, yet still meet the driver's demands and the engine's operating needs. Today this precision is an even more important requirement because those emission limits have become more severe and the motoring public is demanding vastly improved performance in terms of driveability and economy. Unfortunately, those demands are far from being compatible.

The only way these divergent requirements can be reconciled is through extremely accurate control. Electronics is the only method available today that can provide that high degree of accuracy in sensing, computation, and control. Indeed, the power and versatility of the microprocessor make it an ideal candidate for the task at hand. Technological progress in electronics, in general, has never been guaranteed acceptance by automobile manufacturers. However, even the highly cost-conscious automotive industry is beginning to conclude that, with mass production, the microprocessor's cost-effectiveness will have a tremendous impact on the design, performance, and overall drive-ability of automobiles in the years to come.

This thesis is the initial phase of research currently being conducted in the Mechanical Engineering department at Kansas State University into micro-computer engine control. The ultimate objective requires that the spark timing and air-fuel ratio be simultaneously controlled by the microcomputer in such a manner that the optimal desired engine performance is always achieved. The objective of this thesis was narrowed to include only air-fuel ratio control and, in addition, a speed controller. The scope of this research was further limited to testing between the engine speeds of 1000 and 3000 rpm following engine warm-up. The microcomputer was programmed to control the engine at 4 different air-fuel ratios: 11.2, 12.8, 14.4, and 16.0-1. Furthermore, the computer was programmed to control the acceleration, deceleration, or maintenance of constant engine speed within the previously defined operating range.

The remainder of this chapter will provide a discussion of the objective of this thesis, an introduction to the development of microprocessors, and an overview of their potential application to the automotive industry. Chapters 2 and 3 provide detailed descriptions of the subsystems involved. Chapter 4 presents the software developed for these subsystems. The experimental procedures and testing are presented in Chapter 5, and the subsequent results are found in Chapter 6. Chapter 7 provides the summary and recommendations.

1-2 Description of the Objective

The objective of the work presented in this thesis was to investigate problems associated with the implementation of a microcomputer used as a real-time controller of an electronically fuel injected internal combustion engine. This investigation was carried out by the design and subsequent testing of a prototype system consisting of an open loop air-fuel ratio controller and a closed loop speed controller, utilizing a microcomputer as the primary component of the system. The experiments were conducted to investigate the capabilities and limitations of the system while operating the engine, following warm-up, between 1000 and 3000 rpm.

The digital controller used for this research was a KIM-1 microcomputer system, manufactured by MOS Technology, INC. This system included an 8 bit 6502 microprocessor array with instruction set, 13 addressing modes, multiple interrupts and a full 65 K address range. Also included were two MCS 6530 arrays, each with 1024 bytes of read-only-memory, 64 bytes of random-access-memory, 15 input-output pins, and an interval timer.

It should be explained here that the MPU, or microprocessor, is the most expensive component, or group of components, of a microcomputer. It initially fetches the control instructions stored in the memory, then decodes, interprets, and implements them. The MPU manages the temporary storage and retrieval of data and regulates the exchange of information with the outside world through the microcomputer's input and output ports. It incorporates the arithmetic and logic unit, in which all operations are performed, and additional temporary storage registers. Finally, it synchronizes the operation of the various components.

The engine used for this research was a 1968 model, 96.6 cubic inch (1.58 liter) displacement, four cylinder, horizontally opposed, electronically fuel injected, air cooled, spark ignition, internal combustion, Volkswagen engine. Detailed engine specifications are listed in Appendix B. The engine was equipped with a Bosch electronically controlled gasoline injection system which employs electromagnetically actuated injection valves and solid state circuitry for the metering of the injected fuel volume. Various parts of this system were employed in the design of the microcomputer based controller, most notably the injection valves and their driving circuitry.

1-3 Microcomputer Development

To date, the microcomputer's greatest impact has been on the design of electronic systems. In many cases they are replacing systems based on custom designed large-scale-integrated circuits. These specially made integrated circuits can be justified only when they are produced in volumes large enough to amortize their development costs. They combine the advantages of high density and low power dissipation, but they cannot be modified or adapted for an application for which they were not originally designed. Not the least of the microcomputer's attractions is that it eliminates the lengthy effort required to design, "debug", and manufacture a special LSI circuit.

An industry which has the potential to become the largest single user of microcomputers is the automobile industry. In response to the energy shortage, anti-pollution regulations, and increasing public concern about vehicle safety the automobile industry seems ready to make greater changes in its vehicles in the next five years than were made in the last 25 (1). Upon looking at the automobile as a total system, one is led to the conclusion that a present day automobile encompasses a large set of compromises made either intuitively or due to practical constraints and perpetuated almost entirely because they work (2). One or more microcomputers, together with appropriate transducers, actuators, and sensors could replace the custom designed LSI devices already installed by many manufacturers for monitoring brakes, lights, and battery, and speed, skid, and fuel management control. A well conceived system design should give the automotive engineer a freedom of approach not previously enjoyed.

The major problem area associated with the application of microcomputers to the automobile is cost, but this has diminished markedly over the past few years and continues to shrink with each technological advance made by the industry. Since the cost is generated largely by complexity and low volume production, it continues to drop year by year as the components and circuitry are simplified and subject to increased demand. Tied in very closely with the need to reduce costs is the absolute necessity that any electronic package designed for the automobile must be approached on a systems basis. It would be economic suicide for any supplier to attempt to approach the electronic systems package on a component by component basis. It must be designed as a total system, taking into account the total requirements of the vehicle (3). Thus, the appeal of high volume versatile devices, such as microcomputers, incorporating no custom-made features except the contents of a separate and easily programmed memory can be seen.

1-4 Literature Review-Automotive Microprocessor Applications

Due to their exciting potential, microprocessors are being carefully studied by most major automobile manufacturers in the U.S. General Motors has had an extensive research program underway for some time in which several in-vehicle, experimental, integrated, automotive electronic systems have been studied and built (2). Overall systems integration has been studied in the Alpha series of systems, display systems in the Sigma series, diagnostics (both on-board and off-board) in the Delta series, and driver physiological considerations in the Beta system. Each of the four systems will ultimately be superseded by Omega, an automobile central processor.

The fourth version of the Alpha series was the first attempt by General Motors at applying MOS/LSI technology in the design of a cost-effective automotive computer. It used a single-chip, 4-bit parallel microprocessor with subsystems for both digital display and control functions, which included: speedometer, odometer, time of day, elapsed time, engine speed, four-wheel-lock control, cruise control, traction control, ignition timing, ignition dwell, speed warning, speed limiting, and anti-theft. The microprocessor handled the control, display logic, and calculations. All functions were performed in a time sequence on a fixed, real-time computation loop, while interface circuitry handled the asynchronous load associated with the vehicle operation.

The latest version of the Alpha series represents the first use of a microprocessor on a production automobile. The 1977 Oldsmobile Toronado is equipped with an electronic spark timing device; the heart of the system is a 10-bit custom microprocessor made by Rockwell International (4). Engine operational and environmental information, such as engine speed, crankshaft position, manifold vacuum, and engine coolant temperature are fetched by the microprocessor. The MPU then performs logic and computational operations to determine the appropriate spark timing. It signals the high-energy ignition distributor to initiate the spark in each cylinder at the proper instant, with an expected improvement in fuel economy.

The custom microcomputer system centers on two main chips. The first consists of the MPU, 20 input-output ports, 17 scratch pad registers, 26 input-output registers and analog-to-digital conversion circuitry. The other contains a 10,240-bit read-only-memory, specially developed data curves in three-dimensional format and pre-programmed instructions. One instruction is a table look-up interpolation function that enables the microprocessor to locate data inputs between stored points on the curves, reducing ROM requirements.

Ford Motor Company plans to introduce its first microprocessor on a limited number of 1978 model cars. This corporation recently signed a letter of intent with Toshiba for a 12-bit device to control the spark ignition timing and exhaust gas recirculation mass flow based on a number of engine variables. The computer program and associated coefficients, which describe the engine control algorithm, are stored in read-only-memory. Engine control software is contained in about 1500,12-bit words. Input-output data and intermediate results are stored in a 128 word, read-write semiconductor memory. The system also includes an 8-bit analog-to-digital converter with an eight-channel analog multiplexer under CPU control (5).

The Chrysler Corporation has announced development contracts with RCA for an 8-bit C/MOS and with Texas Instruments for a 16-bit N/MOS microprocessor (4). As with the other major auto manufacturers, Chrysler has indicated that the initial use of this device will be for engine control. At this time they have a microprocessor operating in the lean burn system on one of their cars and estimate a production processor will be in use by 1980 at the latest.

CHAPTER II

THE AIR-FUEL RATIO CONTROLLER

2-1 Introduction

The objective of an air-fuel ratio controller should be to sense an engine's fuel requirements as a function of measured engine requirements; to compute the amount of fuel needed to satisfy those requirements; and to control the fuel flow accurately in proportion to the air intake for the desired combustion level.

This chapter will explain the concepts and the physical systems used in the air-fuel ratio controller during this research. Section 2 is a review of the literature concerning automotive air-fuel ratio control, particularly electronic fuel injection. Section 3 discusses the control concept used during the design of this controller, while Section 4 provides a description of the physical system. The final section of this chapter contains the control algorithm derivation.

2-2 Literature Review-Automotive Air-Fuel Ratio Control

Accurate air-fuel ratio control is extremely difficult to achieve in a conventional carbureted engine which functions by mixing the fuel and air at a central point and transporting the mixture to the cylinders. Pressure drop at the venturi controls the fuel flow out of the fuel reservoir, and that vacuum depends on both venturi size and throttle opening. Unfortunately, a venturi of the proper size to pass enough air for full-throttle operations is too large for other conditions. As a result, an idle system has to be tacked on to supply gasoline when the throttle is closed, and a low-speed system for when it is slightly open. Air bleeds are added to keep the mixture from becoming too rich, and power enrichment systems to keep it from becoming too lean. An accelerator pump is added for starting and sudden acceleration, and a choke for cold starts.

Even if the carburetor did succeed in achieving the optimum fuel-air mixture for every driving condition, which it doesn't, problems are encountered while transporting the mixture to the cylinders. This produces manifold wall wetting and fuel particle agglomeration occuring in varying degrees. These conditions result not only in maldistribution but also in fuel delivery inaccuracies during engine transients, when, as the average quantity of fuel delivered is changing, the wetted walls and agglomerated particles may contribute either an effective enrichment or an effective leaning out characteristic.

Ford Motor Company has recently designed a variable-venturi carburetor capable of being mass produced that is to be installed on a limited number of 1977 cars marketed in California. Ford reports (6) that the improved carburetor design can more accurately meter the proper air-fuel mixture to the cylinders over a wide variety of speed, load, and temperature conditions. At full throttle, when airflow is greatest, the venturi is wide open. However, at part throttle it closes somewhat so that the reduced airflow available will still create sufficient pressure drop to draw the proper amount of fuel. A metering rod, attached to the variable venturi, also helps regulate the fuel flow. Thus the carburetor has no need for most of the auxiliary fuel circuits, and matches fuel flow to engine needs more precisely than do conventional carburetors. However, both carburetors share the problem of transporting the mixture to the cylinders.

Fuel injection for spark ignition engines permits closer control of the air-fuel ratios at all operating conditions than is generally possible by carburetion. This is due to the fact that the metering in an injection system can be designed to combine all mechanical and physical parameters for optimum combustion. In addition, the fuel can be atomized by means of injection nozzles located properly in the air induction system. This provides for very precise control of fuel distribution in the individual cylinders of the internal combustion engine under both steady-state and transient operating conditions, thereby permitting more exact control of exhaust chemistry.

The principles of electronic fuel injection have been known for about twenty years. The Bendix Corporation was granted the basic patent in 1961 (7). However, this electronic fuel injection system exhibited an apparent inability to survive in the harsh automotive environment, besides having a poor cost-benefit ratio. As a result, Bendix shelved the program in 1961 because it seemed to hold little promise as a viable product for the corporation.

At this time Robert Bosch GmbH in Germany, a Bendix licensee, began its work on an electronic fuel injection system. Such a system was attractive to a non-U.S. automobile manufacturer because it made it possible to develop about five percent more horsepower from a small-displacement, four cylinder engine than could be developed with a carburetor. As this new research program proceeded, the rapid development of technological advances in electronic circuits and related hardware came about, predictably resulting in a much improved and reliable electronic fuel injection system. In 1967 the Bosch D-Jetronic fuel injection system went into production for a 4-cylinder Volkswagen engine with 1.6 liter displacement (8). This system uses as main control inputs the absolute manifold pressure and engine speed.

By the early 1970's a demand had grown in the U.S. for a more accurate method of metering fuel to reduce exhaust pollutants. The Bendix Corporation reinstated its electronic fuel injection program, and was able to take advantage of the work already done at Bosch. Systems operating with the same concepts as the D-Jetronic fuel injection system were introduced by both the Bendix Corporation (9) and Borg-Warner Corporation (10).

In England, the Joseph Lucas Co. Ltd. was also conducting research on electronic fuel injection. However, their work differed from that done previously in that they developed a digital memory fuel controller for spark ignition electronically fuel injected engines. The Lucas approach was to obtain an approximate but unique value of engine load by electrically measuring the throttle opening angle and to use this signal in conjunction with engine speed to determine injection duration (11).

By the end of 1973 the second generation of Bosch electronic fuel injection systems went into production (12). The new system, called L-Jetronic, was to meet three main goals:

1. Improved performance by use of air flow measurement.
2. Cost reduction by applying integrated circuits in the electronic control unit which at the same time results in higher reliability due to the reduced number of components.
3. Simplification by introduction of the one channel system. Here all injectors are connected electrically in parallel and are operated twice for every camshaft revolution.

The two main input signals come from an air flow meter representing air intake and from the distributor for engine speed. The air flow meter consists of a movable metering plate which is opened by the force of the flowing air against the force of a spring. The position of the metering plate is detected by a potentiometer. The voltage from the wiper of the potentiometer represents air flow.

The third generation of electronic fuel injection systems being developed by Bosch employs the feedback control concept. The feedback element is a zirconium-dioxide oxygen sensor which measures the free oxygen in the exhaust. The voltage characteristic of the oxygen sensor is very nearly a step type, with a stable operating point around 350 mv which corresponds to a chosen air-fuel ratio. Through the utilization of the oxygen sensor and the closed-loop concept it is possible to achieve a very accurate air-fuel ratio and to maintain it independent of changes and drift in the engine and fuel preparation system. By use of a one bed three-way catalyst it is possible within this narrow air-fuel ratio range to reduce carbon monoxide, hydrocarbon, and nitrogen oxide emissions simultaneously. Thus, this new system has the potential to result in very low emissions and good fuel economy.

The Bendix Corporation is developing its own version of closed-loop electronic fuel injection, using the oxygen sensors developed by Bosch (13). While Bosch is developing its closed-loop system around the L-Jetronic fuel injection system, Bendix is adding the concept to its original system which used absolute manifold pressure and engine speed as the two main inputs. Both of these systems are still in the research phase and neither has been offered in a production line automobile as yet.

2-3 The Control Concept

The microcomputer air-fuel ratio controller implemented in this thesis was an open-loop, nonfeedback-type control system. The block diagram of this system is shown in Figure 1. In an open-loop control system the output is not compared with the reference input (14). Hence, for each reference input, there corresponds a fixed, pre-programmed operating condition. Thus, the accuracy of the system depends on the initial calibration. In the presence of disturbances an open-loop control system will not perform the desired task. In

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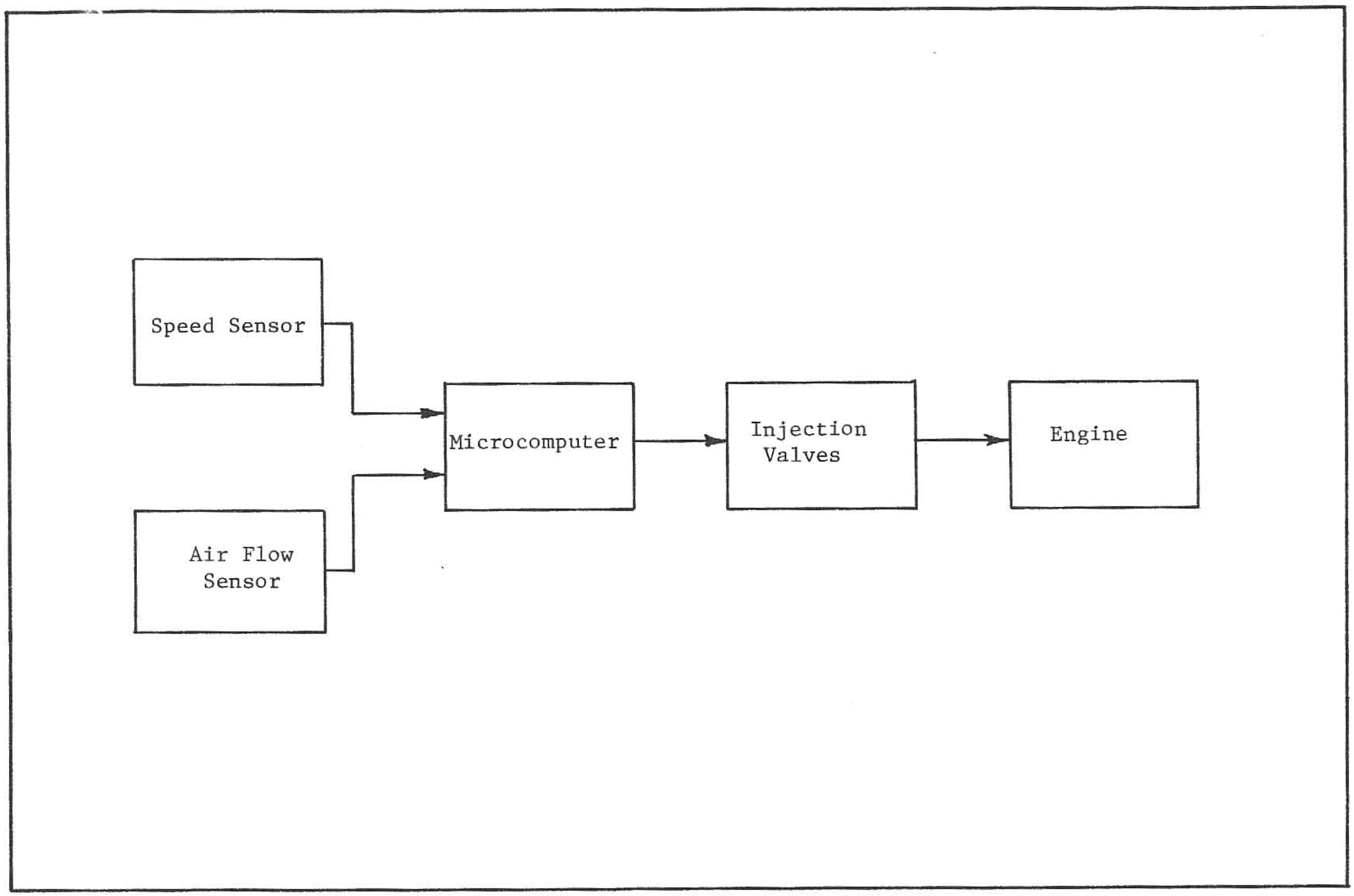

Figure 1. Air Fuel Ratio Control System

performance, the shortcoming of an open-loop system is that it corrects neither for initial inaccuracies nor for subsequent drift. One helpful property of open-loop control, however, is that it offers little or no stability or oscillation problems.

Open-loop control was chosen for this research due to the lack of an appropriate feedback element. A telephone conversation with Mr. J. G. Rivard of the Bendix Corporation revealed that the zirconium-dioxide oxygen sensors they are conducting research with are still in the testing stage. Therefore, it was impossible to obtain one of these devices for this research. A review of the equipment in the Mechanical Engineering department revealed no other devices suitable for use as an exhaust gas sensor.

2-4 Description of the Physical System

The 1968 Volkswagen engine used in this research was equipped with the Bosch D-Jetronic fuel injection system. This system is classed as a pulse-timed manifold injection system, whereby the gasoline is injected onto the heads of the intake valves by electromagnetically actuated nozzle valves. Because Bosch had discovered since this system was developed that measurement of the intake air flow was a better indication of load than absolute manifold pressure, an intake air flow sensor was installed in front of the throttle. The intake air system is shown in Figure 2.

The air flow sensor output was an analog voltage, therefore it had to be converted to a digital value to be used by the computer. For this purpose an analog-to-digital converter manufactured by Analog Devices, Inc., the ADC-10Z, was used. The ADC-10Z is a 10-bit successive approximation type converter. It is monotonic over its entire operating temperature range, and has a maximum relative accuracy error of $\pm \frac{1}{2}$ LSB. The A/D converter has a conversion time of 20 μsec. For this application the 0 to + 10 V input range was used.

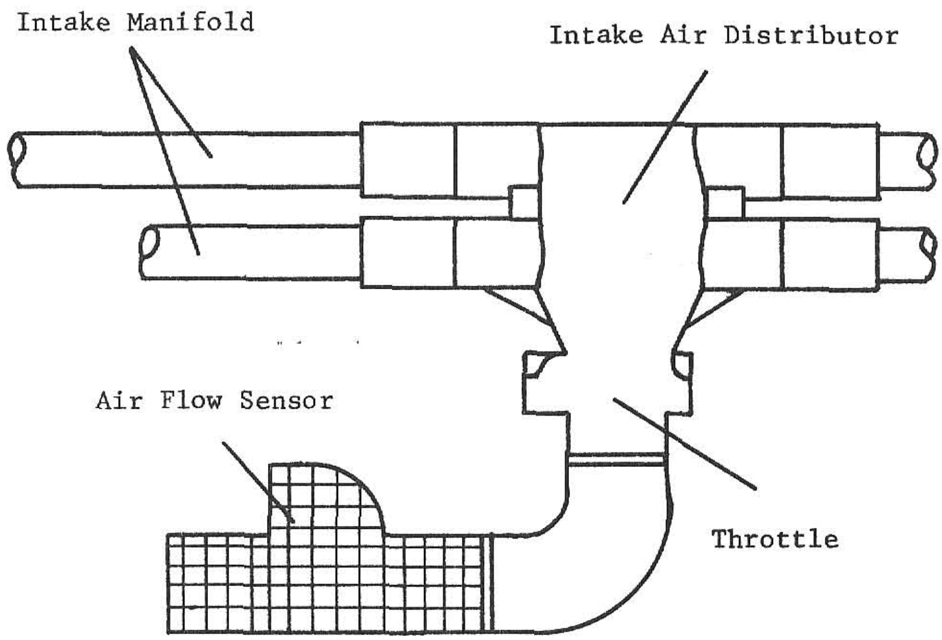

Figure 2. Air Intake System

Another of the important Bosch systems that was utilized was the primary fuel supply system, shown in Figure 3. This consisted of a filter, an electric fuel pump, and a "common rail" with branches leading to the injectors, terminating in the pressure regulator from which excess fuel is returned to the tank. 28 p.s.i. was chosen for the supply pressure by optimizing the desired degree of mixture control accuracy, including perpetual line purging to prevent vapor lock on one hand, and the cost of the primary supply system on the other. Electric power consumption at this pressure, approximately 25 watts for a medium-size engine, could be held within reasonable limits also.

The Bosch system uses four injectors mounted in the intake manifold. Each is actuated electromagnetically once in every working cycle and sprays fuel directly onto the cylinder intake valve. The injectors consist of a housing which is equipped with a connecting hose for the fuel supply at one end, as shown in Figure 4. At the other end an electromagnetically actuated plunger

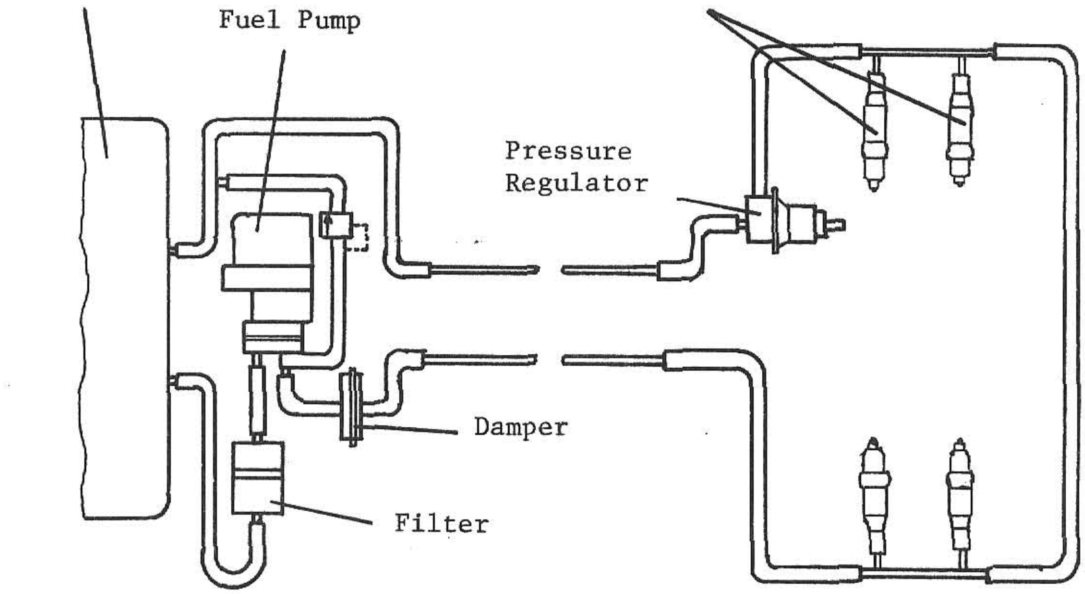

Figure 3. Primary Fuel Supply System

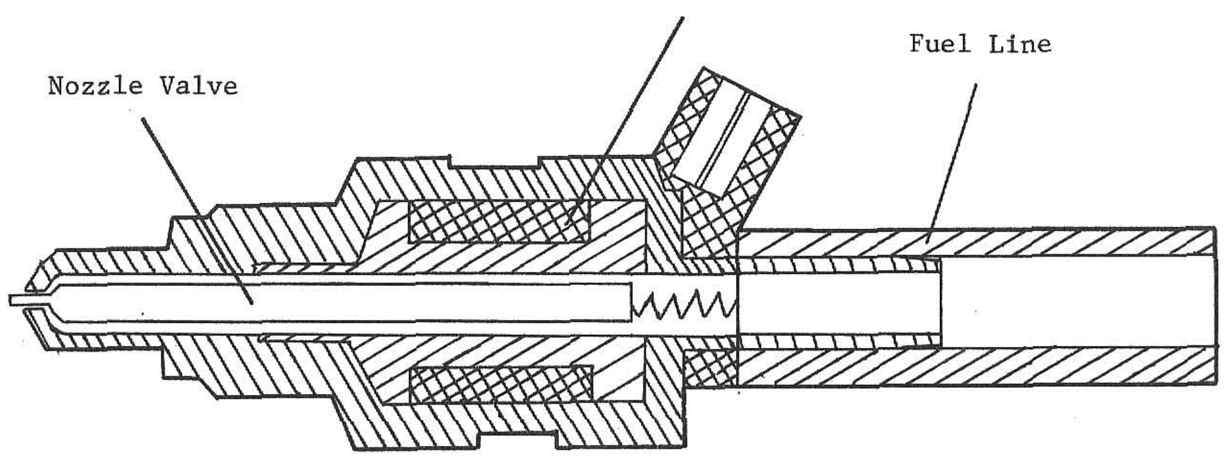

Figure 4. Electromagnetic Fuel Injector

is connected to a nozzle valve which controls fuel flow through the valve seat and valve pintle, atomizing the gasoline.

Electrical pulses transmitted by the microcomputer and amplified by power transistors build up a magnetic field in the injector winding. This attracts the plunger and lifts the nozzle valve from the seat, opening the way for the pressurized fuel. The stroke of the plunger is about 0.15 mm. and its response time is approximately 1 millisecond. Depending on the amount of fuel required, the opening period of the injectors may range from 2-10 milliseconds.

The distributor is equipped with the usual breaker points as well as with the standard centrifugal and vacuum advance. In addition, two nonadjustable trigger contacts spaced 180° apart are located in the lower part of the housing. A single-lobe cam on the distributor shaft alternately closes the trigger contacts, resulting in square-wave signals exactly synchronized with engine speed that are used to signal the start of injection. The signals are also used in conjunction with a counting network that measures the engine speed, as will be discussed in Chapter 3. Figure 5 illustrates the start of the injection pulses of the two pairs of injectors relative to intake valve and spark timing.

Since the fuel delivery was of critical importance, it was decided to utilize the components within the Bosch electronic control unit to amplify the low-power pulses from the microcomputer controller. The circuit, shown in Appendix D-1, uses low power control transistors Q_1 and Q_3 to amplify the TTL-level signal from the microcomputer. The outputs of these transistors are then further amplified by power transistors Q_2 and Q_4. This amplified current actuates the injector solenoids.

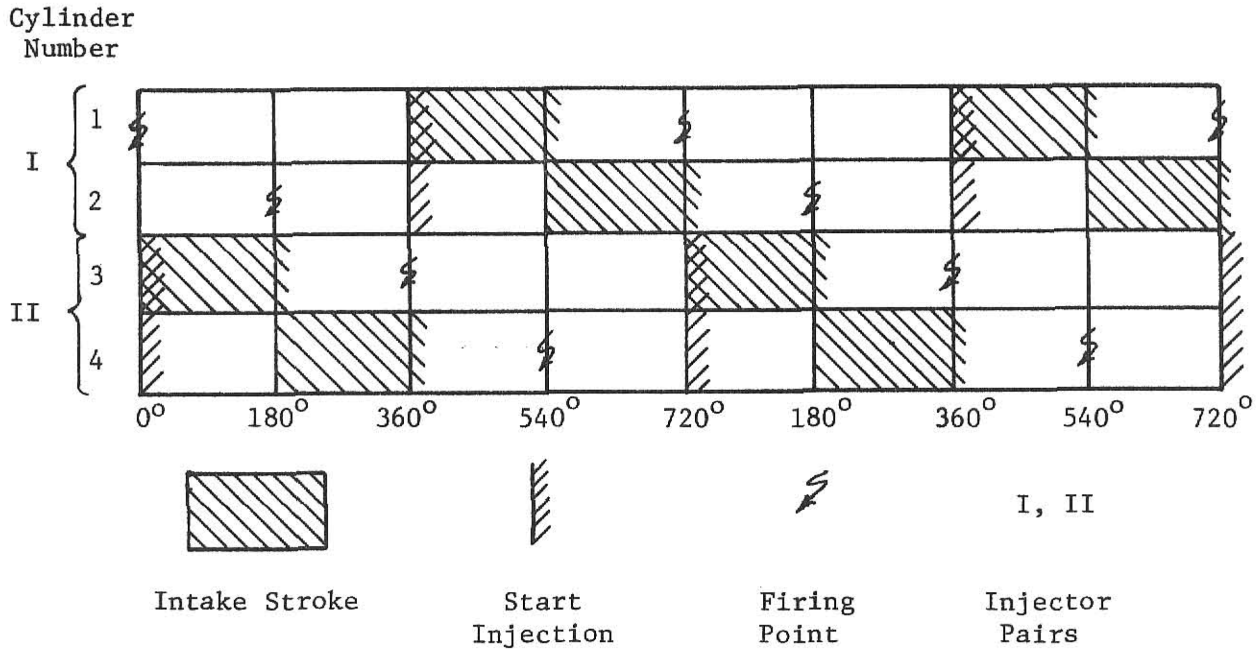

Figure 5. Commencement of Fuel Injection Versus Intake Valve Timing

The heart of the system is the KIM-1 microcomputer. To take full advantage of the microcomputer's capabilities, a design philosophy was developed which provided that the microcomputer be used for all possible decision-making and interpretive processes. When these tasks are delegated entirely to the computer, capital equipment cost is reduced. Also, the operational reliability of the microcomputer is greater than the reliability of separate hardware components. The only functions that were not handled by the computer were the actual measurement and manipulation of process variables.

Digital inputs representing air flow and engine speed were read by the microcomputer once each engine cycle. These inputs were first scaled by the computer by table look-up procedures described in Chapter 4. A third table look-up procedure was utilized which effectively used the scaled values for speed and air flow to derive the appropriate value for injection time. These procedures will be explained in full in Chapter 4.

2-5 Development of the Control Algorithm

In order to implement real-time control using the microcomputer, a control algorithm had to be derived so that engine operating conditions could be measured and combined to obtain a single control signal. The control variable for the pulsed electronic fuel injection system is the mass of fuel injected each cycle. Since the mass of fuel injected per cycle is a function of the time duration of injector opening, the control algorithm must therefore be a mathematical relation which can be processed by the microcomputer and which results in the time duration of injection.

The following relation was derived for the time duration of injection for a single engine cycle:

$$t = K_t \, K_{f/a} \, M_a \qquad (1)$$

$$Ma = \frac{m_a}{2N} \qquad (2)$$

where:

t = time injector is open in milliseconds (ms)

K_t = calibration constant to convert the mass of fuel injected (lb) per injection into time duration of injection (ms)

$K_{f/a}$ = fuel to air mass ratio constant

M_a = mass of air inducted per engine revolution into one cylinder of a four cylinder engine (lb)

m_a = mass air flow rate (lb/min)

N = engine rpm

Measurement of N required that the device used to sense engine speed be calibrated. The speed sensor itself is described in Chapter 3.

Calibration of the device follows the relation:

$$N = \frac{f\ (60)}{COUNT} \qquad (3)$$

where:

f = frequency of clock (cycles/sec)

COUNT = value of rpm sensor

This relation is shown graphically in Figure 6.

The evaluation of K_t required a calibration be made of the fuel injectors. This calibration is shown in Figure 7. The calibration was performed by measuring the mass of fuel consumed by the engine over a measured length of time. Each point on the graph of Figure 7 represents the average of three tests made at a certain speed and load. The points were entered into a least-squares regression routine and the resulting best fit relation is:

$$t = \frac{M_f + 0.6326}{1.0288} \qquad (4)$$

where:

M_f = Mass of fuel (lb) per injection

A third calibration was required for the air flow sensor. Data for this calibration was obtained by operating the engine at a set speed and load and recording the voltage from the air flow sensor's potentiometer. The pressure drop across a 1.59 in. (4.04 cm) ASME long radius flow nozzle was measured with a 10 in. (25.4 cm) water micro-manometer. The nozzle was placed in one end of a surge tank from which air was being drawn by the engine, Figure 8. The corresponding air mass flow rate was calculated using

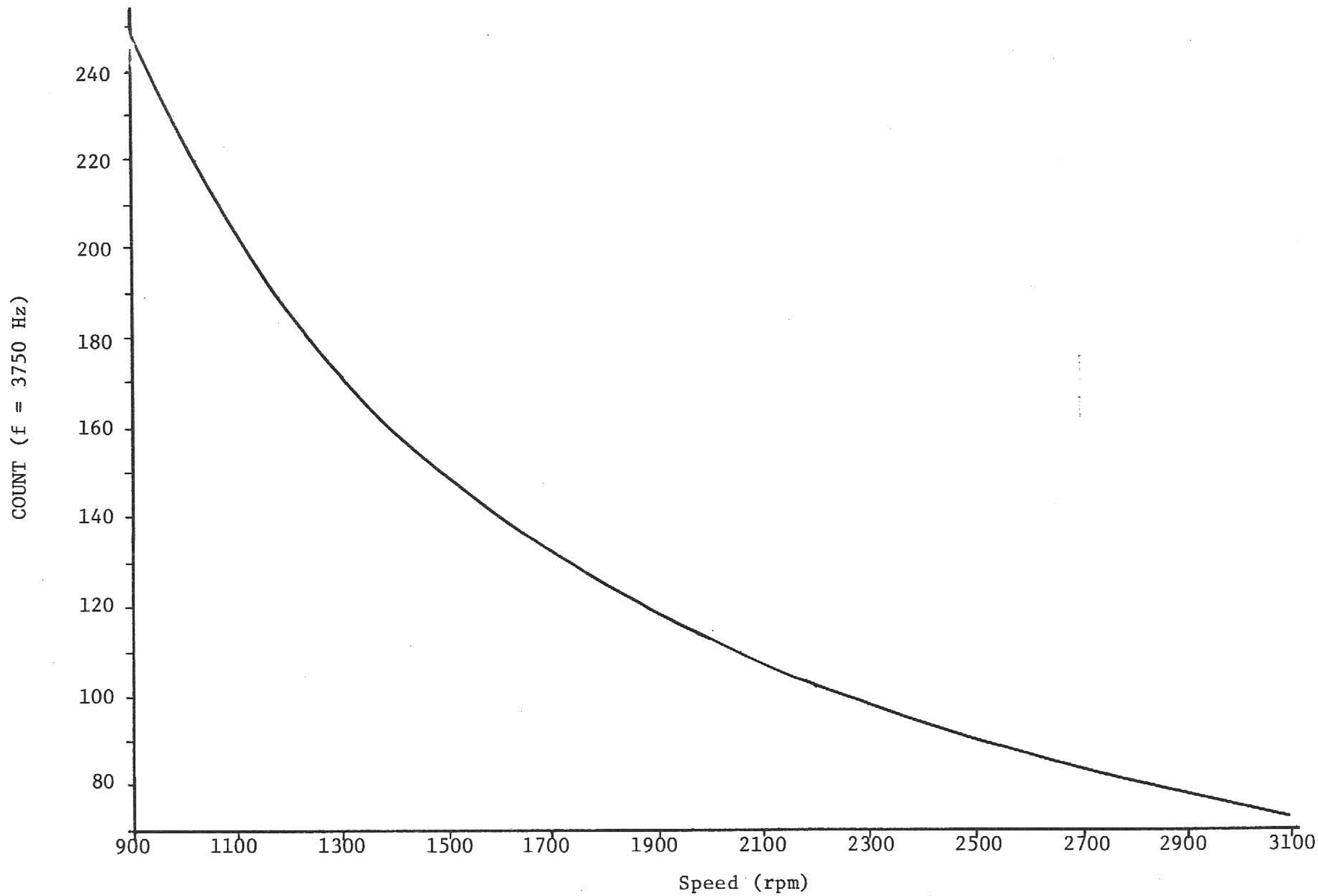

Figure 6. Speed Sensor Calibration

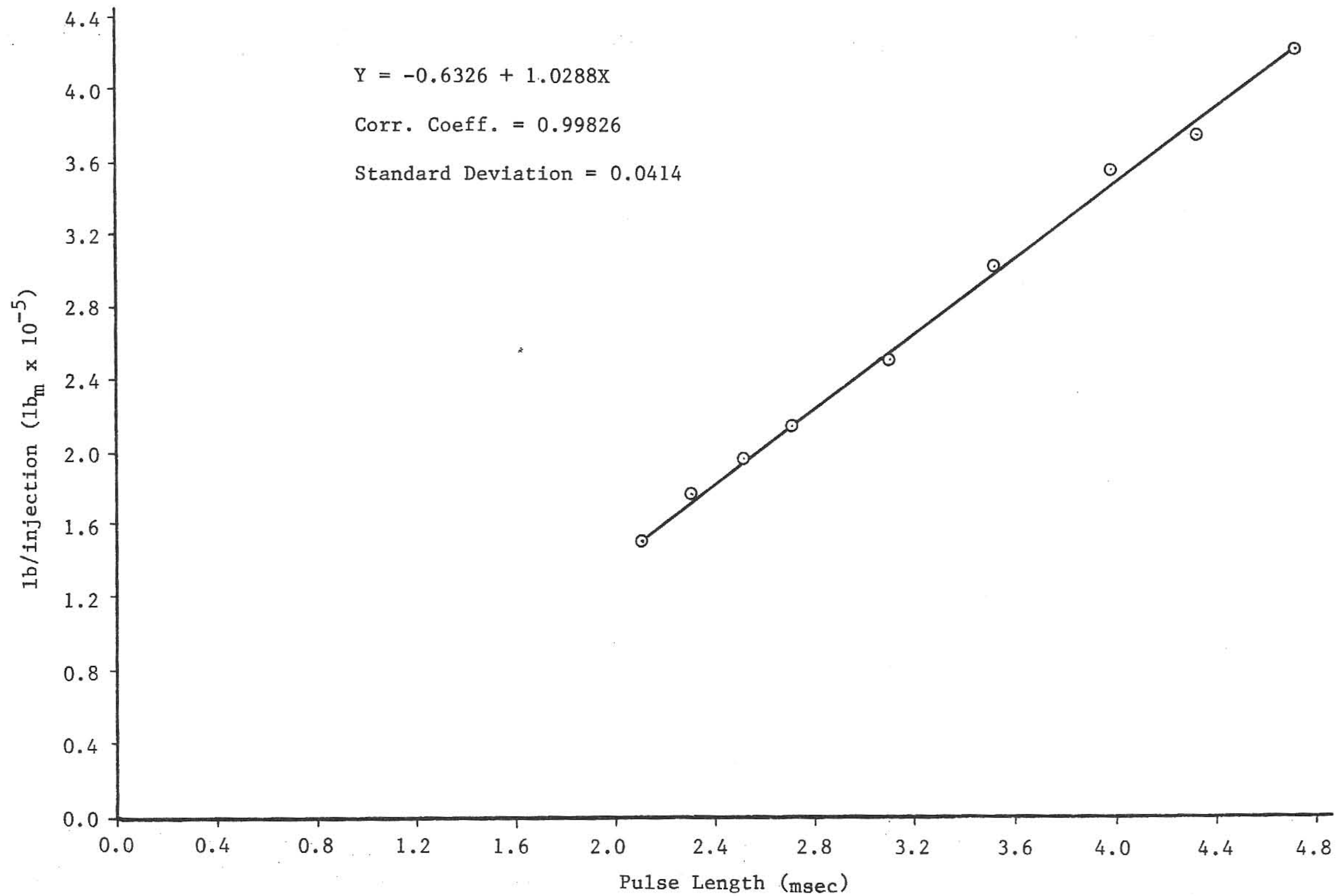

Figure 7. Fuel Injector Calibration

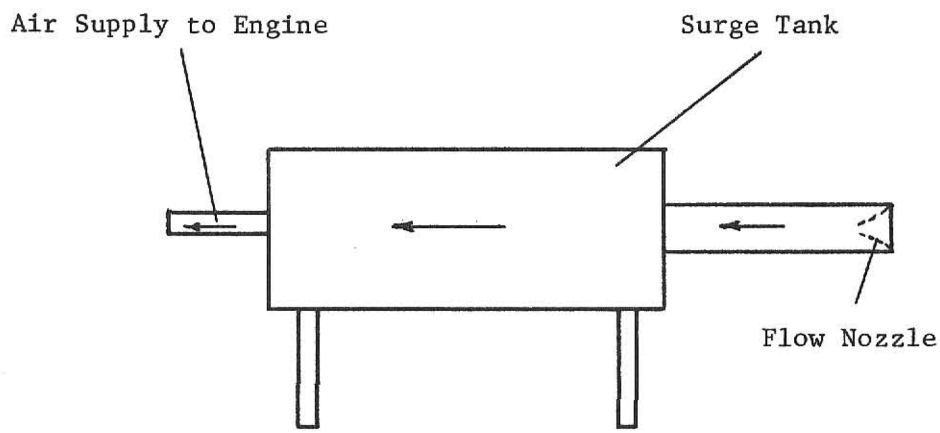

Figure 8. Preliminary Air Intake System

a series of equations which will be developed in Chapter 5. The engine operating conditions were then changed and new data was taken. An "eyeball" best fitted curve was drawn through the data points and this curve was used in further scaling. The resulting graph of air mass flow rate versus the air flow sensor voltage is shown in Figure 9.

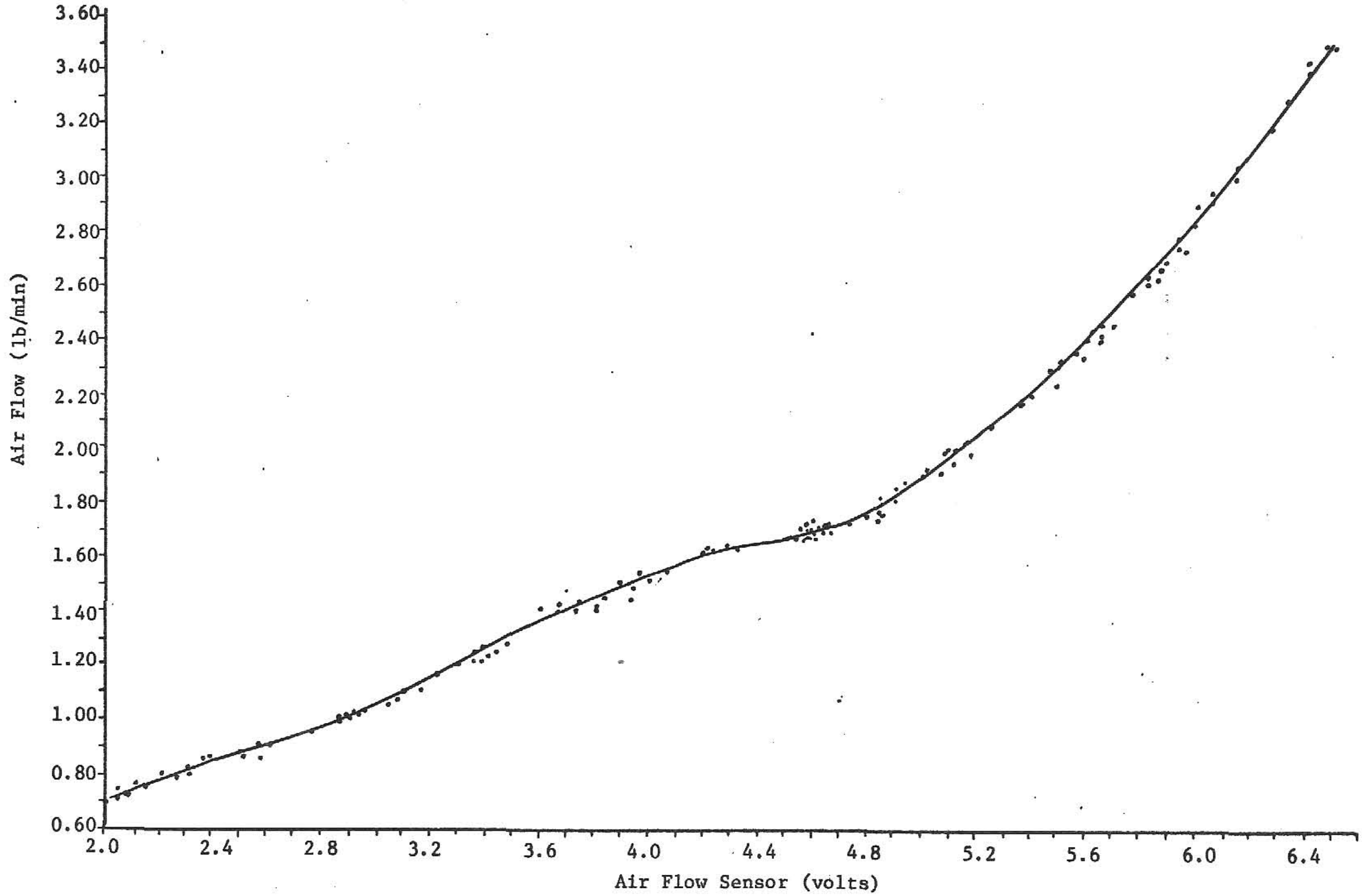

Figure 9. Air Flow Sensor Calibration

CHAPTER III

THE SPEED CONTROLLER

3-1 Introduction

The automatic microcomputer speed controller that was designed and implemented for this research was a feedback control system that had the ability to hold the engine speed *constant* for varying load conditions. To accomplish this objective, the system monitored engine speed and compared it to a set, desired speed. Any deviation in engine speed would cause an actuator to open or close the engine throttle as required to eliminate the speed error. The reference speed is set by the operator's instruction to the microcomputer to maintain the existing speed, increase the engine speed, or decrease the speed simply by changing the value stored in one memory location. In this speed control system, all logic was performed entirely within the microcomputer. A speed sensor was needed to get engine speed feedback into the system, while an actuator was needed to convert the microcomputer output signals into the mechanical actions necessary to actuate the throttle.

The second section of this chapter provides a review of the literature on the automotive speed controllers that were used as a basis for the design of the microcomputer system. Section three contains a discussion of the control concept used for the digital speed control employed in this research. The fourth section describes the physical systems involved in the controller, while the last section presents the control system analysis.

3-2 Literature Review-Automotive Speed Control

There were two main references that were used during the design of the microcomputer speed controller. R. Feit (15) developed a design for a digital speed controller including open-loop transfer functions and Nyquist and Bode frequency response plots. His design philosophy was summarized by four guidelines:

1. Use the computer for all decision-making and interpretive processes.
2. Select actuators and sensors that have characteristics suitable for time-shared operation with a digital computer.
3. Improve reliability at minimum cost by adding redundant units for the components, such as transducers and actuators, which may be the weak links in system reliability.
4. Examine the possible failure modes, the diagnostic techniques available to detect them, and the courses of action to take for each failure.

It is important to note that the logic to implement any of these actions should be totally delegated to the digital computer.

For this speed controller comparators in the computer accepted digital inputs proportional to the reference and actual engine speed. These values were then used in a proportional-integral-derivative type transfer function to obtain the desired output value to be sent to actuate the stepping motor.

The second major electronic speed controller was one developed by the Philco-Ford Corporation (16). This system utilized electronic circuits to perform the necessary logic and memory functions. A frequency to voltage converter accepted the variable frequency input signal from the speed sensor and converted it to a linearly varying analog voltage proportional to the vehicle speed. The memory capability was provided for by storing the analog speed voltage in a capacitor.

A servo amplifier accepted the error signal from the comparator and amplified it to drive the solenoid valves in an electropneumatic servo unit. System stability and linearity were improved through negative feedback from a position sensor. The position sensor feedback to the servo amplifier was a voltage proportional to the throttle opening. Therefore, the servo amplifier, combined with the servo unit and feedback sensor, comprised a linear throttle position controller with negative feedback.

3-3 The Control Concept

The control concept utilized for the microcomputer speed controller was that of the closed-loop, feedback type control, as described in the introduction. Important properties of closed-loop systems as compared to open-loop systems are :

1. Increased accuracy in obtaining desired values of the output variable.
2. Reduced sensitivity to internal and external disturbances.
3. Potential for instability and oscillation.

A closed-loop, or error correcting, system uses a pre-selected reference input parameter, in this case the desired speed. The logic, or microcomputer, receives information from the controlled engine setting also. It compares the input signals and keeps correcting the throttle setting until the difference between the actual and the selected reference settings disappears.

Closed-loop control systems have several inherent advantages over open-loop control. One advantage of the closed-loop control system is that the use of feedback makes the system response relatively insensitive to external disturbances and internal variations in system parameters. Therefore, it is possible to use relatively inaccurate and inexpensive components to obtain the accurate control of a given system. Moreover, closed-loop controls can be used to compensate for nonlinearities in the system, although this can make the control design particularly complicated. In addition, a closed-loop system allows retention of system calibration over extended periods of time.

The closed-loop control approach always has the potential of instability and oscillation, however. This stems from the fact that a closed-loop system may tend to overcorrect errors which may cause oscillations of constant or changing amplitude.

3-4 Description of the Physical System

The two primary components of the speed control system, the engine and the microcomputer, have already been described and will not be discussed further in this chapter. However, two other components which are of great importance to the system have not been discussed yet and these will be presented now. These devices are the measuring instrument utilized for the control, the speed sensor, and the actuating device, the stepping motor.

In a closed-loop system the accuracy depends almost entirely on the feedback element; therefore the speed sensor is a very important element. In addition to the requirement that the speed sensor be accurate two further requirements were added. These were that the sensor have characteristics that would make it suitable for use with a digital computer and that it be easily implemented into the original physical system. To meet these requirements a counting circuit was built using TTL integrated circuits, as shown in Figure 10. The distributor signal, a square wave, was readily available so the only signal external from the original physical system that was needed was the clock. During this research the clock signal was provided by using a function generator which delivered 0 to 5 volt pulses at a set frequency.

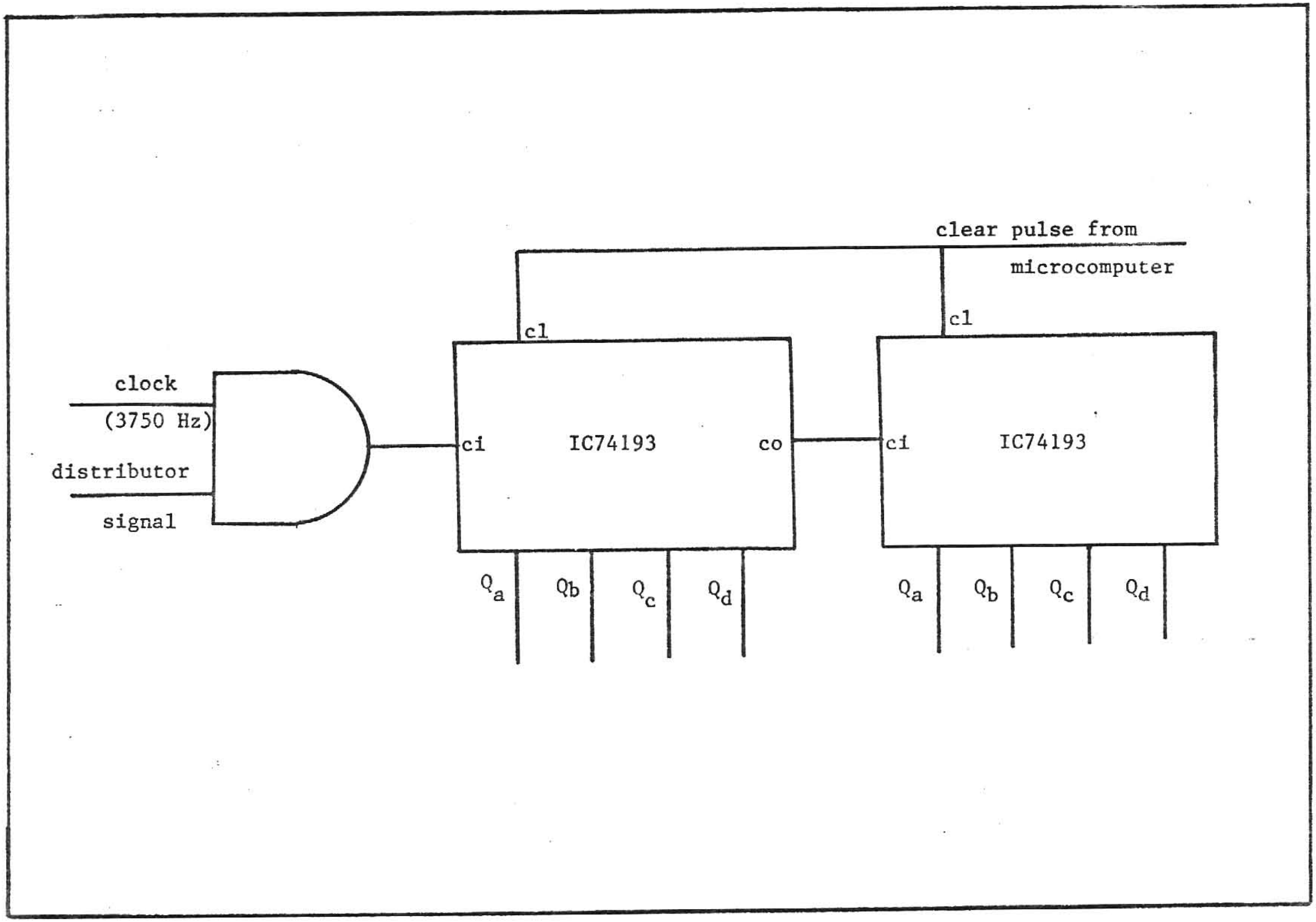

Figure 10. Speed Sensor

The sensor operated by allowing clock pulses to pass through the counting network while the distributor pulse was at its high level. The counting network was built using two 4-bit up-down binary counters. When the distributor pulse returned to its low level the "and" gate in the 7408 chip kept pulses from entering the counting circuit and the result was an 8-bit value which, when calibrated, accurately represented the engine speed. As soon as this value was read by the computer, the computer would generate a pulse which cleared the counters and the cycle was complete.

The stepping motor is nearly an ideal actuator for use in an incremental control system such as this one. The stepping motor used was a 120 volt, 1 amp, 60 Hz motor which had been modified to operate at a lower voltage. The motor required 200 steps per revolution but already had an integral gear train added which increased this to 866.6$\underline{6}$ steps per revolution. Later examination of the operating range of the engine throttle revealed that further gear reduction was needed, so an external gear train was provided which resulted in the requirement of 6240 steps per revolution of the throttle shaft.

The inputs required to drive the stepping motor were two square wave signals with the correct frequency and phase relationships to control the direction and stepping rate of the stepping motor. These relationships are depicted in Figure 11. To actuate the stepping motor one signal must lead the other by a phase of 90°. In this case the motor would be increasing the throttle opening. Conversely, if the phase relationship is reversed so that the first signal lags the other by a phase of 90° the motor would be decreasing the throttle opening. The signals were generated by a program within the computer which will be discussed in the next chapter.

Two identical power amplifiers were needed to amplify the square wave inputs so they could be capable of providing the current necessary to drive

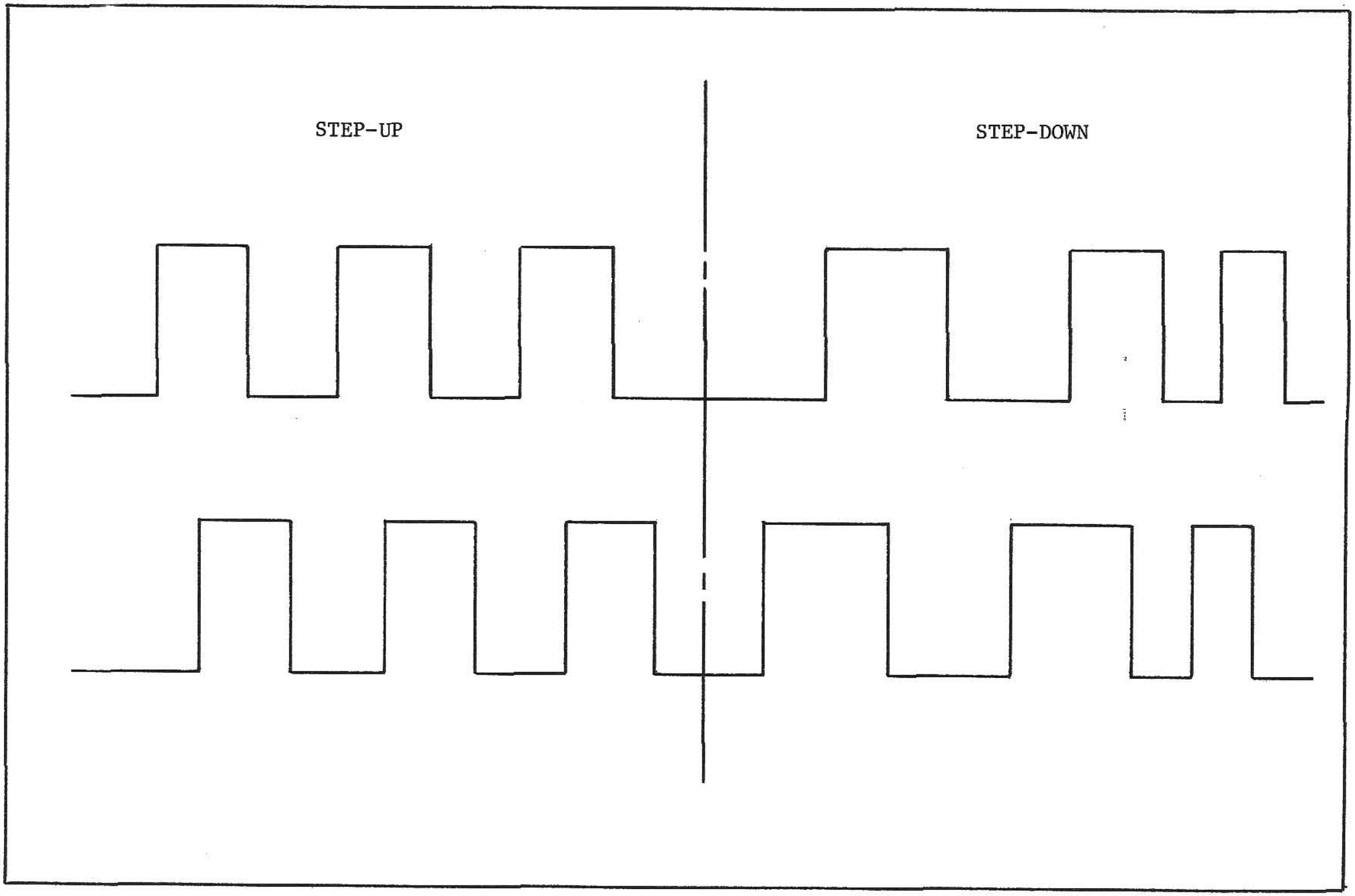

Figure 11. Stepping Motor Input Signals

the stepping motor. A circuit developed by Chande (17) for this purpose in earlier research was utilized here. The detailed circuit diagram of this subsystem may be found in the appendix, Figure D-2. The first component in each power amplifier is a pair of μA-741 operational amplifiers. The first operational amplifier has a bias voltage applied to center the 0 to 5 volt input signals. The second amplifies the ± 2.5 volt signal to a ± 15 volt square wave.

The second component consists of a μA-741 control amplifier driving a pair of complementary push-pull transistor stages connected in a Darlington configuration. The transistors are a complementary pair to provide equivalent operating characteristics for positive and negative inputs and a smooth transition at crossover. The power supplied to both the control amplifier and the transistors was ± 15 volts. The control amplifier provides stability and a quick, smooth response while the transistors provide current amplification.

An electrically controlled clutch was attached to the output shaft of the stepping motor's external gear train. The output shaft of the clutch actuated the throttle linkage. The clutch provided a quick and foolproof method of disengaging the stepping motor system in case of complications.

3-5 Control System Analysis

The block diagram for the microcomputer speed control system is shown in Figure 12. The controller is classed as a discrete-time system, that is, it is a dynamic system in which the speed variable is measured only at discrete instances of time. Discrete-time systems differ from continuous-time ones in that the signals for a discrete-time system are in sampled-data form.

Perhaps the most difficult task in solving this control problem was the development of a mathematical model of the physical system to be controlled. Such a model was required in order to apply the tools of control systems

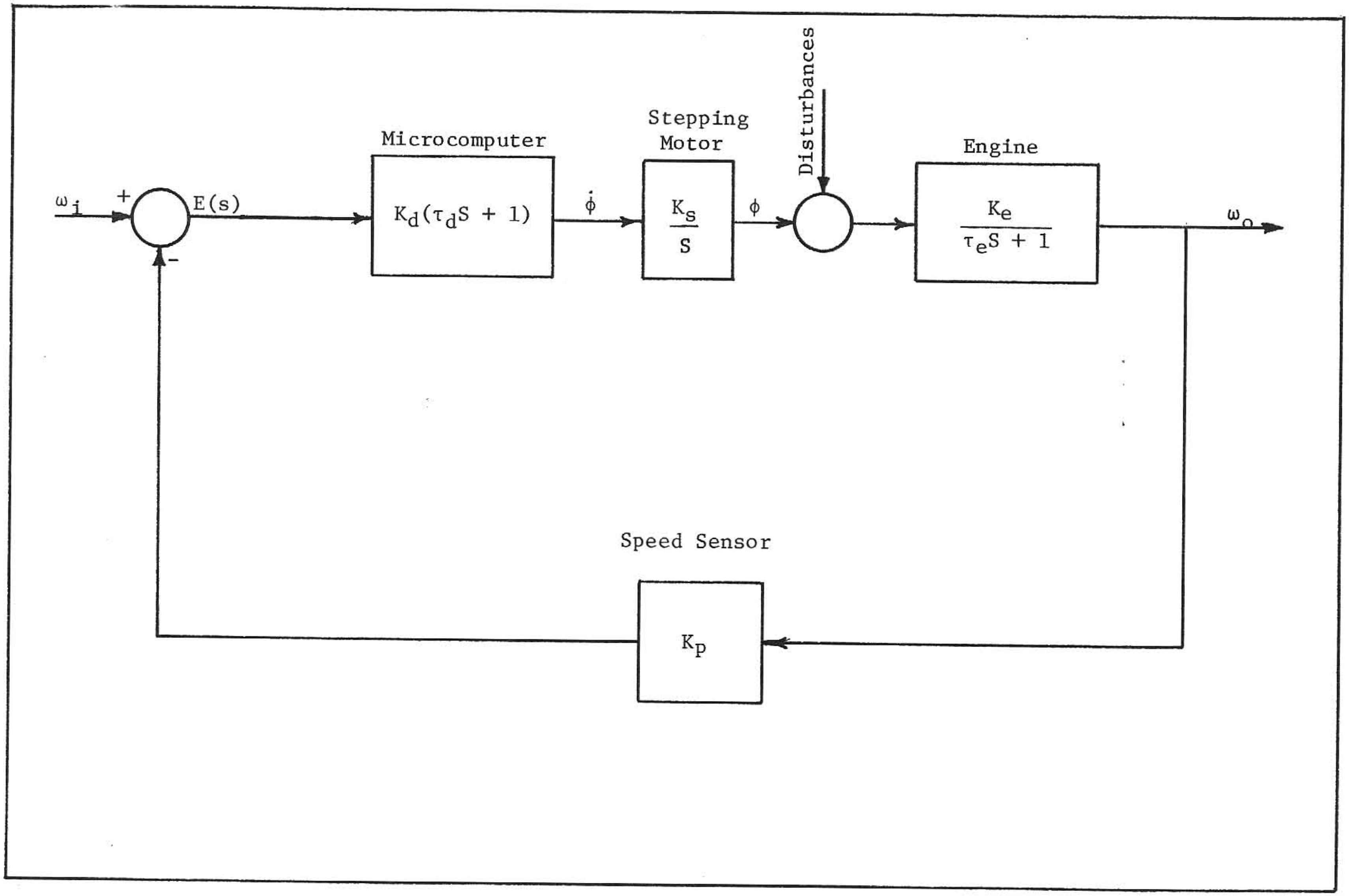

Figure 12. Speed Control System

analysis. To build a model for systems as complex as the internal combustion engine based on equations of motion, thermodynamics, and fluid mechanics would be extremely difficult. Fortunately, in a review of the literature a mathematical model for an engine was provided in the form of a transfer function in the work by Feit, described earlier.

The engine's time constant was one parameter of this function that had to be given a value. The time constant, τ_e, is defined as the time for the engine speed to obtain 63% of the difference between its initial and final values and is a measure of the speed of response of the system. This definition is strictly accurate only in the case of a system described by a first-order time invariant differential equation. For the engine speed controller, the time constant is physically related to a great extent to the response of the actuator. During experimental observation of the engine tests the time constant, τ_e, was determined to be 3 seconds.

To determine the engine gain, K_e, a rotary potentiometer was connected to the throttle shaft to help calculate the angular displacement of the throttle over the range in which the engine was to be operated, 1000 to 3000 rpm. This span was found to be rather small, only 18.18^o. As a result, the engine gain was calculated to be 2000 rpm/18.18^o = 110.01 rpm per degree.

The number of pulses for one revolution of the stepping motor, including the internal gear train, is (200)($4.33\underline{3}$) or $866.\underline{6}$ steps per revolution. The addition of the external gear system resulted in a total of 6240 pulses per revolution. Therefore, the gain of the stepping motor, K_s, was $360^o/6240$ = 0.0577 degrees per step.

The gain of the speed sensor is determined by dividing the change in its output value by the change in its input value, the engine speed. For this system, while the engine varies from 1000 to 3000 rpm the sensor value varies nonlinearly from 75 to 225. This nonlinear relationship is then scaled to produce a linear function of speed sensor output value to engine speed, resulting in a sensor gain of 0.1.

After examining the transfer functions representing the stepping motor and engine a control relation was needed for the microcomputer controller that would result in a stable system. To fill this need a proportional-plus-derivative control action was chosen. The proportional aspect of the control is essentially an amplifier with an adjustable gain. The derivative control action, or rate control, is where the magnitude of the controller output is proportional to the rate of change of the actuating error signal. The derivative time, τ_d, is the time interval by which the rate action advances the effect of the proportional control action. The addition of derivative control action has the advantage of being anticipatory; however, it has the disadvantages that it amplifies noise signals and may cause a saturation effect in the actuator.

For the proportional-plus-derivative control the transfer function is $K_d\ (1 + \tau_d s)$, where K_d represents the proportional sensitivity and τ_d represents the derivative time. This transfer function transforms to the equation:

$$m(t) = K_d\ e(t) + K_d \tau_d \frac{de(t)}{dt} \quad (5)$$

$$= K_d \left[e(t) + \tau_d \frac{de(t)}{dt} \right] \quad (6)$$

In discrete difference equation form this expression becomes:

$$m(t) = K_d\ (\varepsilon + \frac{\tau_d}{\Delta t} \Delta\varepsilon) \quad (7)$$

where Δt represents the sampling interval of the controller. This value was chosen to be 0.5 seconds, therefore K_d and τ_d remained as adjustable parameters.

A Nyquist frequency response approach was used to determine optimal values for these variables, resulting in K_d = 4.46 and τ_d = 0.50. These parameters result in a phase margin of 45^o, as shown in Figure 13. This design should result in a maximum percent overshoot of 28%, and a peak time of 4.5 seconds.

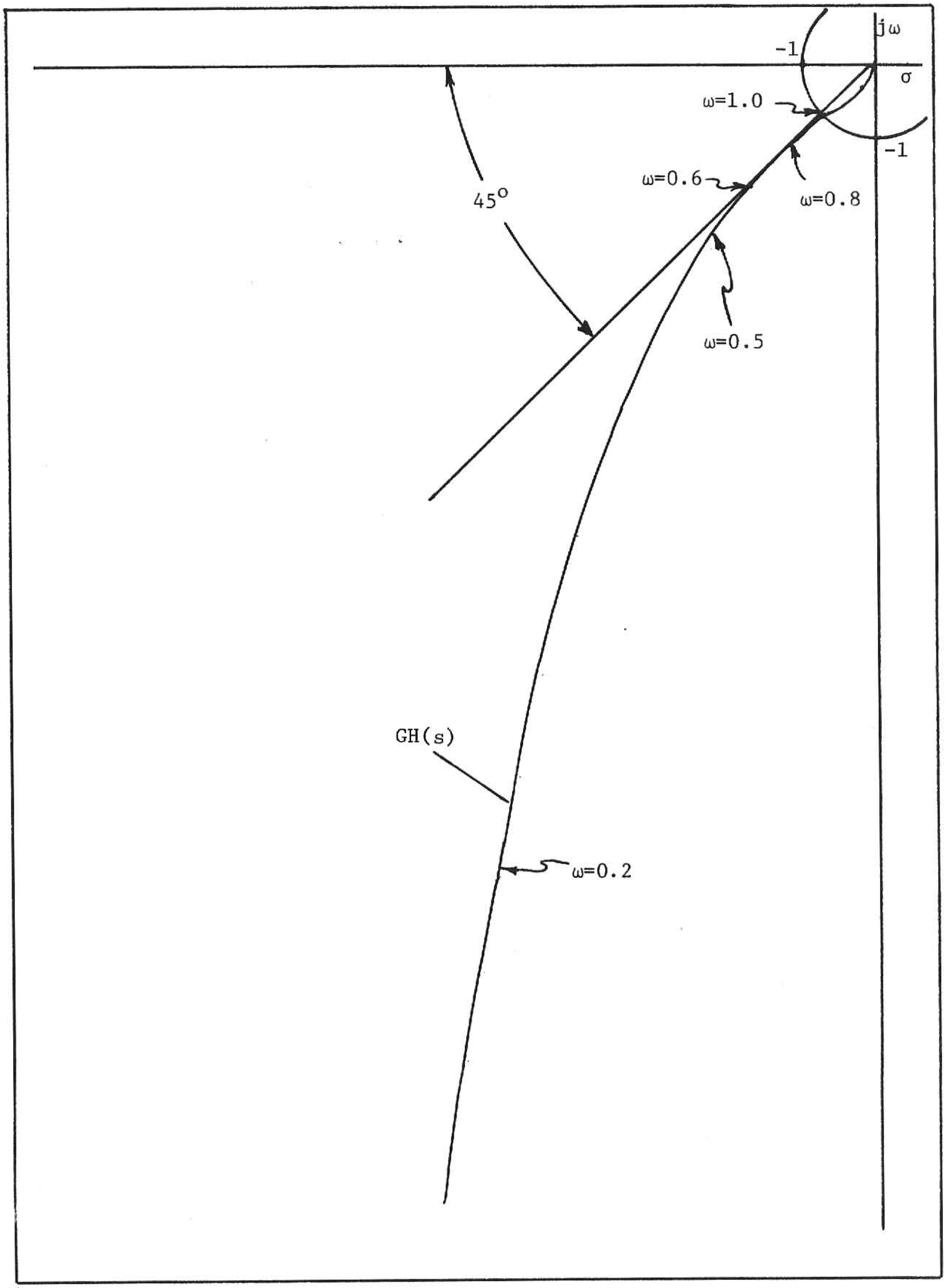

Figure 13. Speed Control Nyquist Plot

CHAPTER IV

THE SOFTWARE

4-1 Introduction

The tremendous appeal involved in the use of microcomputers in control system applications, as was mentioned in the first chapter, is the versatility afforded by its programmability. For this reason the software developed for this research may very well be the most important aspect of this work. In order that the amount of hardware used be as little as possible, the computer was used for all decision-making and interpretive processes.

At this time some of the programming nomenclature should be explained. "Bit" refers to a single binary digit. An 8-bit combination of data is referred to by the term "byte". In a large computer which operates simultaneously on multiple bytes of data, the number of bytes which is transferred and operated on by the machine in parallel is called a "word". Because this microprocessor is an 8-bit microprocessor, the words and bytes are of equal length. Therefore, in the text of this thesis "byte" and "word" will be used synonymously.

The programming of the microcomputer was all done in hexadecimal machine code. This was accomplished with two different devices. One was a Teletype Model 33 teletypewriter which also enabled hard copy memory to be kept in the form of punched paper tape. The second was a keyboard and display, mounted on the KIM-1 microcomputer board, which proved to be very helpful while operating the computer in the lab alongside the engine. A second feature of the KIM-1 microcomputer was an audio-cassette interface for cassette memory.

This also was quite helpful in the operation of the computer while conducting tests in the laboratory.

The next section of this chapter will explain the initialization sequence that was executed at the beginning of every set of tests. The third section of the chapter provides the program which determines the injection value. Sections four and five describe the programs for the two types of interrupts available with the KIM-1. Section six provides the routine which generated the signals to drive the stepping motor. The final two sections of the chapter describe the multiplication and division routines utilized for this research.

4-2 The Initialization Sequence

Every time the microcomputer is reset an initialization program must be executed to define certain vectors which are critical to its operation. A flowchart of the program that was written to fulfill this need is shown in Figure 14. The actual program is listed in Appendix E along with the rest of the software used in this research.

The first operation to be executed is to initialize the stack, so that the microprocessor may be ready for any interrupt or non-maskable interrupt operation which might occur during the rest of the start-up sequence. The stack is a push-down stack implemented by a processor register called the stack pointer. In this program the stack pointer is initialized to location 01FF. Thereafter the stack is controlled by the microprocessor which loads data into memory based on an address constructed by adding the contents of the stack pointer to a fixed address, Hexadecimal address 0100. Every time the microprocessor loads data into memory using the stack pointer, it automatically decrements the stack pointer, thereby leaving the stack pointer pointing at the next open memory byte. Conversely, every time the microprocessor accesses

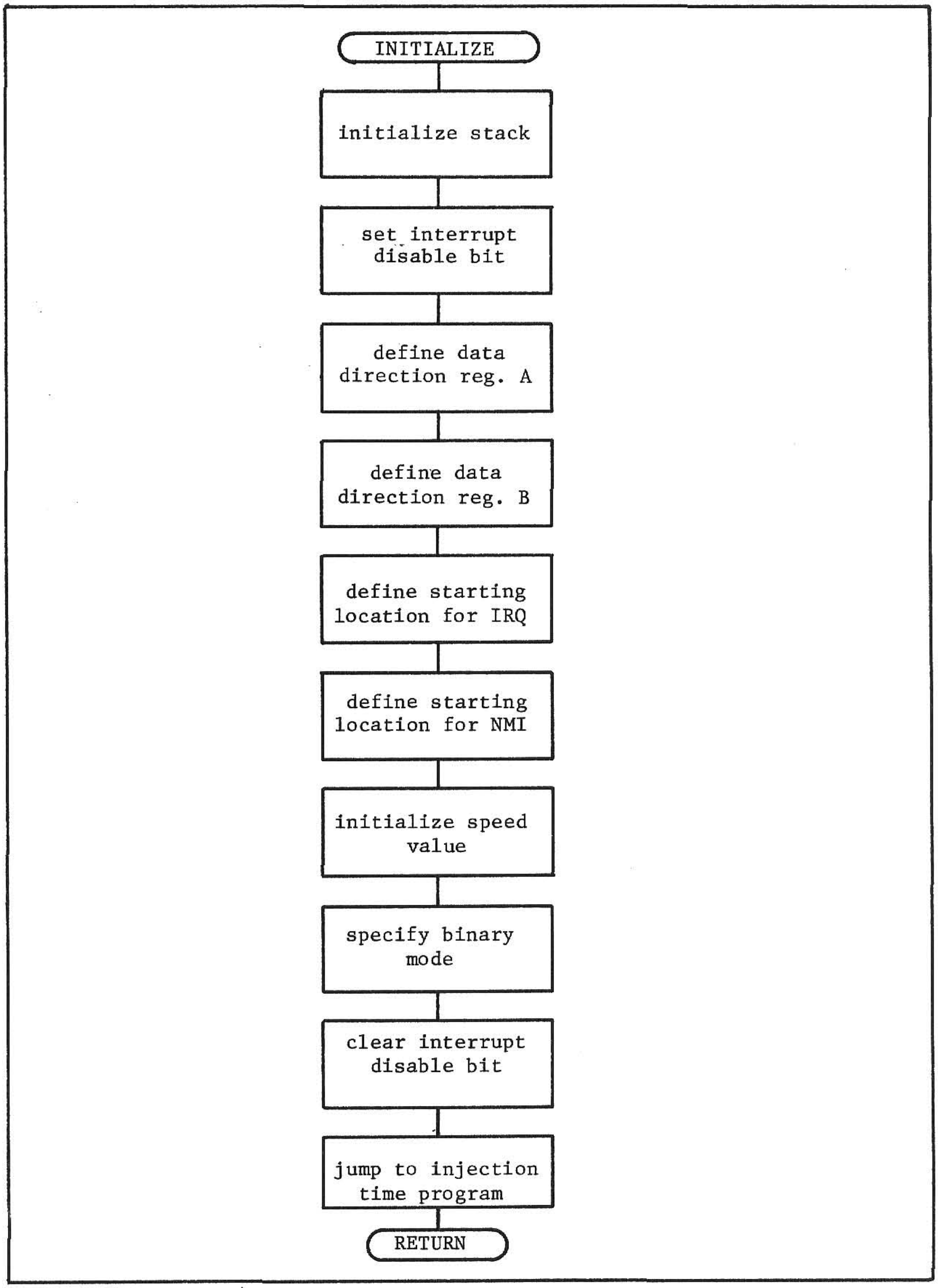

Figure 14. Initialization Program

data from the stack it adds 1 to the current value of the stack pointer and reads the memory location by putting out the address 0100 plus the stack pointer. By using a stack the microprocessor can store interim data without the programmer having to worry about the actual memory location in which data will be directly stored.

The second instruction to be executed in the initialization routine was to set the interrupt disable bit in the status register. This was done simply to keep interrupt request signals from affecting the microprocessor until the initialization sequence was completed.

The next two steps of this program define the status of the input-output ports. The KIM-1 microcomputer has 15 I/O ports available for application usage and these are in turn broken down into data registers A and B, with 8 and 7 I/O ports, respectively. Each port must be defined as either an input, designated by its data direction bit being "0", or an output, designated by its data direction bit being a "1". Thus, the status of each port of each data register is defined by the value stored in its respective data direction register.

The next two operations define the starting vectors for interrupt request signals and non-maskable interrupt signals. Although these two types of interrupts will be discussed more fully later in this chapter it must be stated at this time that when either type of interrupt signal is received, the microprocessor branches to an interrupt routine. The microprocessor must know where to find the corresponding interrupt routine. This requirement is filled by specifying addresses which correspond to the beginning locations of the interrupt routines.

The next operation initializes a value into a register in the speed controller program to insure that the program functions properly the first time. The next operation initialized the decimal mode bit in the status register to the cleared state which stipulates to the arithmetic unit to perform binary as opposed to decimal adds and subtracts. The last operation clears the interrupt disable flag that was set earlier. Once this program has been executed the computer would normally jump to the injection time routine, to be described next.

4-3 The Injection Time Program

At the outset of this research one of the objectives that was chosen was to develop an air-fuel ratio controller. At that time an algorithm was developed, as explained in Chapter 2, that computed the injection time needed by the fuel injection system to maintain a desired air-fuel ratio given the measured inputs of engine speed and mass air flow inducted into the cylinders. After examining the calibration curves involved along with the algorithm being used, a decision was made to use a table look-up method to determine the correct injection time rather than determine it using a mathematical model within the computer. The microcomputer had addition and subtraction instructions provided in the microprocessor, however multiplication and division routines were not available. These functions could be attained through the use of the addition and subtraction instructions but they would have to be developed specially for this task and would be comparatively slow, also. On the other hand, the table look-up method would be extremely fast, an important consideration when the cycle time of the engine is measured in milliseconds. The major disadvantage of this method is that it requires a considerable amount of memory. This was available, however, so the table look-up method was chosen. The flowchart is given in Figure 15.

This method operates on the basis that the values read by the air flow sensor and speed sensor should be combined in such a manner that they

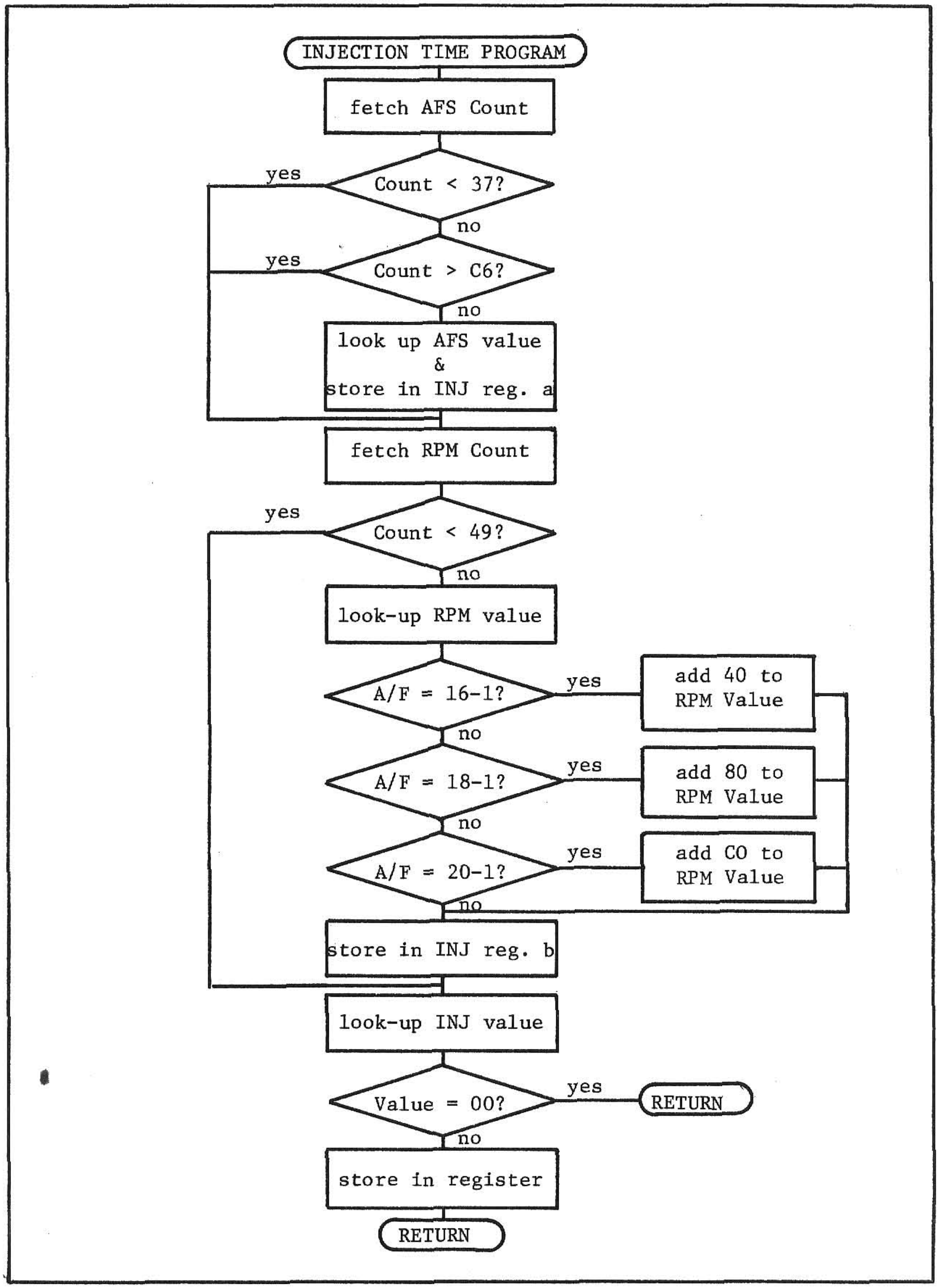

Figure 15. Injection Time Program

define an address that contains an injection time corresponding to those inputs. However, before this objective could be met, the inputs had to be scaled. During this process the ranges of the respective input values were examined and broken down into discrete increments. The number of increments was limited by the amount of available memory, in this case about 8 K of memory.

The air flow sensor scaling shall be explained first. During initial calibration and testing the range of digital values given as output by the sensor varied from HEX 37 to HEX C6. It was decided to break this range down into 30 discrete values, therefore the computer would only be able to distinguish 30 different values of air flow. Each value corresponded to a "page" (256 bytes) of memory which contained values of injection time corresponding to that value of air flow and the range of values for speed. This scaling is listed in full in Table 1.

The speed scaling was done in much the same way. During initial testing the range of digital values for the operating range to be used during this thesis was from HEX 49 to HEX FA. This range was in turn broken into 64 discrete values, enabling the computer to distinguish between 64 different values of speed for the air-fuel ratio control. Each value corresponded to a "word" of memory which, when combined with the "page" determined by the earlier scaling, resulted in a specific injection time corresponding to that combination of speed and air flow. This scaling is shown in Table 2.

To this point 30 pages of memory are designated to be used in the look-up program and 64 words are used of each page. Since there are 256 words per page only one-fourth of each page is being utilized. However, these values correspond to only one specific air-fuel ratio. By programming the computer to operate the engine at four possible air-fuel ratios the entire 30 pages of

TABLE 1. INJECTION TIME AIR FLOW SENSOR SCALING

AFS COUNT	AFS VALUE								
37	21	54	24	71	29	8E	2C	AB	33
38	21	55	25	72	29	8F	2C	AC	33
39	21	56	25	73	29	90	2C	AD	34
3A	22	57	25	74	29	91	2D	AE	34
3B	22	58	25	75	2A	92	2D	AF	34
3C	22	59	25	76	2A	93	2D	B0	35
3D	22	5A	25	77	2A	94	2D	B1	35
3E	22	5B	25	78	2A	95	2D	B2	35
3F	22	5C	25	79	2A	96	2D	B3	36
40	22	5D	26	7A	2A	97	2E	B4	36
41	22	5E	26	7B	2A	98	2E	B5	37
42	23	5F	26	7C	2A	99	2E	B6	37
43	23	60	26	7D	2A	9A	2E	B7	38
44	23	61	26	7E	2B	9B	2E	B8	38
45	23	62	26	7F	2B	9C	2F	B9	39
46	23	63	27	80	2B	9D	2F	BA	39
47	23	64	27	81	2B	9E	2F	BB	39
48	23	65	27	82	2B	9F	2F	BC	3A
49	23	66	27	83	2B	A0	30	BD	3A
4A	23	67	27	84	2B	A1	30	BE	3B
4B	23	68	27	85	2B	A2	30	BF	3B
4C	24	69	28	86	2B	A3	30	C0	3B
4D	24	6A	28	87	2B	A4	31	C1	3C
4E	24	6B	28	88	2C	A5	31	C2	3C
4F	24	6C	28	89	2C	A6	31	C3	3D
50	24	6D	28	8A	2C	A7	32	C4	3D
51	24	6E	29	8B	2C	A8	32	C5	3E
52	24	6F	29	8C	2C	A9	32	C6	3E
53	24	70	29	8D	2C	AA	33		

TABLE 2. INJECTION TIME SPEED SENSOR SCALING

RPM COUNT	RPM VALUE										
FA	00	DC	04	BE	08	A0	0F	82	18	64	27
F9	00	DB	04	BD	08	9F	0F	81	19	63	28
F8	00	DA	04	BC	09	9E	0F	80	19	62	28
F7	00	D9	04	BB	09	9D	10	7F	19	61	29
F6	00	D8	04	BA	09	9C	10	7E	1A	60	2A
F5	01	D7	04	B9	09	9B	10	7D	1A	5F	2B
F4	01	D6	04	B8	09	9A	10	7C	1B	5E	2C
F3	01	D5	05	B7	0A	99	11	7B	1B	5D	2C
F2	01	D4	05	B6	0A	98	11	7A	1C	5C	2D
F1	01	D3	05	B5	0A	97	11	79	1C	5B	2E
F0	01	D2	05	B4	0A	96	12	78	1D	5A	2F
EF	01	D1	05	B3	0A	95	12	77	1D	59	2F
EE	01	D0	05	B2	0B	94	12	76	1D	58	30
ED	01	CF	05	B1	0B	93	12	75	1E	37	31
EC	02	CE	06	B0	0B	92	13	74	1E	56	32
EB	02	CD	06	AF	0B	91	13	73	1F	55	33
EA	02	CC	06	AE	0B	90	13	72	1F	54	34
E9	02	CB	06	AD	0C	8F	14	71	20	53	35
E8	02	CA	06	AC	0C	8E	14	70	20	52	36
E7	02	C9	06	AB	0C	8D	14	6F	21	51	37
E6	02	C8	07	AA	0C	8C	15	6E	22	50	38
E5	02	C7	07	A9	0D	8B	15	6D	22	4F	39
E4	03	C6	07	A8	0D	8A	15	6C	23	4E	3A
E3	03	C5	07	A7	0D	89	16	6B	23	4D	3B
E2	03	C4	07	A6	0D	88	16	6A	24	4C	3C
E1	03	C3	07	A5	0E	87	16	69	24	4B	3D
E0	03	C2	08	A4	0E	86	17	68	25	4A	3E
DF	03	C1	08	A3	0E	85	17	67	26	49	3F
DE	03	C0	08	A2	0E	84	17	66	26		
DD	03	BF	08	A1	0F	83	18	65	27		

memory can be filled. This was accomplished by adding a set value to the one determined by the speed scaling to get the microprocessor into a different range of injection times corresponding to the different air-fuel ratio.

Hopefully, the flowchart of this program explains the method more clearly. A failsafe feature was built into the software of this routine which assured a reasonable injection time value in case one of the sensors malfunctioned and resulted in an erroneous value read by the microprocessor. As can be seen by the flowchart, comparisons were made to determine if the air flow sensor reading was outside of the range it had been programmed to handle. If the reading was outside this range the microcomputer simply kept the old value of air flow and proceeded to look up the speed value. The same failsafe feature was utilized for the speed value.

In all, 7680 words of memory were used by this table look-up method and the programming of this amount of data was very time-consuming and fairly tedious. In order to shorten the amount of time that was required for this extensive programming certain sections of the table were excluded which could never be attained over the range in which the engine was to be operated, i.e. maximum air flow at minimum speed, and these sections were loaded with zeroes. A third failsafe feature was that if one of these areas was entered for some reason, the microcomputer would simply retain the previous injection value and proceed on.

4-4 The Interrupt Request Program

The concept of interrupt is used to signal the microprocessor that an external event has occurred and the microprocessor should devote attention to it immediately. This technique accomplishes processing in which the microprocessor's program is interrupted and the event that caused the interrupt is serviced (18). Transferring most of the data and control to I/O devices in an interrupt driven environment will usually result in maximum program efficiency. Each event is serviced when it occurs which means there is a minimum amount of delaying in servicing events. It is possible to interrupt an interrupt processing routine and, therefore, all the interrupt logic uses the stack which allows processing of successive interrupts without any penalty other than increasing the stack length.

This interrupting concept was used in conjunction with the speed controller, the second objective of this research. A flowchart of this routine is provided in Figure 16. As was explained in Chapter 3, the engine speed value was updated every one-half second for the speed controller. Therefore, every one-half second a negative-going pulse was put on the IRQ line of the microcomputer.

This signal was generated in much the same manner that the speed sensor functions. Another TTL circuit was constructed utilizing two binary up-down counters, shown in Figure 17. This time, however, the input to these counters was a constant frequency train of pulses. The counting network, consisting of 8 bits, would count up to a value of 255 before resetting, therefore a function generator operating at 512 Hz was used as a clock. At this frequency the circuit would count up to its maximum value and reset every 0.5 seconds. The resulting signal was then used as an input to a 74121 Monostable Multivibrator to enable a longer pulse to be generated, for failsafe operation. This signal, in turn, was used as the input to a 7474 D-type edge-triggered flip-flop, causing the output of the flip-flop to go low. This signal was connected to the IRQ line of the microcomputer. The computer was programmed to generate another pulse after it had acknowledged the interrupt to reset the flip-flop to its normally high state.

The speed control program was not based on the look-up method used for the air-fuel ratio control. Because this program was only executed every 0.5

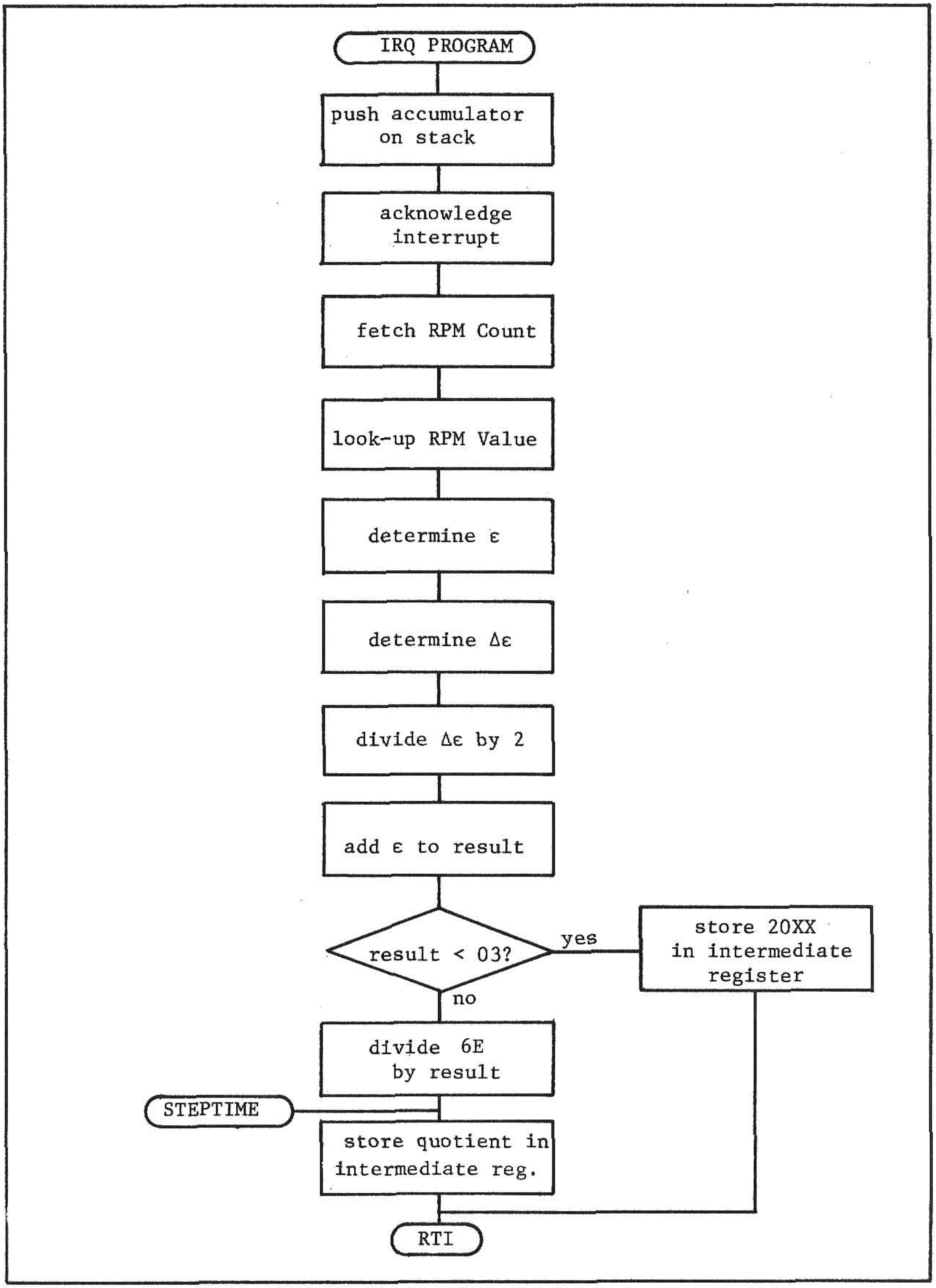

Figure 16. Interrupt Request Program

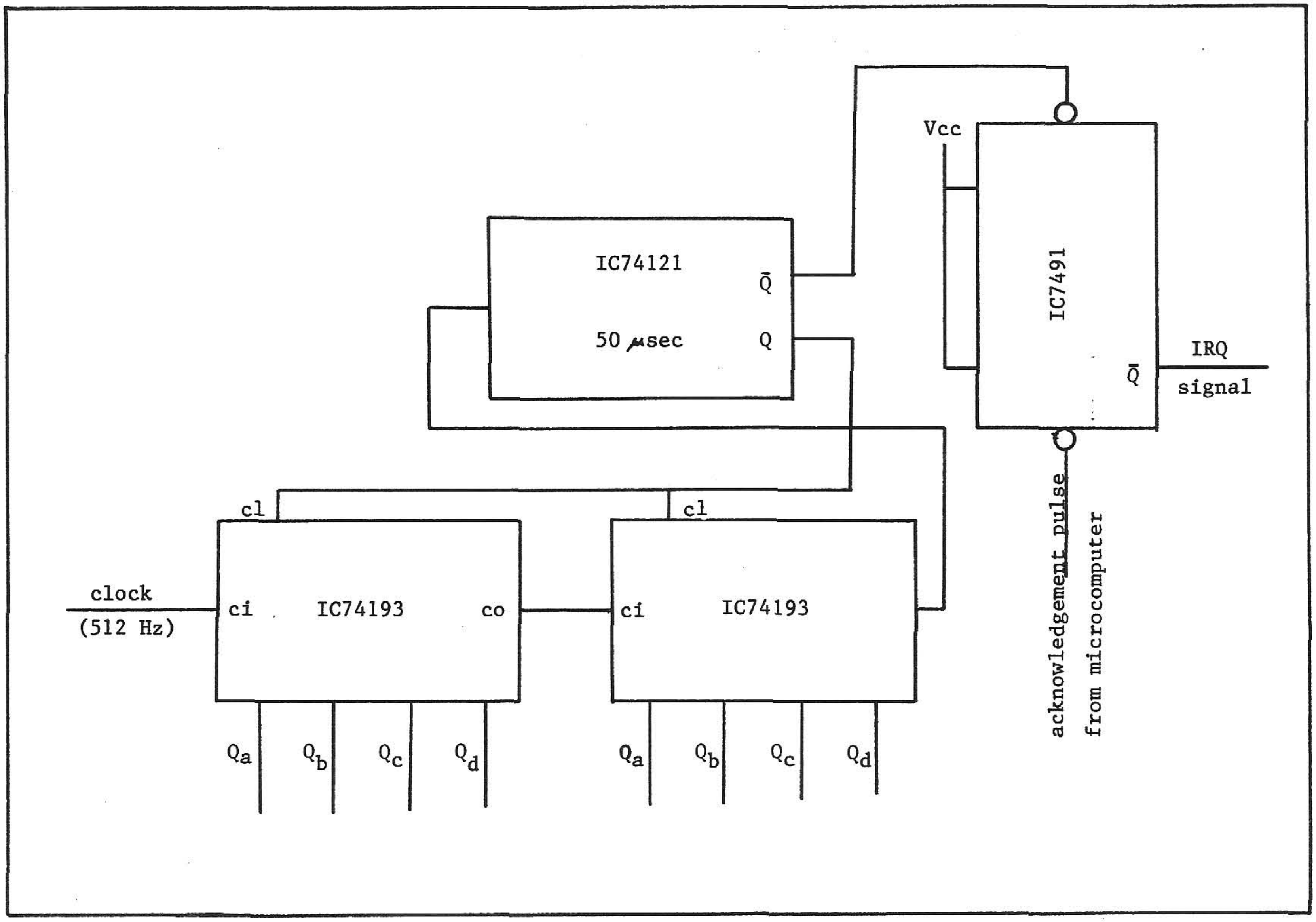

Figure 17. IRQ Pulse Generator

second, it was felt that the additional time required to execute multiply and divide routines could be afforded. Also, a large portion of the available memory was devoted to the look-up tables of the air-fuel ratio controller, requiring the speed control program to be much more efficient as far as usage of memory was concerned. In addition, the algorithm derived for the speed control was easily implemented using arithmetic operations.

The first step of this program was to once again scale the measured engine speed count into a more easily usable engine speed value. This operation was already performed in the air-fuel ratio injection time program, however, this scaling does not provide enough resolution for accurate control of the engine speed. Therefore, another scaling was done for this control which provided for a resolution of 10 rpm. This scaling is listed in full in Table 3.

Every half second the above scaling was performed to update the speed value used in the rest of this program. The values ε and $\Delta\varepsilon$ were computed and the number of pulses which were to be sent to the stepping motor to correct the speed error were computed using the algorithm derived in Chapter 3:

$$\text{STEP NO.} = 4.46 \left(\varepsilon + \frac{\Delta\varepsilon}{2}\right) \qquad (8)$$

To enable the engine to respond smoothly to error corrections the resulting number of steps was divided into 0.5 seconds to determine the amount of time to be counted off between the steps sent to the stepping motor. A programmable interval timer incorporated into one of the peripheral devices was used to count these delays. For this program the timer was programmed to operate at a frequency of 976 Hz, or a period of 1.024 milliseconds. Therefore, the time required between steps was calculated using the equation:

$$\text{STEPTIME} = \frac{\dfrac{0.500}{1.024 \times 10^{-3}}}{4.46\left(\varepsilon + \dfrac{\Delta\varepsilon}{2}\right)} \qquad (9)$$

TABLE 3. SPEED CONTROL SCALING

RPM COUNT	SPEED VALUE										
FA	00	DC	0C	BE	1C	A0	33	82	53	64	87
F9	00	DB	0D	BD	1D	9F	33	81	54	63	89
F8	01	DA	0D	BC	1E	9E	34	80	56	62	8B
F7	01	D9	0E	BB	1E	9D	35	7F	57	61	8E
F6	01	D8	0E	BA	1F	9C	36	7E	58	60	90
F5	02	D7	0F	B9	20	9B	37	7D	5A	5F	93
F4	02	D6	0F	B8	20	9A	38	7C	5B	5E	95
F3	02	D5	10	B7	21	99	39	7B	5D	5D	98
F2	03	D4	10	B6	22	98	3A	7A	5E	5C	9A
F1	03	D3	11	B5	22	97	3B	79	60	5B	9D
F0	04	D2	11	B4	23	96	3C	78	61	5A	A0
EF	04	D1	12	B3	24	95	3D	77	63	59	A3
EE	04	D0	12	B2	24	94	3E	76	65	58	A6
ED	05	CF	13	B1	25	93	3F	75	66	57	A9
EC	05	CE	13	B0	26	92	40	74	68	56	AC
EB	06	CD	14	AF	26	91	41	73	6A	55	AF
EA	06	CC	14	AE	27	90	42	72	6B	54	B2
E9	06	CB	15	AD	28	8F	43	71	6D	53	B5
E8	07	CA	15	AC	29	BE	44	70	6F	52	B8
E7	07	C9	16	AB	29	8D	45	6F	71	51	BC
E6	08	C8	16	AA	2A	8C	47	6E	72	50	BF
E5	08	C7	17	A9	2B	8B	48	6D	74	4F	C3
E4	09	C6	18	A8	2C	8A	49	6C	76	4E	C6
E3	09	C5	18	A7	2D	89	4A	6B	78	4D	CA
E2	09	C4	19	A6	2D	88	4B	6A	7A	4C	CE
E1	0A	C3	19	A5	2E	87	4D	69	7C	4B	D2
E0	0A	C2	1A	A4	2F	86	4E	68	7E	4A	D6
DF	0B	C1	1A	A3	30	85	4F	67	80	49	DA
DE	0B	C0	1B	A2	31	84	50	66	82		
DD	0C	BF	1C	A1	32	83	52	65	85		

$$\text{STEPTIME} = \frac{110}{(\varepsilon + \frac{\Delta\varepsilon}{2})} \qquad (10)$$

This value was calculated in accordance with the flowchart of Figure 16. The value was then stored in an intermediate register for use by another program.

4-5 The Non-Maskable Interrupt Program

It is often desirable to have the ability to interrupt an interrupt with a high priority device which cannot afford to wait during the time interrupts are disabled. For this reason the KIM-1 had a second interrupt line, called a Non-Maskable Interrupt. The input characteristics of this line are different than the interrupt request line which senses it needs service when it remains low. The non-maskable input is an edge-sensitive input which means that when the NMI line goes from high to low, the microprocessor sets an internal flag such that at the beginning of the next instruction, no matter what the status of the interrupt disable, the microprocessor executes the non-maskable program.

Because it was imperative that the injection pulses occur when desired, the non-maskable interrupt was used to start and stop these injection signals. The timing relationship of these pulses is shown in Figure 18. As can be seen, an injection pulse is put out by the microcomputer every revolution of the engine on the edge of the distributor signal. These pulses are created by setting an output bit high and starting the interval timer of the microcomputer, operating at a period of 64 microseconds, by loading the interval timer register with the computed injection time value. The interval timer would, in turn, generate a non-maskable interrupt when the programmed time had elapsed. At this time the output bit used to generate the injection pulse would be set low again. Following the completion of injection, either the air flow sensor count or rpm count would be read depending on whether the distributor signal was high or low.

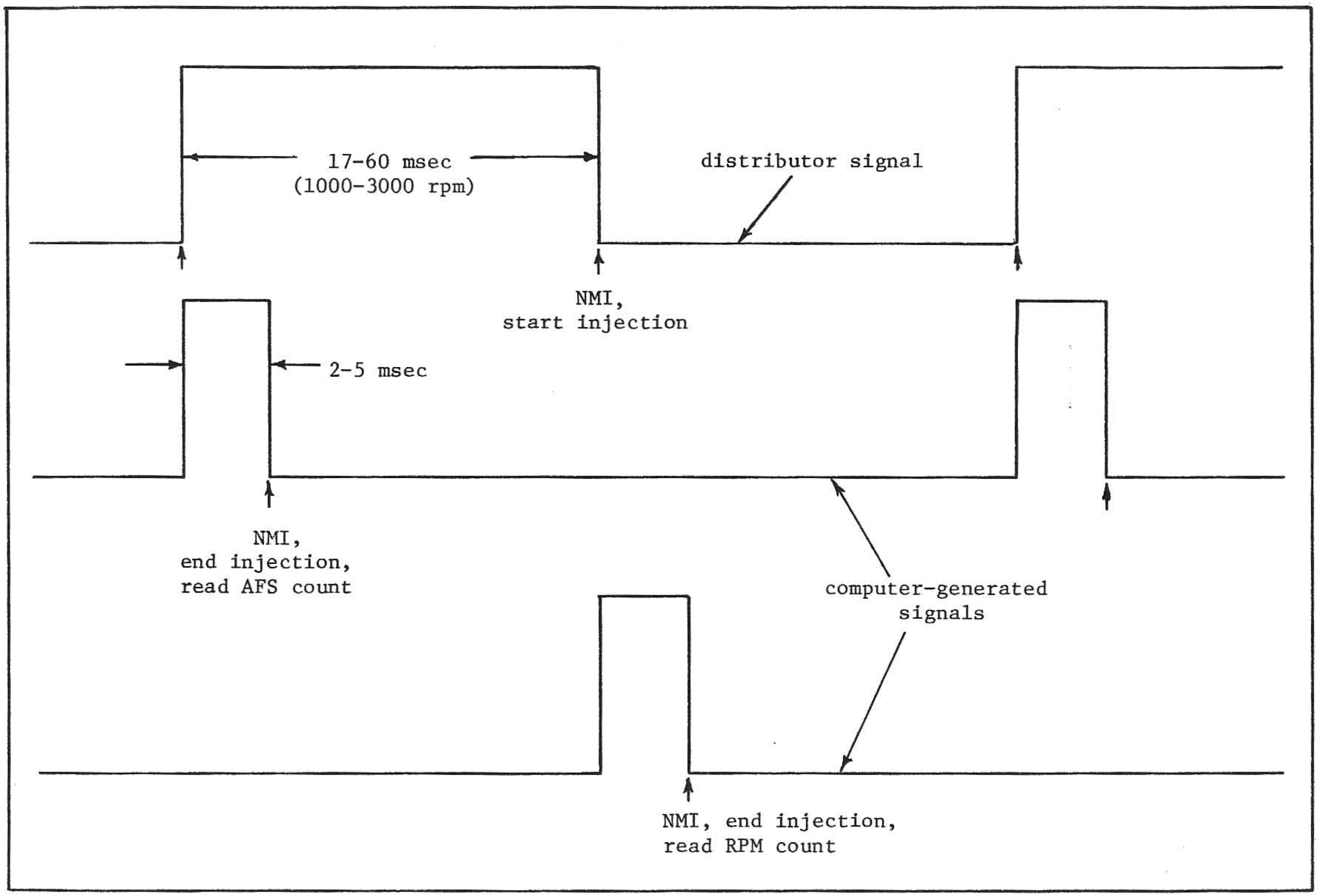

Figure 18. Injection Pulse Timing

There was only one interval timer on the KIM-1 that was available for application purposes. Therefore, it had to be used to time both the injection pulse lengths and the STEPTIME lengths. This was accomplished by stopping the STEPTIME count at the beginning of an injection, correcting the count value for the injection length, then resuming the STEPTIME count upon termination of the injection pulse. Because the STEPTIME count also used the interval timer, a non-maskable interrupt was generated when this count reached zero, too. This NMI signal had to be differentiated from the other interval timer interrupt, therefore a flag was set within the computer at the beginning of an injection pulse sequence. If this flag was still set when an interval timer interrupt occurred, it meant that the injection signal was to be terminated. On the other hand, if the flag was not set, it meant the STEPTIME count was completed and a pulse was to be sent to the stepping motor. The flow chart describing the NMI program is presented in Figure 19.

4-6 The Increment-Decrement Subroutine

As has been stated before, the microcomputer generated the signals which were sent to the stepping motor. This was accomplished with the increment-decrement subroutine, shown in flowchart form in Figure 20. Two bits, defined as outputs, were devoted toward the sending of these signals. These signals had to be 90° out of phase with each other, therefore two registers were initialized to values such that one was one count larger than the other. Using this relationship, the second-most least significant bits were isolated to be loaded into the output ports. This operation results in two signals 90° out of phase, as desired. If the stepping motor was to open the throttle, the values in the registers would be incremented and the designated signal would lead the other by 90°. Conversely, if the stepping motor was to close

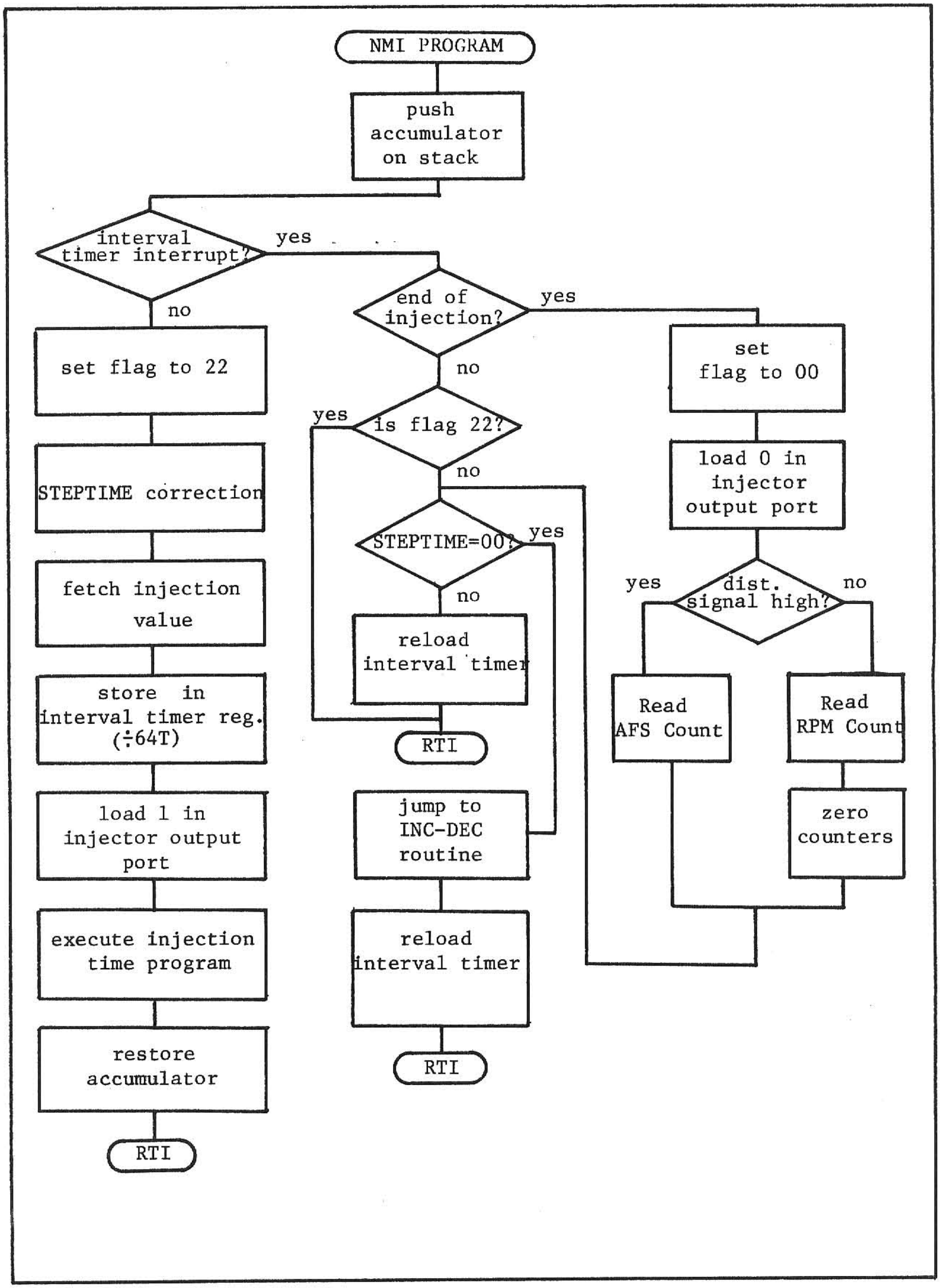

Figure 19. Non-Maskable Interrupt Program

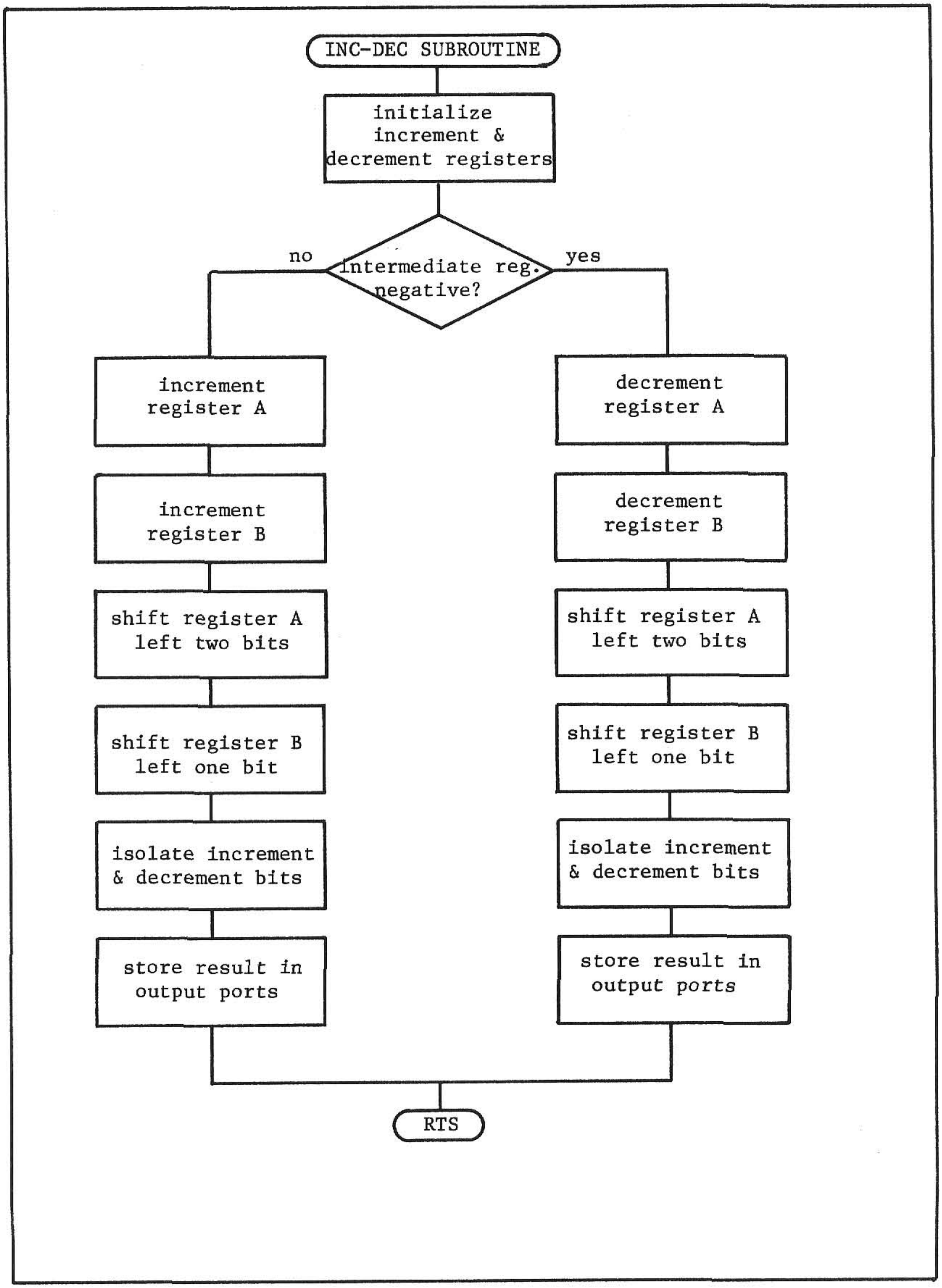

Figure 20. Increment-Decrement Subroutine

the throttle, the register values would be decremented and the signal would lag the other by 90^o.

4-7 The Divide Subroutine

The microcomputer used during this research was capable of performing addition and subtraction directly using built-in instructions. However, multiplication and division was needed for implementation of the speed controller. Therefore, multiply and divide routines had to be written using addition and subtraction instructions. The division routine, shown in Figure 21, actually consists of repeated subtractions of the divisor from the dividend until the result is negative. For every subtraction, a value of one was added to the partial quotient. To provide the needed accuracy, the subtraction operations were done in double-precision. Provisions were also made to take care of the signs of both the divisor and dividend, resulting in a double-precision, signed, division subroutine.

4-8 The Multiplication Subroutine

A multiplication subroutine was also written to perform double-precision, signed, multiplication. This operation was not needed, however, since the speed controller algorithm consisted of a single division. Basically, the multiply routine is a series of tests and shifts of the multiplier and multiplicand. Upon the completion of 8 such operations, the multiplication is complete. Therefore, as might be suspected, the multiplication routine, on the average, is much faster than the division subroutine that was written. This subroutine is shown in Figure 22.

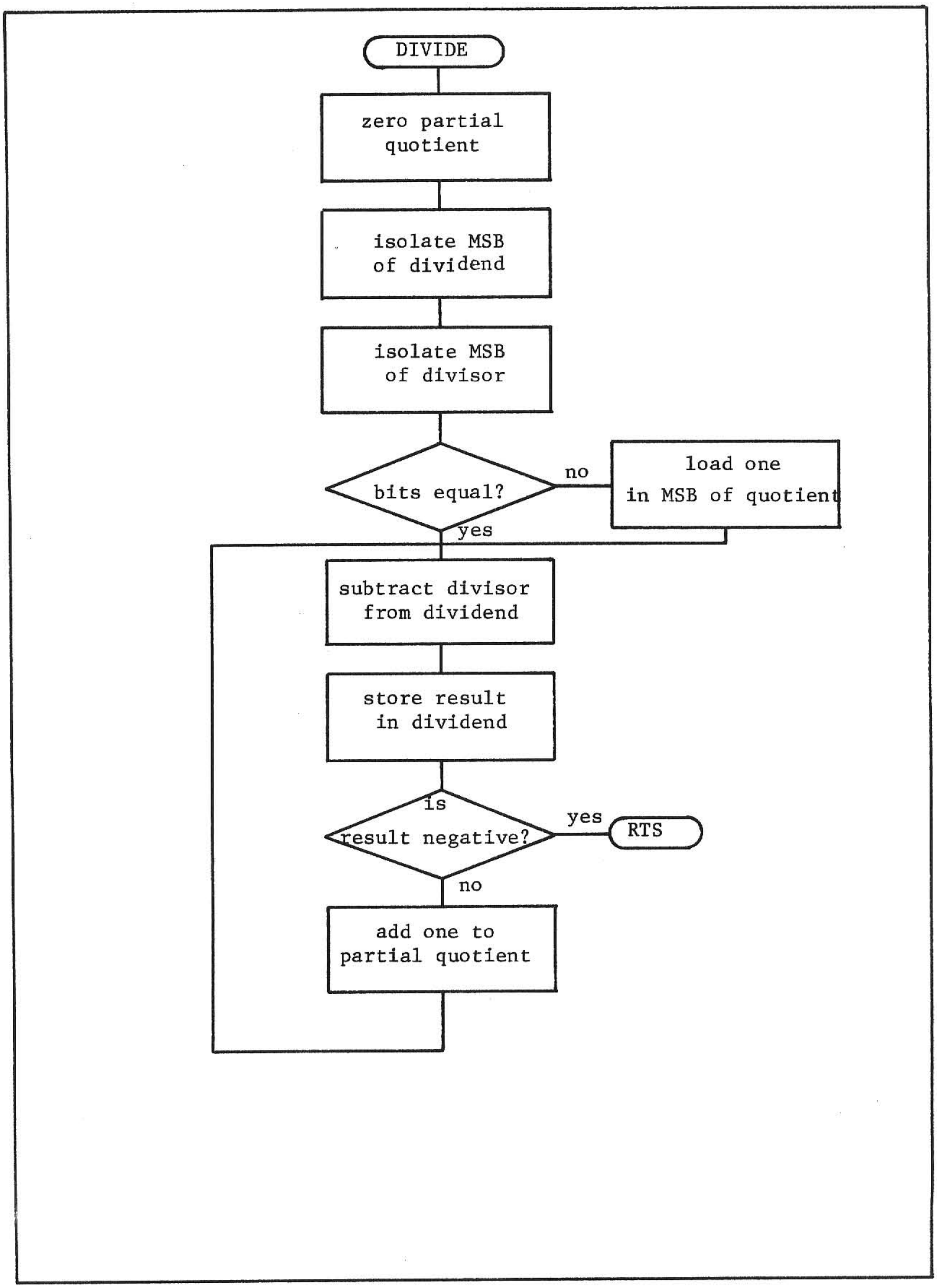

Figure 21. Divide Subroutine

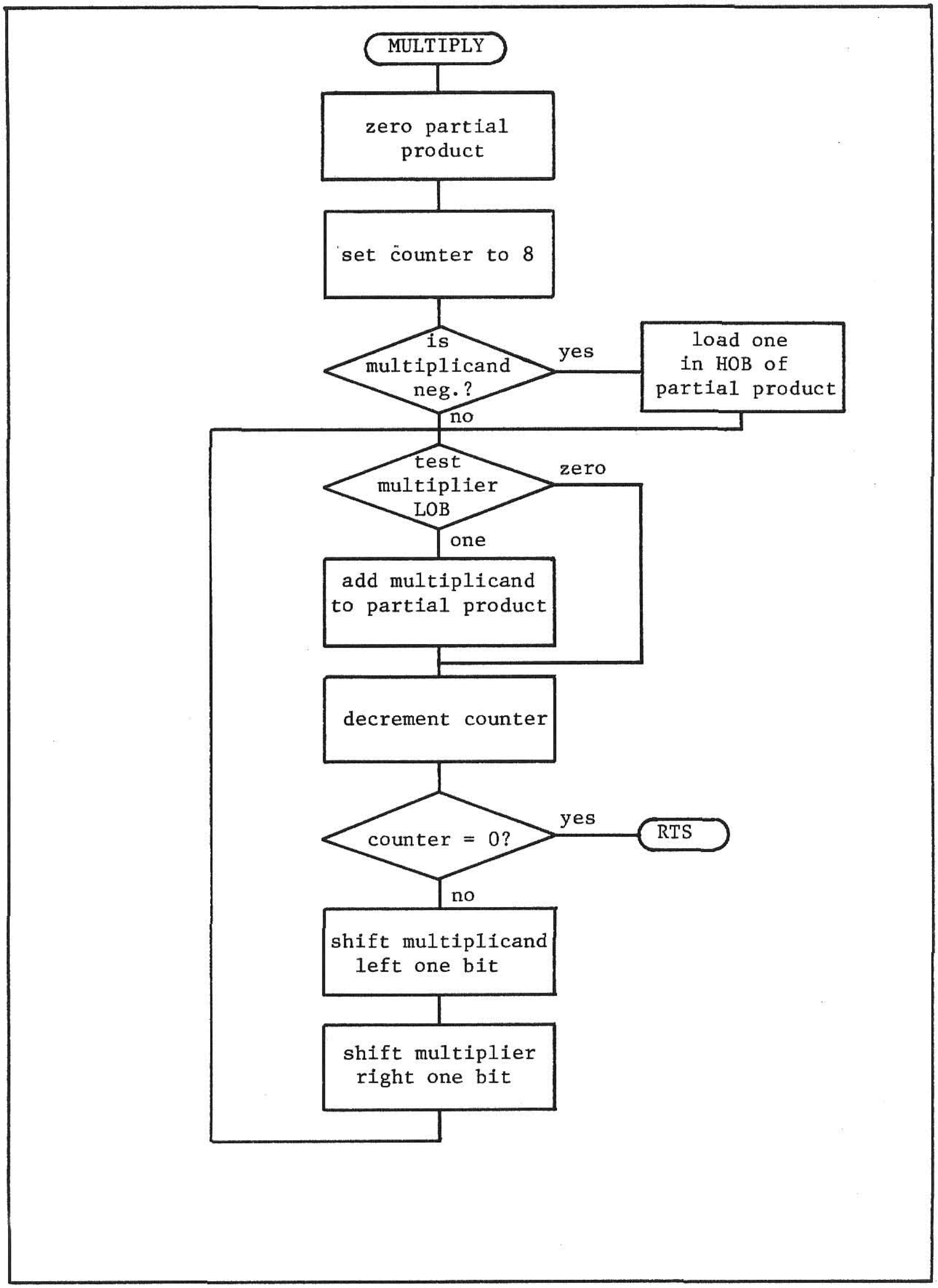

Figure 22. Multiply Subroutine

CHAPTER V

EXPERIMENTAL PROCEDURES AND TESTING

5-1 Introduction

In this chapter the experimental procedures which were followed throughout this research will first be discussed. Next, the testing and data taking method used will be presented. The second section of the chapter will be concerned with the Bench testing arrangement. Section 3 will contain a description of the air-fuel ratio controller procedures and testing, while Section 4 contains a similar description of the speed controller testing and procedures.

5-2 The Bench Testing Arrangement

The microcomputer control system designed for this research was fully tested in the laboratory prior to the time the equipment was taken to the area in which the engine was located. This preliminary testing consisted largely of de-bugging the software written for the microcomputer. One of the features incorporated into the microcomputer which facilitated this debugging was a single-step routine which allows the programmer to step through the software one instruction at a time. Intermediate registers could then be checked to detect any errors or aid in their correction.

The Volkswagen engine and KIM-1 microcomputer used in this research have already been presented briefly in the first chapter. Detailed specifications are listed for these two machines in appendices A and B respectively. Also used during this research and testing were two digital counters, one for monitoring the frequencies of the function generators used as clocks for the counting networks previously described, and another to count the elapsed time of fuel consumption during air-fuel ratio tests. Two function generators were used as just described. A Daytronic Instrument Module was utilized to provide digital readouts of speed, load, and horsepower as the engine was operating. A digital multimeter was used to monitor the voltage of the air flow sensor's potentiometer. The microcomputer and TTL circuitry required a 5 volt power supply, while the analog-to-digital converter and operational amplifiers required $\pm$ 15 volts to be supplied to them. The potentiometer on the air flow sensor was calibrated using a 10 volt power supply, and the microcomputer required, in addition, + 12 volts when the audio cassette tape memory interface was being utilized. A water micro-manometer was used to calculate air flow rates during the testing. Finally, a sling psychrometer was used to measure the wet and dry bulb temperatures of the air during test runs. The actual laboratory testing arrangement was photographed, and these pictures are presented in Plates 1-3.

5-3 Air-Fuel Ratio Controller Testing

The objective of the air-fuel ratio controller, once again, was to accurately control the air-fuel ratio at which the engine was operating at any given time. The desired air-fuel ratios at which testing was conducted were between 11.2-1 and 16.0-1. To experimentally determine what air-fuel ratio the engine was operating at the quantities of fuel consumption, time duration of test, room wet and dry bulb temperature, atmospheric pressure, and the pressure drop in the micro-manometer were measured. In addition, recordings were made of the speed, load, desired air-fuel ratio, and air-flow sensor voltage. Throughout most of the testing the injection pulse length was also recorded as measured on the oscilloscope.

EXPLANATION OF PLATE 1

Item	Description
1	Strip Chart Recorder
2	KIM-1 Microcomputer and Additional Memory
3	Oscilloscope
4	Function Generator
5	Function Generator
6	Daytronic Modular Instrument System
7	Electronic Counter
8	TTL Circuitry
9	Analog-to-Digital Converter
10	Bosch Electronic Control Unit
11	Hydraulic Oil Return to Filter
12	Cooling Water Supply
13	Hydraulic Oil Reservoir
14	Manual Pressure Regulating Valve
15	Strain Guage Transducer
16	Hydraulic Pump Dynamometer

THIS BOOK CONTAINS SEVERAL DOCUMENTS THAT ARE OF POOR QUALITY DUE TO BEING A PHOTOCOPY OF A PHOTO.

THIS IS AS RECEIVED FROM CUSTOMER.

THIS BOOK CONTAINS NUMEROUS PICTURES THAT ARE ATTACHED TO DOCUMENTS CROOKED.

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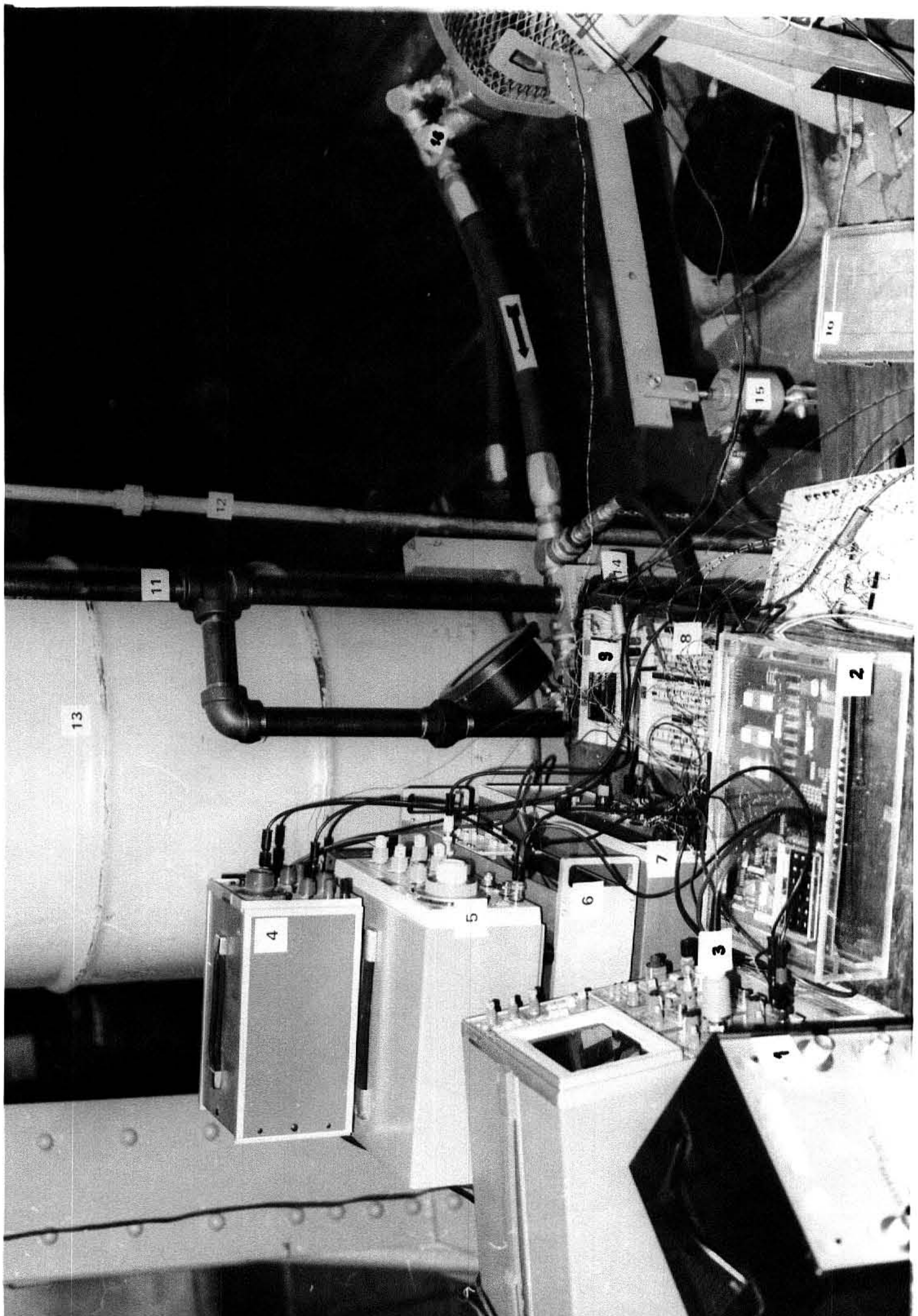

Plate 1. Foreground View

EXPLANATION OF PLATE 2

Item	Description
1	Gasoline Supply
2	Mass Balance
3	Micro-Switch Gating Device
4	Electronic Counter
5	Sling Psychrometer
6	Distilled Water
7	Water Micro Manometer

Plate 2. Side View

EXPLANATION OF PLATE 3

Item	Description
1	Air Flow Sensor
2	Digital Multimeter
3	Stepping Motor Amplifiers
4	Stepping Motor and External Gearing
5	Dual Power Supplies

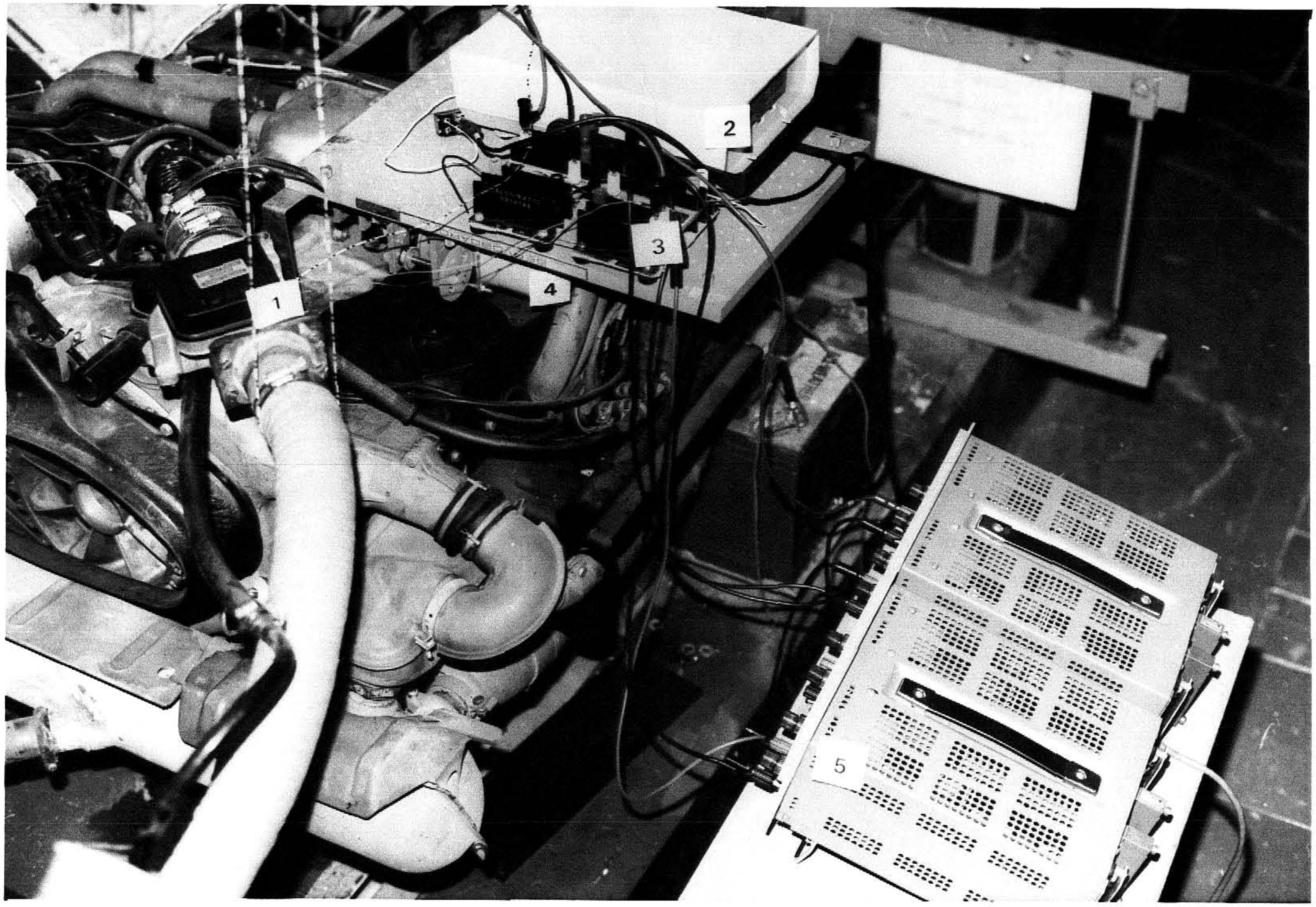

Plate 3. Background View

The amount of fuel consumed during each test was kept at a constant 0.40 lb. To determine the time duration of test, a circuit utilizing a micro switch and electronic counter was built. The engine was allowed to run, causing the weight of the fuel tank to decrease and its platform would rise. The other platform would fall, until the micro switch made contact, causing the electronic counter to begin counting up. The 0.40 lb weight would then be added to the fuel tank's weight, once again releasing the micro switch. When this amount of fuel had been consumed the switch would again make contact, this time causing the electronic counter to stop counting. The resulting value was the length of time it took for the engine to consume 0.40 lb of fuel.

The air mass flow rate was calculated from the pressure drop across a 1.59 inch (4.04 cm) ASME long radius flow nozzle as measured with the 10 inch (25.4 cm) water micro-manometer. A calibration sequence performed by Williams (19) enabled the CFM of air into the engine to be calculated as a function of the pressure drop across the nozzle, PMN. The result of this calibration was

$$CFM = (62.0524)(PNSD)^{0.5014} \tag{11}$$

where PNSD represented the standard density pressure drop across the nozzle. The value PNSD was calculated from the relation:

$$PNSD = PMN \left(\frac{0.075}{DENAIR}\right) \tag{12}$$

where DENAIR is the density of the air at test conditions. This, in turn, was calculated from:

$$DENAIR = \frac{(ATMPR)(0.491) - 0.38\left[PW - \frac{(ATMPR)(.491)(TDB - TWB)}{2700}\right]}{(0.37)(TDB)} \tag{13}$$

where ATMPR is the atmospheric pressure of the air in " Hg, PW is the vapor pressure of water in the air at the wet-bulb temperature, TDB is the dry bulb temperature of the air, and TWB is the air wet-bulb termperature.

After finding the CFM, the weight of air consumed per minute was determined by:

$$AMFR = (CFM)(DENAIR) \tag{14}$$

Room wet and dry bulb temperatures were measured using a sling psychrometer, while the atmospheric pressure was measured with a barometer located in a nearby room. As is proper, the wick of the wet bulb thermometer was wetted with distilled water.

The engine speed was obtained by using a fixed magnetic pick-up and a 60 tooth gear mounted on the driveshaft between the clutch and a dynamometer. The pulses from the pick-up transducer were input to the Daytronic Instrument Module which, in turn, gave a digital read-out of the engine speed.

The torque against the engine was measured by a strain gauge transducer. An aviation hydraulic pump, shown in Figure 23, was used to apply the torque

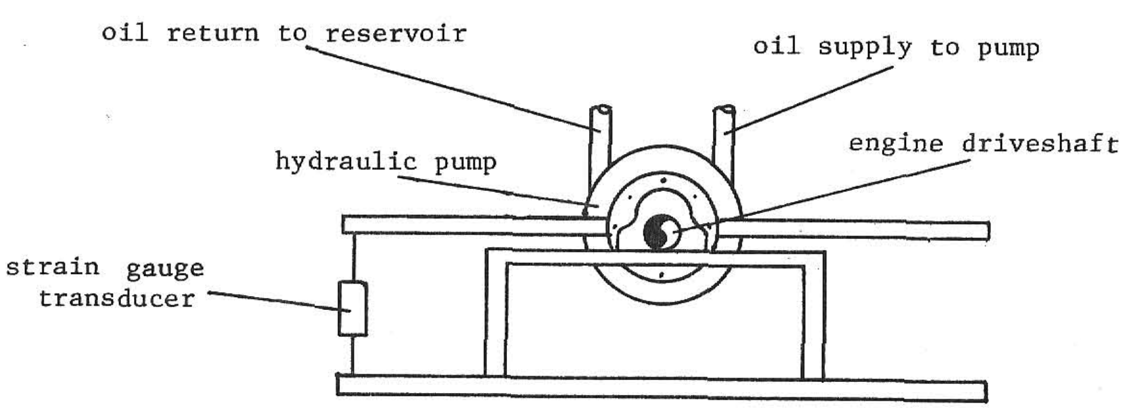

Figure 23. Dynamometer Configuration

to the engine. Low pressure oil was drawn from a 55 gallon (208.2 liter) reservoir and pumped back again through a manual pressure regulating valve and filter. The pressure regulating valve provided a means of increasing the pressure against which the hydraulic pump had to do work, resulting in an increase in the load on the engine. The varying electrical signal from the strain guage transducer was input to the Daytronic Module also, again resulting in a digital readout of the load in Lb-ft on the engine. Maximum torque that could be applied to the engine using this dynamometer was approximately 45 lb-ft.

For the air-fuel ratio testing the engine was allowed to warm-up for several minutes before data was taken. Changing the control of the injection pulse signals was easily accomplished with a switch mounted on the Bosch electronic control unit. When it was desired to have the microcomputer control the fuel injection, rather than the Bosch system, the switch was thrown which allowed the microcomputer signals to pass through the Bosch amplification circuitry and actuate the injection valves. During these tests data was taken while operating the engine at five different speeds: 1200, 1600, 2000, 2400, and 2800 rpm. The speed was controlled using the microcomputer speed control system. The load applied to the engine was set at three different values: 10, 25, and 40 lb-ft.

Generally speaking, the engine speed and load would be set at given values and the microcomputer would be programmed to control the engine at one of the four air-fuel ratios. After running three tests at these conditions the load would be increased to its next higher value and three more tests would be run. After tests had been completed at the maximum torque value the engine speed would be changed and the cycle started again. Finally, when all tests were taken at all combinations of speed and load the air-fuel ratio demand was changed in the microcomputer and the whole set of tests run again. Testing of the air-fuel ratio control was completed when all combinations of speed, load, and air-fuel ratio had been achieved and data taken at them.

It should be noted that some of the TTL circuitry tested in the lab had to be altered before bench testing was conducted, due to engine noise largely. The distributor signal was not quite a perfect square wave which could be used in the circuitry previously designed. It was possible to condition this signal, however, utilizing a μA-741 operational amplifier configured as a unity-gain voltage follower, so that it could be used in the previously designed circuitry. The greatest problem lay in the form of engine noise causing extraneous signals to be put on some of the lines. Since monostable multivibrators were used to a large extent in generating interrupt signals to the computer, a great deal of havoc was created when noise caused the multivibrators to put out signals when they weren't supposed to.

The majority of the problems arose when monostable multivibrators were used to generate NMI pulses on the edges of the distributor signals to initiate injection pulses. It was found to be impossible to filter out the noise on these lines using capacitors, therefore an alternate method was conceived for generation of these pulses which utilized shift registers in conjunction with "AND" gates. This operation is probably best explained by seeing how the signals were actually shifted, therefore it is depicted in Figure 24.

5-4 Speed Controller Testing

Speed controller testing was much less time-consuming than the air-fuel ratio testing, although the results will undoubtedly occupy the greater part of the next chapter. These results are all in the form of strip-chart recordings, achieved by using an analog output voltage signal proportional to the

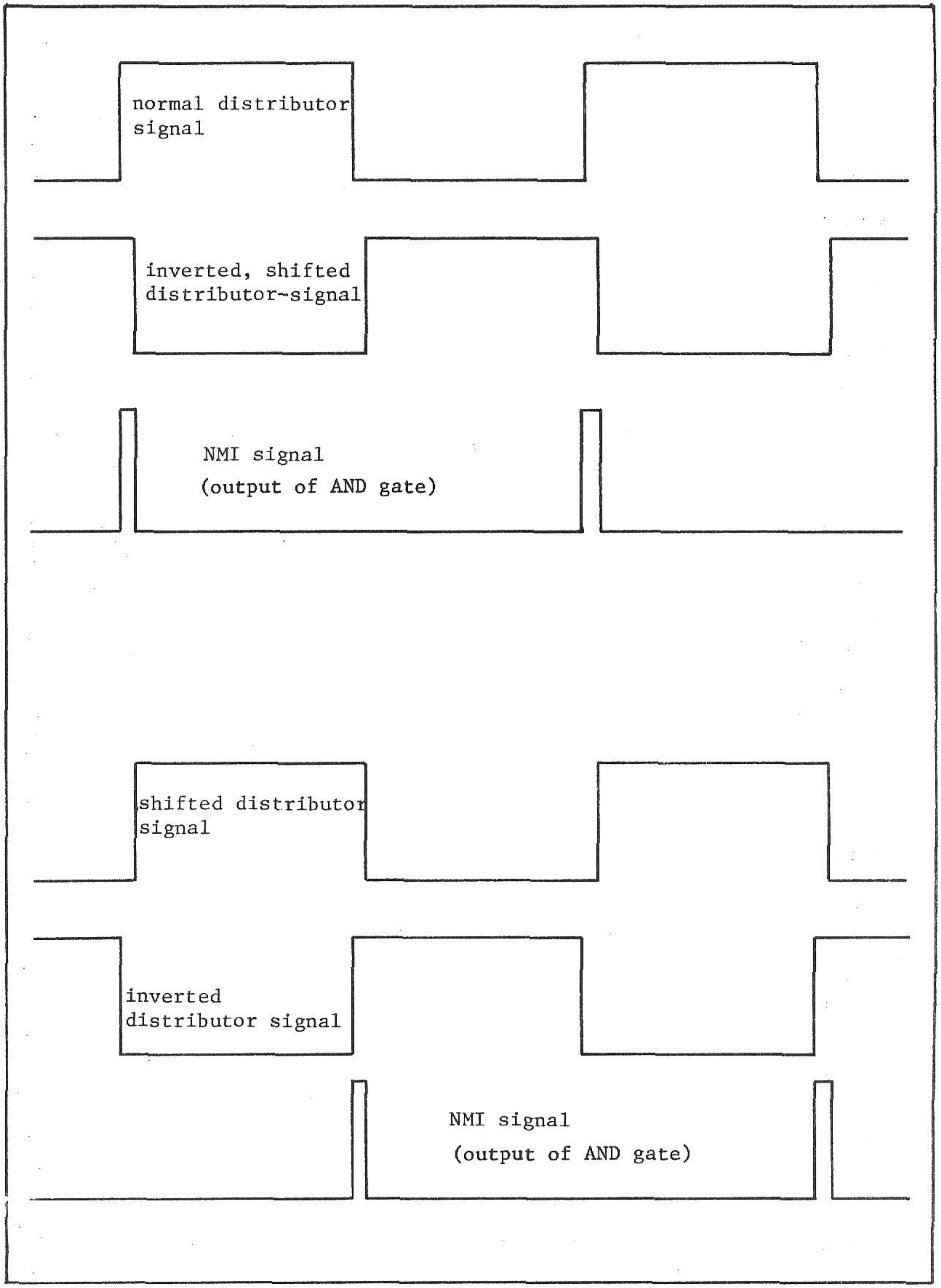

Figure 24. Shift Register Results

speed provided by the Daytronic frequency-to-voltage converter within the Instrument Module. The testing itself was conducted largely while accelerating or decelerating the engine speed. As before, five main engine speeds were maintained: 1200, 1600, 2000, 2400, and 2800 rpm. A preliminary test was made while operating the engine at a constant 1200 rpm with combinations of manual speed control, microcomputer speed control, Bosch electronically controlled fuel injection, and microcomputer controlled fuel injection at an air-fuel ratio of 12.8-1.

Following this testing, acceleration and deceleration tests were made while controlling the speed with the microcomputer and using the Bosch fuel injection system. Complete tests were made while accelerating and decelerating the engine between these five speeds at combinations of three different loads: 10, 25, and 40 lb-ft. Upon completion of this testing the tests were rerun using both the microcomputer speed controller and microcomputer fuel injection controller,at a 13-1 air-fuel ratio. Table 4 provides a listing of the speed demand values which were programmed into the microcomputer to maintain a desired engine speed. This table is actually a smaller version of Table 3 which was provided in Chapter 3.

TABLE 4. SPEED VALUES

DESIRED ENGINE SPEED	SCALED DEMAND VALUE
1000	0A
1050	0F
1100	14
1150	19
1200	1E
1250	23
1300	28
1350	2D
1400	32
1450	37
1500	3C
1550	41
1600	46
1650	4C
1700	50
1750	55
1800	5A
1850	5F
1900	64
1950	69
2000	6E
2050	73
2100	78
2150	7D
2200	82
2250	87
2300	8C
2350	91
2400	96
2450	9B
2500	A0
2550	A5
2600	AA
2650	AF
2700	B4
2750	B9
2800	BE
2850	C3
2900	C8
2950	CD
3000	D2

CHAPTER VI

PRESENTATION OF RESULTS

6-1 Introduction

Extensive bench testing was conducted on both the air-fuel ratio controller and the speed controller. The results of this testing are presented in this chapter. Air-fuel ratio control results are provided in section 2, while the speed control results are presented in the last section.

6-2 Air-Fuel Ratio Control Results

Data obtained from the air-fuel ratio testing described in the previous chapter was reduced using the computer program listed in Appendix F. The raw data is listed in Appendix G, while the computed results are provided in Appendix H. For this presentation the results were broken into three figures. Figure 25 provides the results of testing in which the four different desired air-fuel ratios were held constant over the range of engine speeds from 1200 to 2800 rpm, and the load was held at a constant 10.0 lb-ft. The following two figures represent the same type of testing, except the loads were changed to 25.0 and 40.0 lb-ft respectively. Each point on the graphs represents the average of three tests taken at that condition. It should be noted, no graph was made of a 16-1 air-fuel ratio at 40 lb-ft of load. It was extremely difficult to operate the engine at this condition, therefore rather than take partial or incomplete tests, or risk harming the engine, it was decided not to take any data at these conditions.

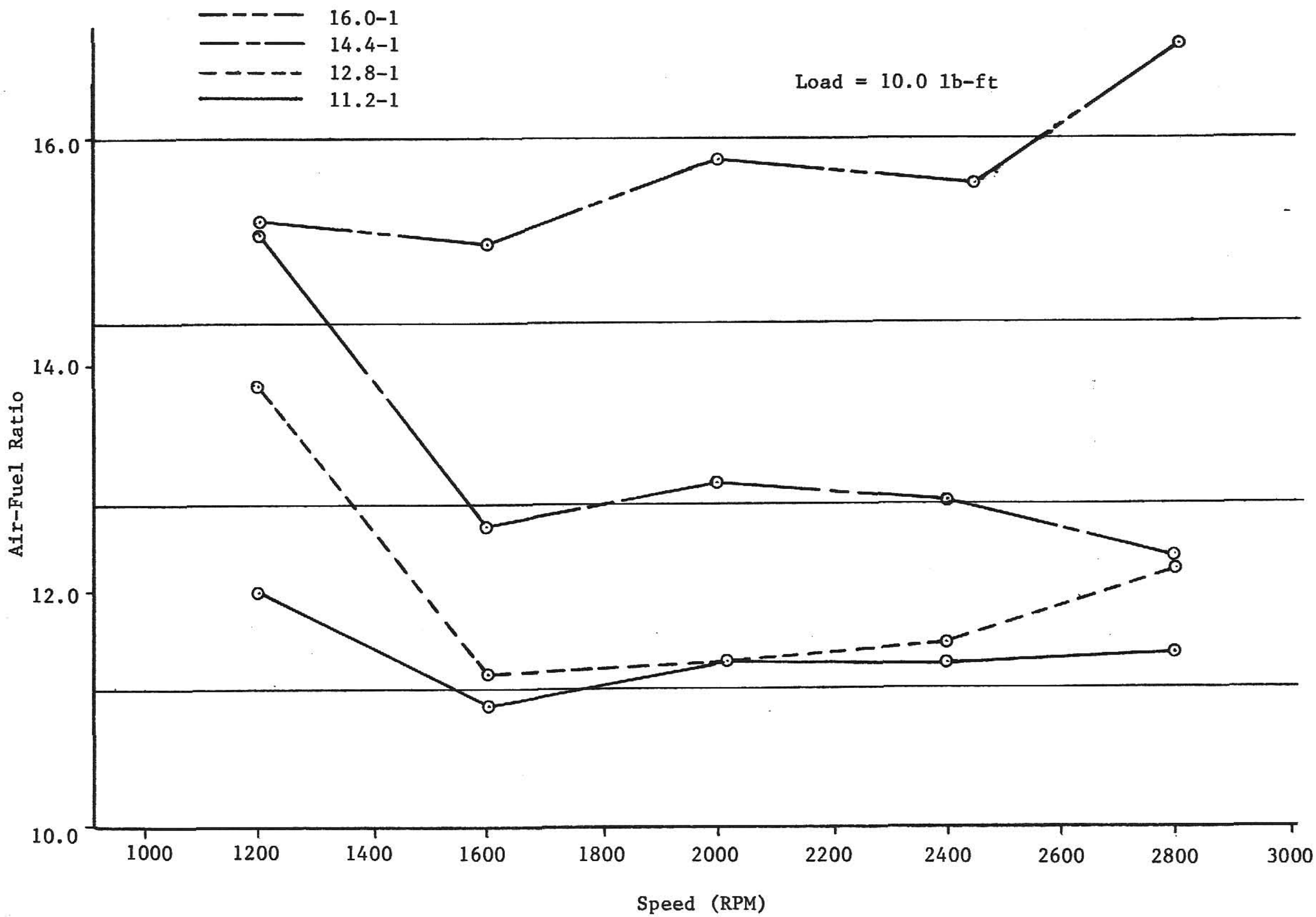

Figure 25. Air-Fuel Ratio vs. Engine Speed at a Load of 10.0 Lb-ft

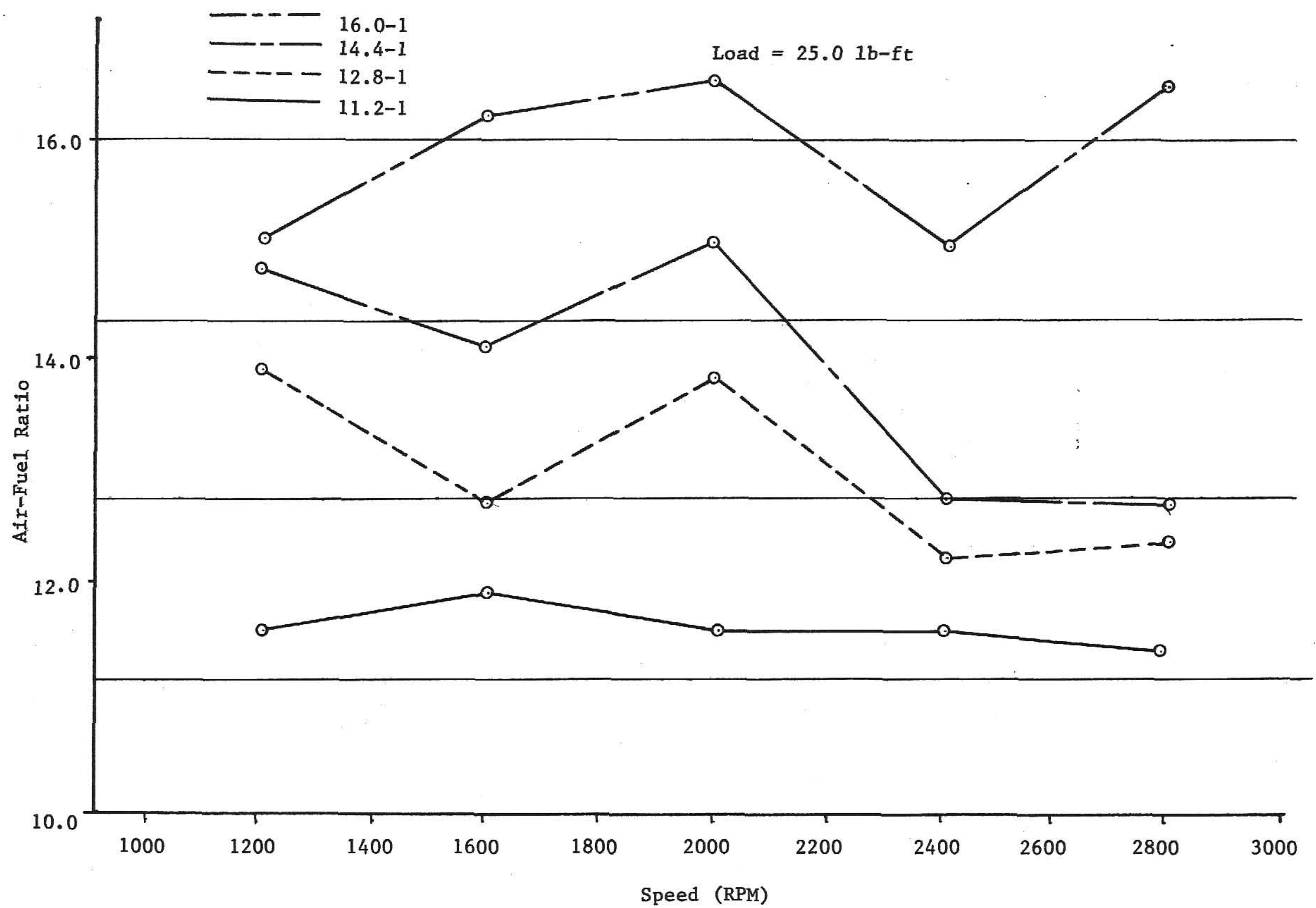

Figure 26. Air-Fuel Ratio vs. Engine Speed at a Load of 25.0 Lb-ft

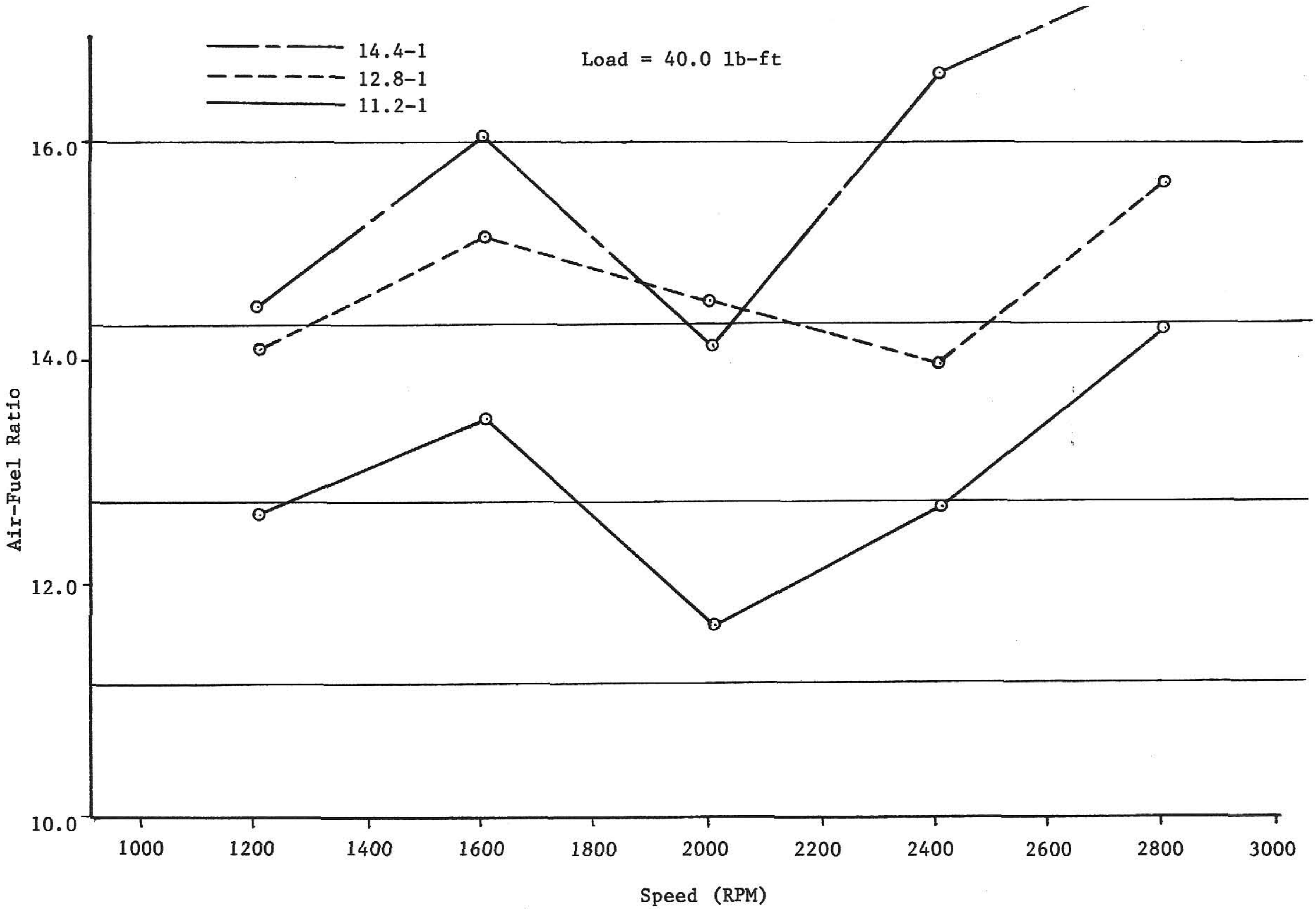

Figure 27. Air-Fuel Ratio vs. Engine Speed at a Load of 40.0 Lb-ft

A statistical analysis was made of the data represented by these graphs, in which the mean, standard deviation, and percent standard deviation from the mean were calculated for several different sets of the results. This analysis is provided in Table 5. In addition, an uncertainty analysis was made of the air-fuel ratio results. This analysis, provided in Appendix C, resulted in the limit of error for the air-fuel ratio results to be calculated as 3.29%.

A study of these graphs shows that the curves exhibit a rise and fall characteristic over the ranges of speeds and loads. The patterns made by the rise and fall characteristics of the air-fuel ratios across the range of speeds at each given load seem to be correlated to each other. This characteristic may be a result of nonlinearities in the air induction and distribution system. Some variation may have also been caused by the changes in room temperature and atmospheric pressure while the testing was being conducted over the three day period. The tests made at a desired air-fuel ratio of 14.4-1 were made on the first day, tests at 12.8-1 were conducted on the second day, and tests at 11.2-1 and 16.0-1 air-fuel ratios were made on the third day. The overlap of the 12.8-1 and 14.4-1 air-fuel ratio curves in Figure 27 are likely the result of an erroneous data value programmed into the injection time array.

A summary of Table 5 shows that the air-fuel ratio was maintained within a percentage standard deviation from the mean between 5.3% and 11.5%. Also, the actual, measured air-fuel ratios differed from the desired air-fuel ratios by a minimum of 0.85% at a desired air-fuel ratio of 11.2-1, to a maximum of 7.42% at a desired air-fuel ratio of 16.0-1.

6-3 Speed Control Results

The results of the initial speed control tests are presented in figures

Table 5. Air-Fuel Ratio Control Results

Desired Air-Fuel Ratio	Number of Tests	Load	Mean Air-Fuel Ratio	Standard Deviation	% Standard Deviation	Percent Offset
11.2	15	10.0	11.4687	0.439	3.83	
	15	25.0	11.6188	0.738	6.35	
	15	40.0	13.0053	0.952	7.32	
	45		12.0309	1.006	8.35%	7.42%
12.8	15	10.0	12.0917	0.996	8.23	
	15	25.0	13.0094	0.969	7.45	
	15	40.0	14.6877	0.751	5.11	
	45		13.2629	1.406	10.60%	3.62%
14.4	15	10.0	13.1487	1.116	8.49	
	15	25.0	13.8776	1.095	7.89	
	15	40.0	15.8064	1.389	8.79	
	45		14.2775	1.637	11.46%	0.85%
16.0	15	10.0	15.7154	0.890	5.66	
	15	25.0	15.8536	0.817	5.13	
	30		15.7844	0.843	5.33%	1.35%

28-31. Comparisons were made between the different operating systems while the engine was trying to run at a constant 1200 rpm. The chart speed for these four recordings is 1 mm/sec and the sensitivity was held at 50 mv/division which in turn corresponds to approximately 40 rpm/mm. These results would indicate that employing the microcomputer injection system caused the engine to run smoother than when the Bosch system was being used, although it is questionable whether the speed controller maintained the constant speed any better than the manual, set throttle.

The following recordings, figures 32-43 show the engine response to an acceleration of 400 rpm while the microcomputer speed control was in use and the Bosch injection system was being employed. Once again the sensitivity for all these recordings is 50 mv/div or about 40 rpm/mm, with the exception of figure 41 where the sensitivity is less. Each page contains recordings of acceleration tests over a specific range of speed, but at three different loads. Figures 32-34 show the varying engine control system response characteristics over the different loads. It appears that at a load of 10.0 lb-ft the control system is underdamped, while at a load of 40.0 lb-ft the control system is critically damped. The characteristics of the system at 25.0 lb-ft of load are between these values.

An analysis was made of figures 32-43 to roughly determine the different transient response characteristics they possessed. One characteristic studied was percent overshoot. When operating at 10.0 lb-ft of load the control system responded with an overshoot of from 90% to as low as 40%, with the highest value occurring during the acceleration from 1200 to 1600 rpm and the lowest value ocurring in accelerating from 2400 to 2800. Operating the engine at a 25.0 lb-ft load resulted in percent overshoot ranging from 30% to 10% with the

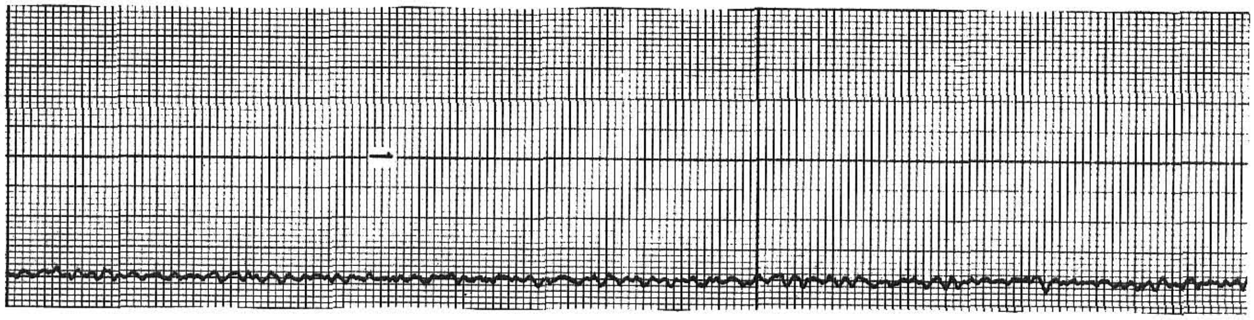

Figure 28. Engine Speed at a Set 1200 rpm and 10.0 lb-ft Load; Manual Throttle; Bosch Fuel Injection, Chart Speed = 1 mm/sec

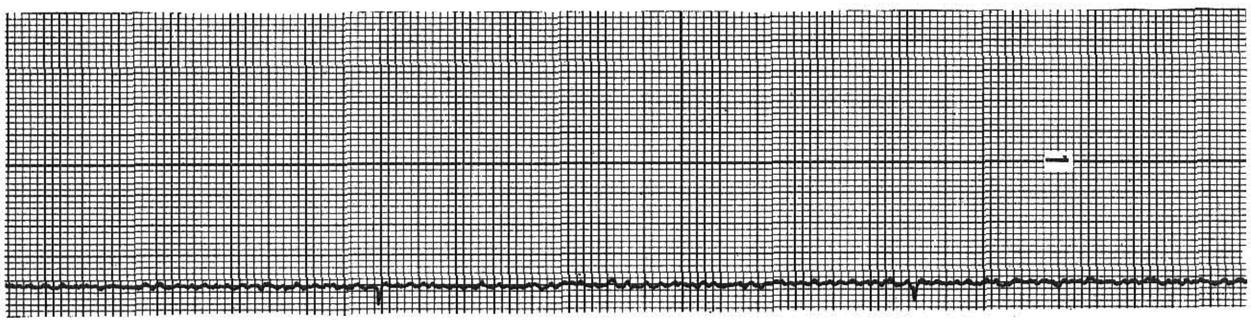

Figure 29. Engine Speed at a Set 1200 rpm and 10.0 lb-ft Load; Manual Throttle; Microcomputer Injection; Chart Speed = 1 mm/sec

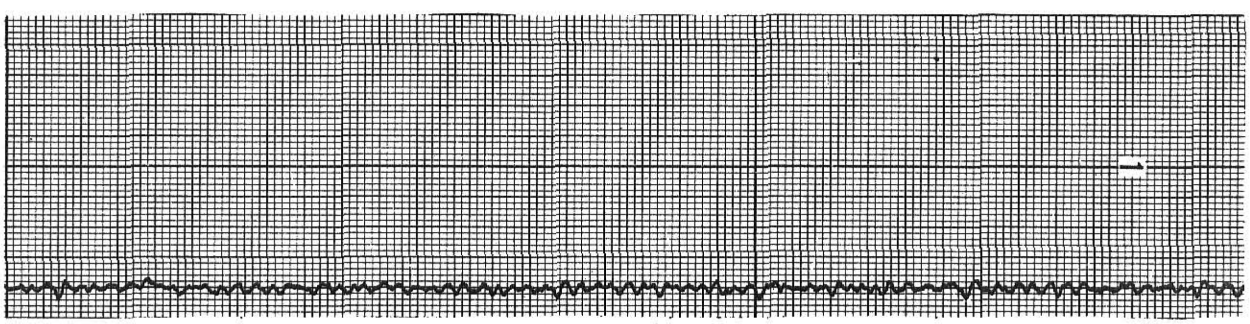

Figure 30. Engine Speed at a Set 1200 rpm and 10.0 lb-ft Load; Microcomputer Speed Control; Bosch Injection; Chart Speed = 1 mm/sec

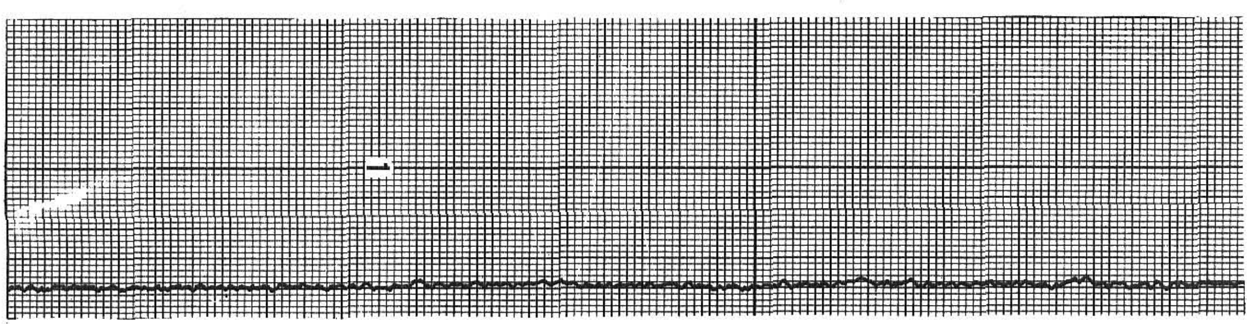

Figure 31. Engine Speed at a Set 1200 rpm and 10.0 lb-ft Load; Microcomputer Speed and Injection Control; Chart Speed = 1 mm/sec

Figure 32. Acceleration From 1200 to 1600 rpm at 10.0 lb-ft Load; Bosch Injection; 5 mm/sec = Chart Speed

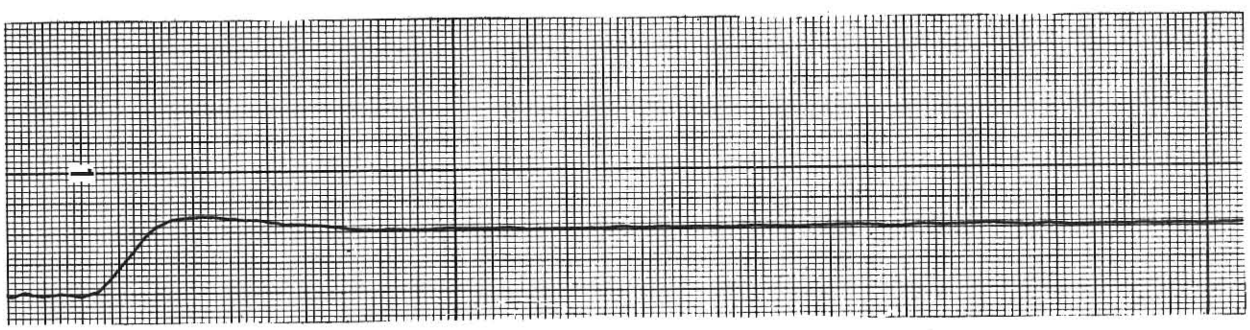

Figure 33. Acceleration From 1200 to 1600 rpm at 25.0 lb-ft Load; Bosch Injection; 5 mm/sec

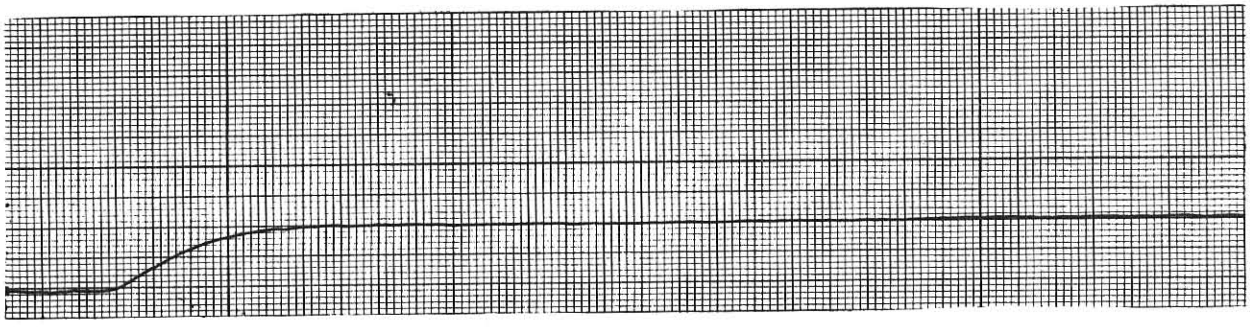

Figure 34. Acceleration From 1200 to 1600 rpm at 40.0 lb-ft Load; Bosch Injection; 5 mm/sec

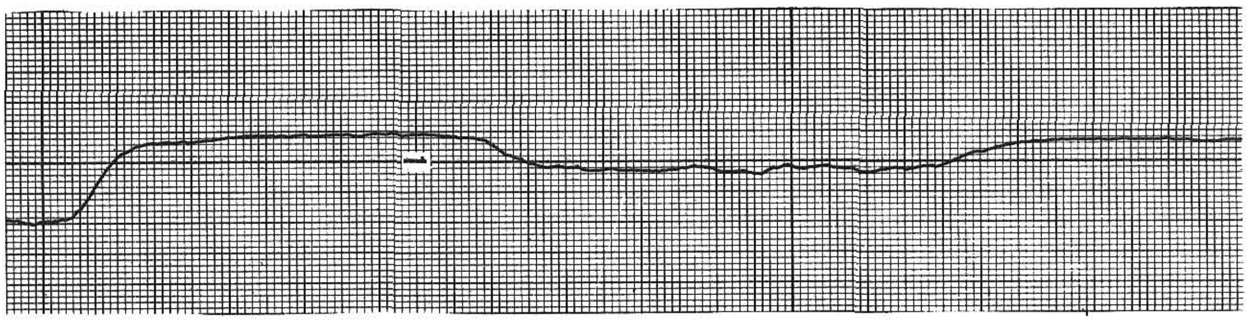

Figure 35. Acceleration From 1600 to 2000 rpm at 10 lb-ft Load; Bosch Injection; 5 mm/sec

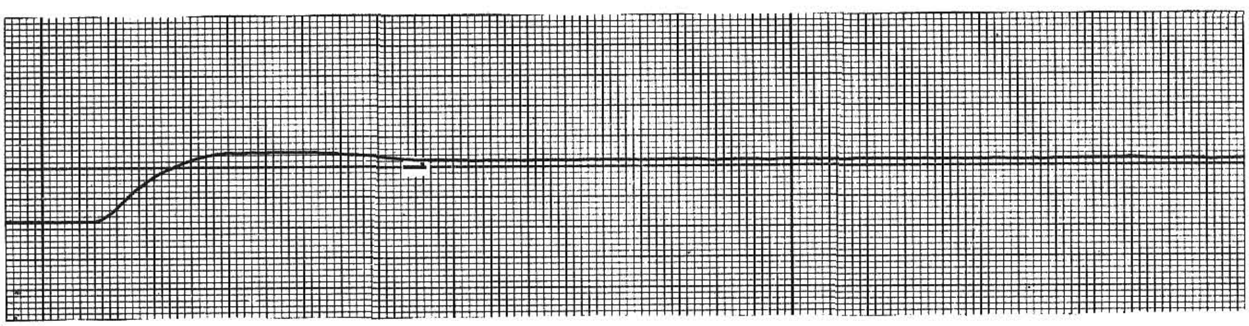

Figure 36. Acceleration From 1600 to 2000 rpm at 25.0 lb-ft Load; Bosch Injection; 5 mm/sec

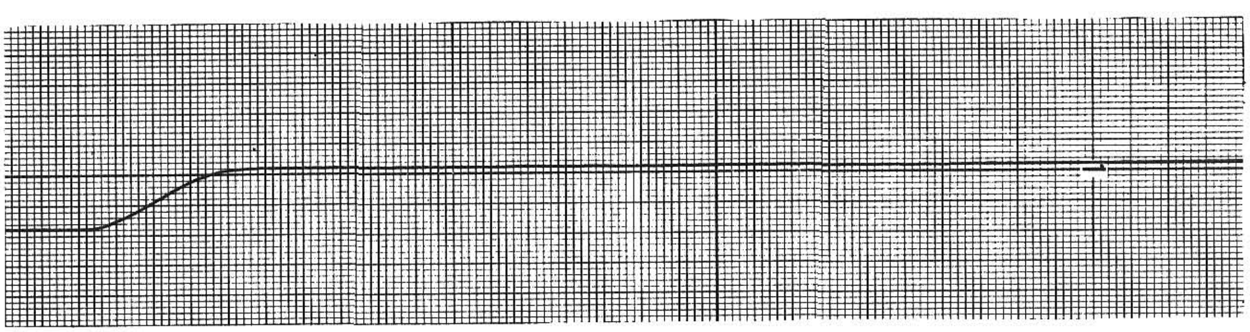

Figure 37. Acceleration From 1600 to 2000 rpm at 40.0 lb-ft Load; Bosch Injection; 5 mm/sec

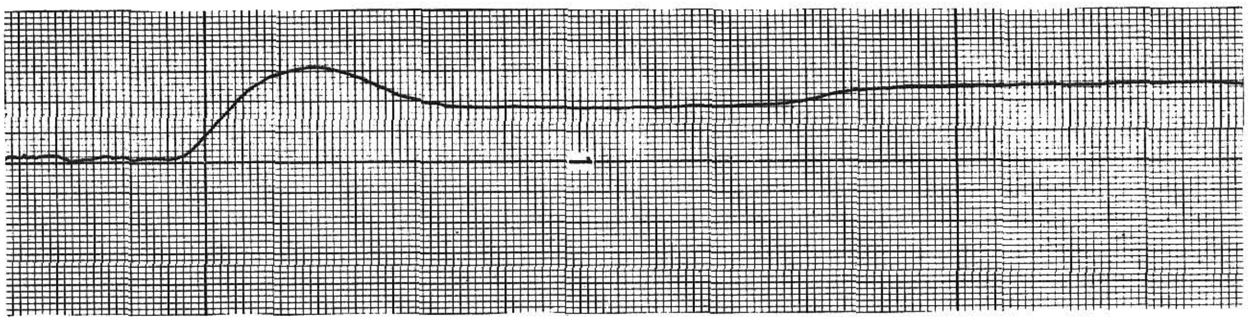

Figure 38. Acceleration From 2000 to 2400 rpm at 10.0 lb-ft Load;
Bosch Injection; 5 mm/sec

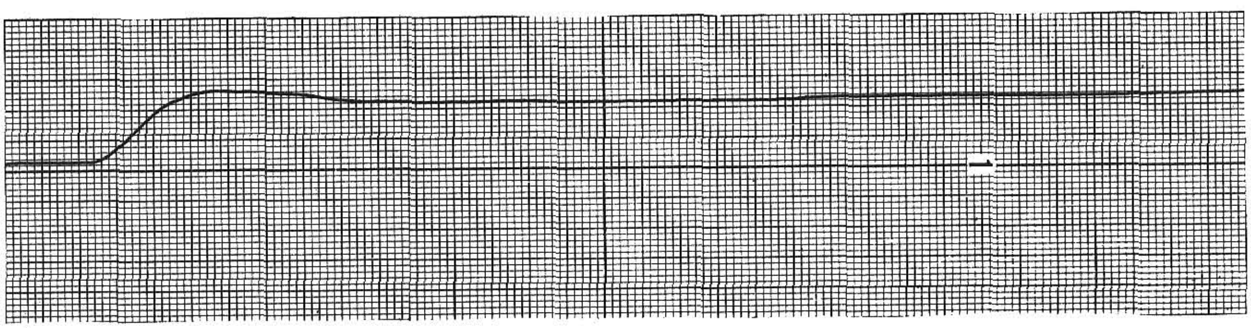

Figure 39. Acceleration From 2000 to 2400 rpm at 25.0 lb-ft Load;
Bosch Injection; 5 mm/sec

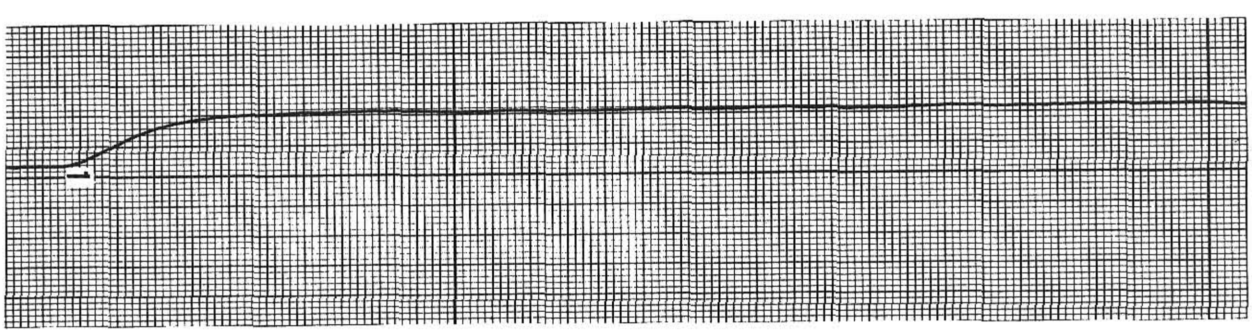

Figure 40. Acceleration From 2000 to 2400 rpm at 40.0 lb-ft Load;
Bosch Injection; 5 mm/sec

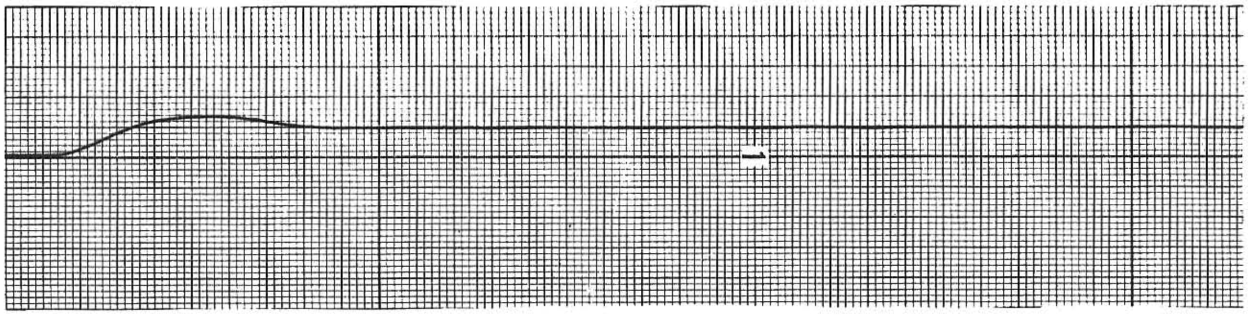

Figure 41. Acceleration From 2400 to 2800 rpm at 10.0 lb-ft Load; Bosch Injection; 5 mm/sec

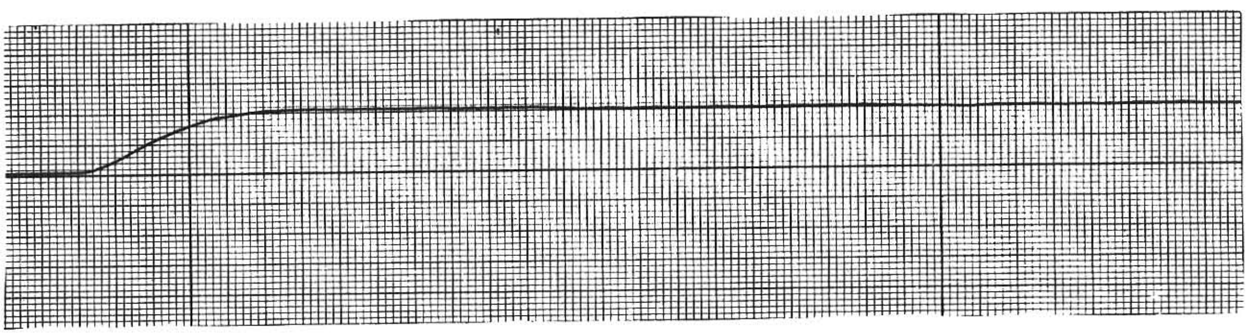

Figure 42. Acceleration From 2400 to 2800 rpm at 25.0 lb-ft Load; Bosch Injection; 5 mm/sec

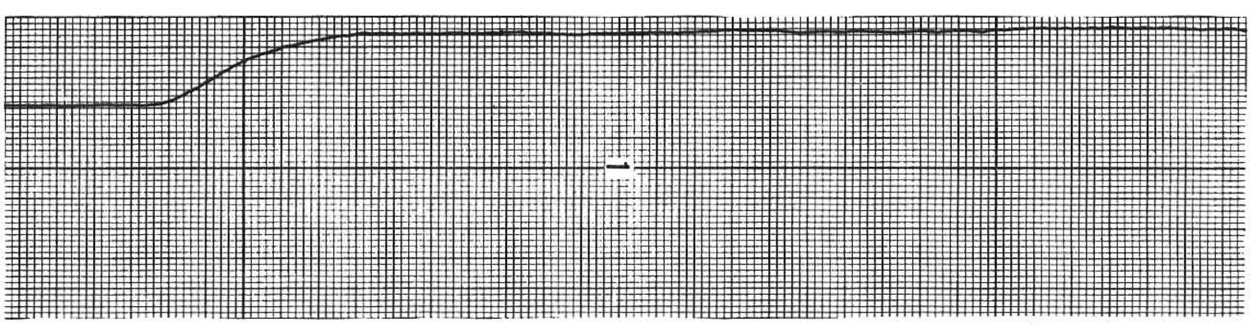

Figure 43. Acceleration From 2400 to 2800 rpm at 40.0 lb-ft Load; Bosch Injection; 5 mm/sec

same pattern as before. At a load of 40.0 lb-ft the engine exhibited no overshoot throughout the entire range.

A second property that was studied was settling time, defined as the time required for the response to reach and stay within a range of 5% of its final value. Typically the largest settling times occurred when then engine was operating at a load of 25.0 lb-ft. At this condition the settling time was approximately 7-8 seconds. Settling times while operating the engine at 10.0 lb-ft and 40.0 lb-ft were very nearly the same, ranging from 4.5 to 6 seconds, with the exception of two tests run at 10.0 lb-ft of load. These tests, shown in figures 35 and 38, indicate that the engine response was unstable when accelerating between 1600 and 2400 rpm at 10.0 lb-ft of load, and therefore the settling time was quite long.

A third study was made of the time response of the engine under the various operating conditions, in which the time response is defined as the time required for the engine to attain 63% of its final, desired value. This analysis showed the fastest response times to occur when the engine was operating at 10.0 lb-ft of load, at which the response time was 0.9 to 1.5 seconds. At 25.0 lb-ft of load the response time varied from 1.2 to 1.6 seconds, while at 40 lb-ft of load the response time was nearly a constant 2.2 seconds.

Figures 44 through 55 show the results of deceleration tests in which the engine was commanded to decelerate 400 rpm over the range of operating speeds and loads. These results are a reflection of the response characteristics just examined in the acceleration results. Once again, the chart speed for these tests was maintained at 5 mm/sec and the sensitivity was 40 rpm/mm except for Figure 53 in which it is less. Figures 47 and 50 again show the instability of the speed control over the range of 2400 to 1600 rpm at 10.0 lb-ft of load. Evidently the parameters of the speed control program need to be altered for

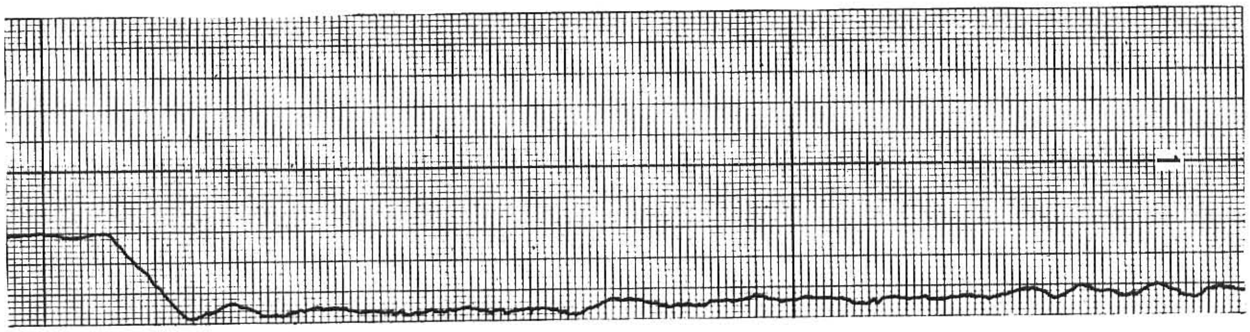

Figure 44. Deceleration From 1600 to 1200 rpm at 10.0 lb-ft Load;
Bosch Injection; 5 mm/sec

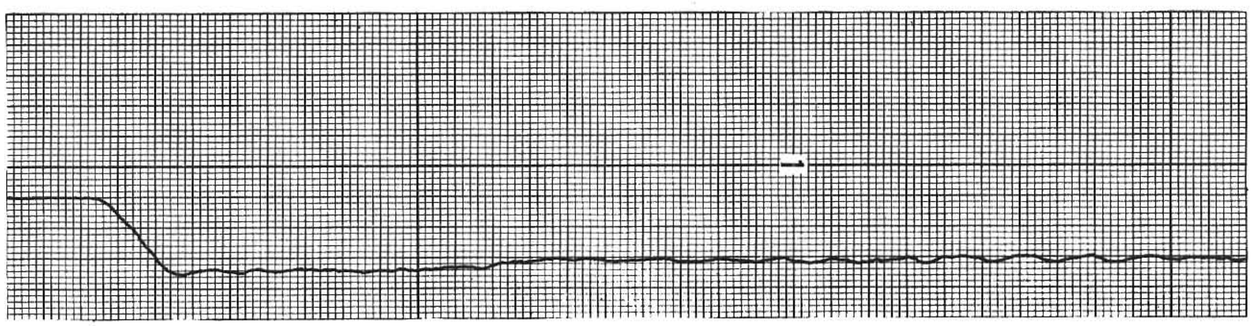

Figure 45. Deceleration From 1600 to 1200 rpm at 25.0 lb-ft Load;
Bosch Injection; 5 mm/sec

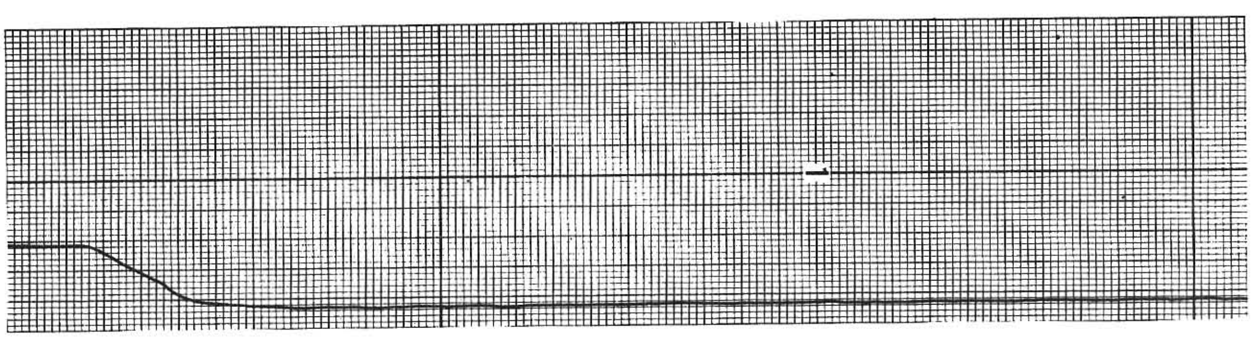

Figure 46. Deceleration From 1600 to 1200 rpm at 40.0 lb-ft Load;
Bosch Injection; 5 mm/sec

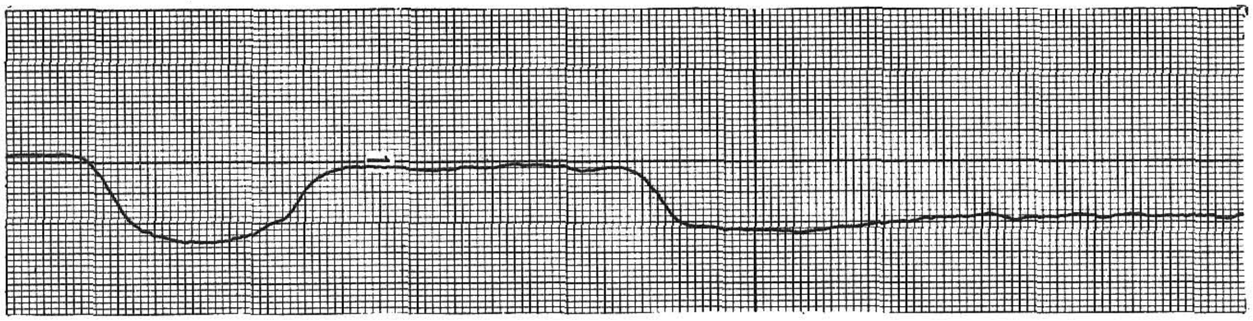

Figure 47. Deceleration From 2000 to 1600 rpm at 10.0 lb-ft Load; Bosch Injection; 5 mm/sec

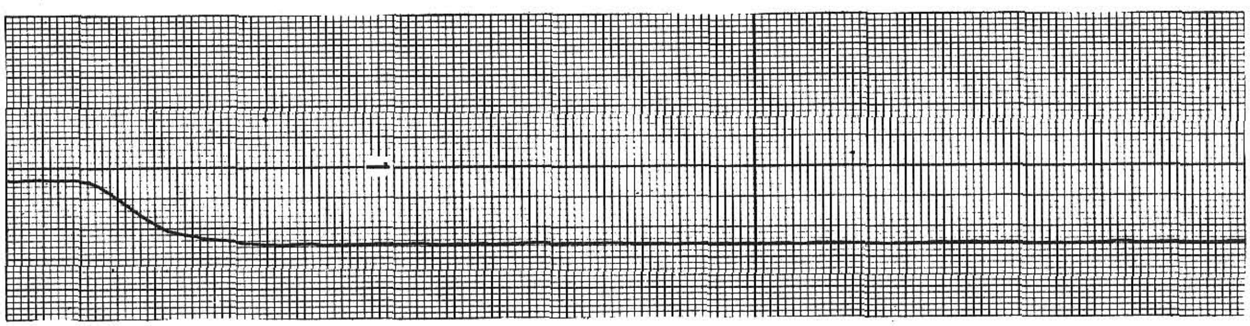

Figure 48. Deceleration From 2000 to 1600 rpm at 25.0 lb-ft Load; Bosch Injection; 5 mm/sec

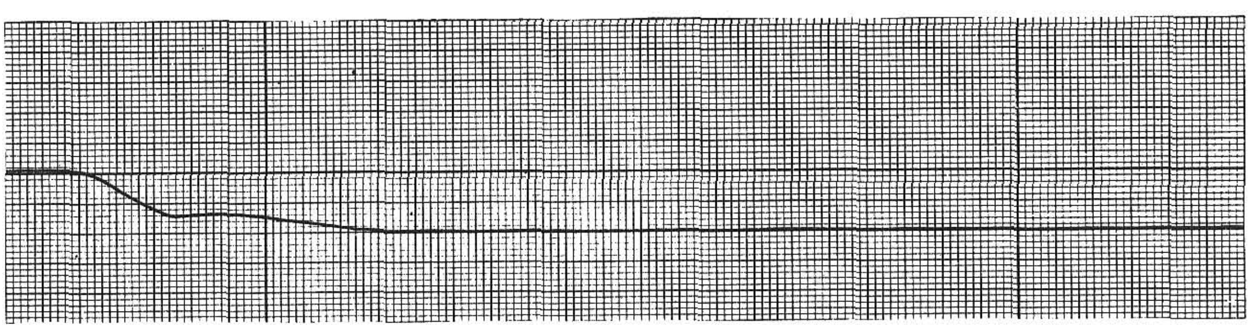

Figure 49. Deceleration From 2000 to 1600 rpm at 40.0 lb-ft Load; Bosch Injection; 5 mm/sec

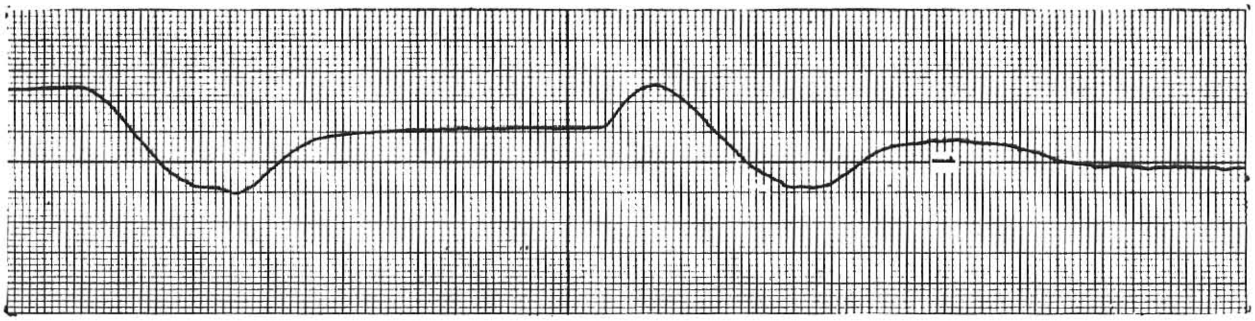

Figure 50. Deceleration From 2400 to 2000 rpm at 10.0 lb-ft Load; Bosch Injection; 5 mm/sec

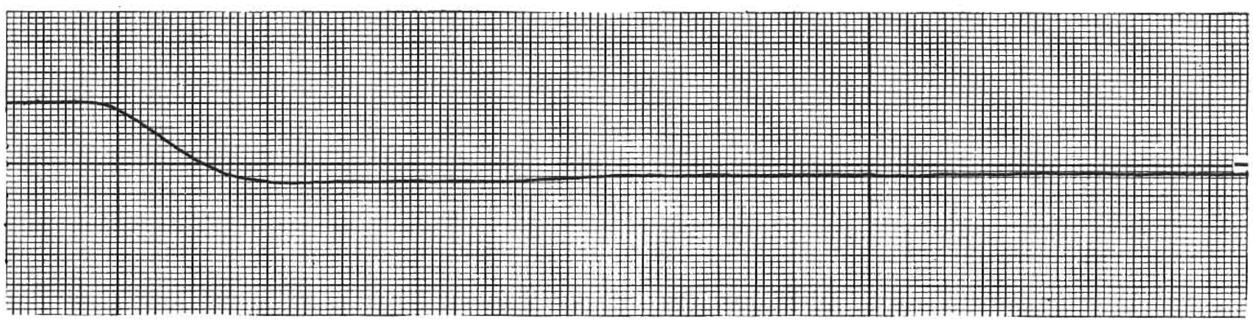

Figure 51. Deceleration From 2400 to 2000 rpm at 25.0 lb-ft Load; Bosch Injection; 5 mm/sec

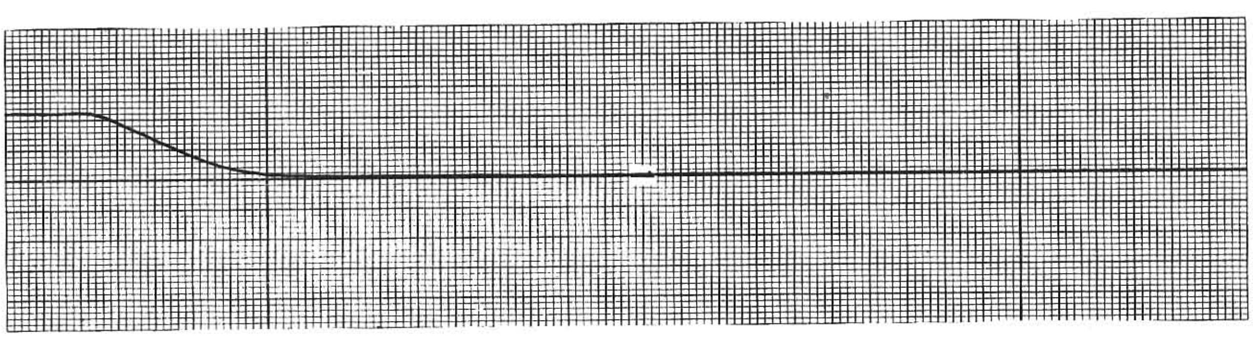

Figure 52. Deceleration From 2400 to 2000 rpm at 40.0 lb-ft Load; Bosch Injection; 5 mm/sec

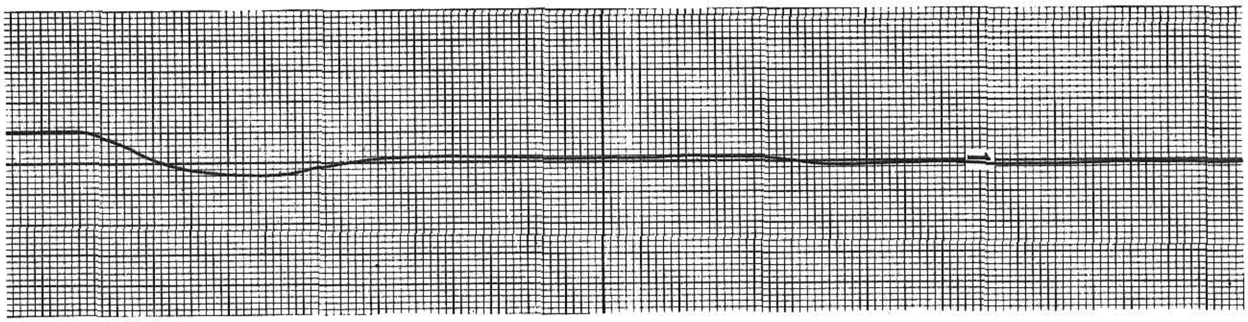

Figure 53. Deceleration From 2800 to 2400 rpm at 10.0 lb-ft Load; Bosch Injection; 5 mm/sec

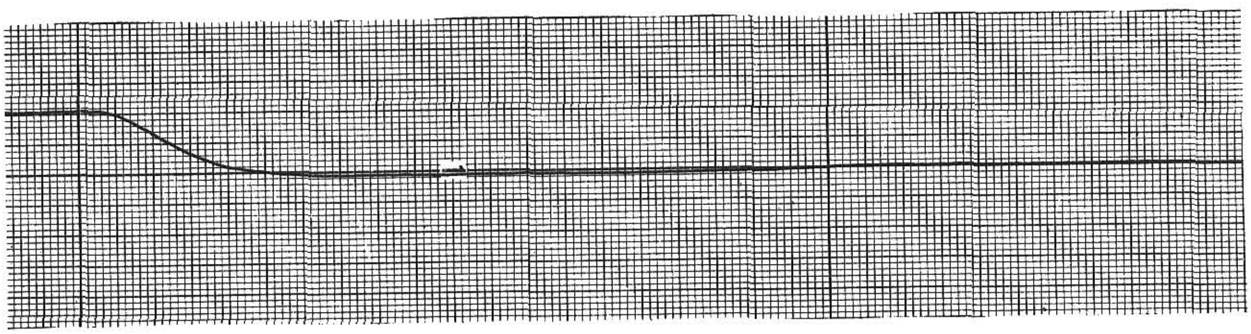

Figure 54. Deceleration From 2800 to 2400 rpm at 25.0 lb-ft Load; Bosch Injection; 5 mm/sec

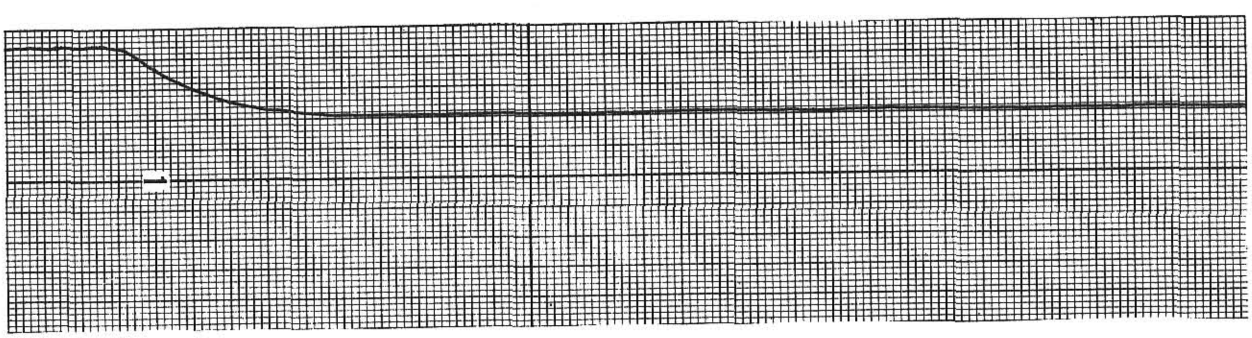

Figure 55. Deceleration From 2800 to 2400 rpm at 40.0 lb-ft Load; Bosch Injection; 5 mm/sec

stable response over this range in which the engine characteristics must change significantly as compared to the other operating conditions. This could be easily remedied, since the speed control program can easily be altered to result in a more stable response.

The results from the third set of tests are presented in figures 56 to 71. During these tests both the microcomputer speed control and fuel injection control systems were operating simultaneously. These tests were more difficult to perform due to the operations that had to be performed to switch the engine over to the microcomputer injection control system. As a result, the engine's response to the change in injection systems also altered the speed control response. Once again the chart speed is 5 mm/sec and the sensitivity is about 40 rpm/mm. Difficulty was encountered in operating the engine at 40.0 lb-ft of load while the speed control was trying to accelerate the engine speed, due to the switching of injection systems, therefore these tests were not made.

The final set of tests, shown in figures 72 to 75, are to represent the response of the engine speed control to a disturbance, a sudden change in load applied to the engine. These tests were again made at a recording speed of 5 mm/sec and sensitivity of 40 rpm/div.

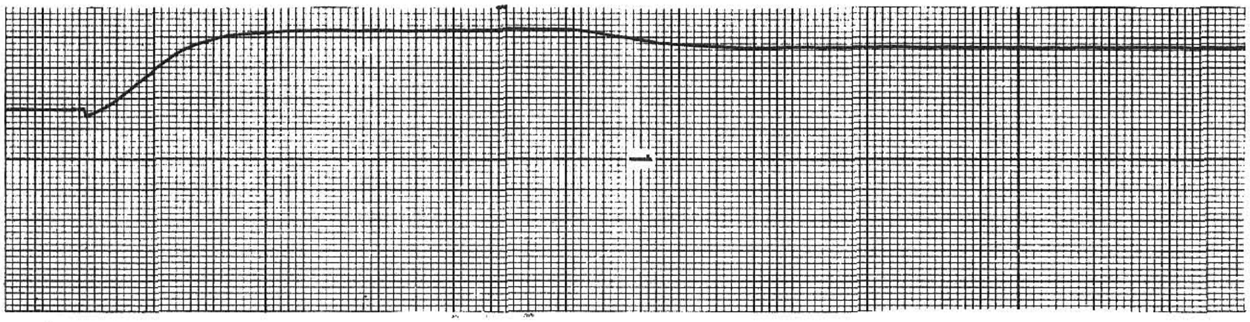

Figure 56. Acceleration From 2400 to 2800 rpm at 10.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

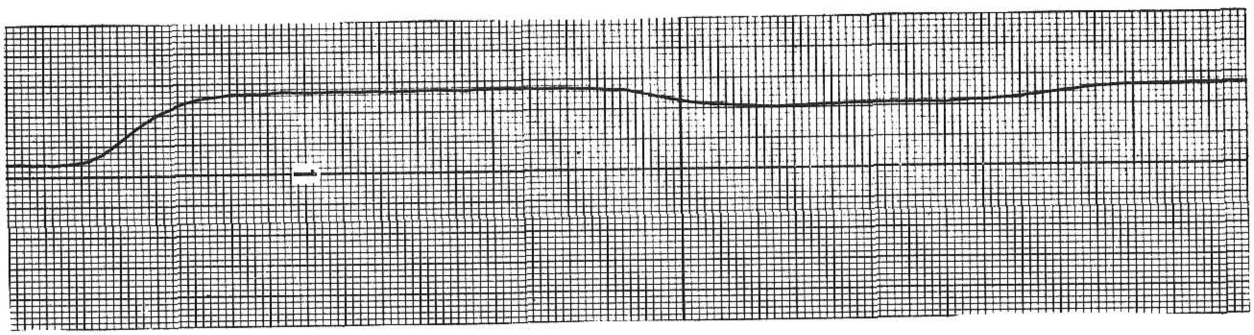

Figure 57. Acceleration From 2000 to 2400 rpm at 10.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

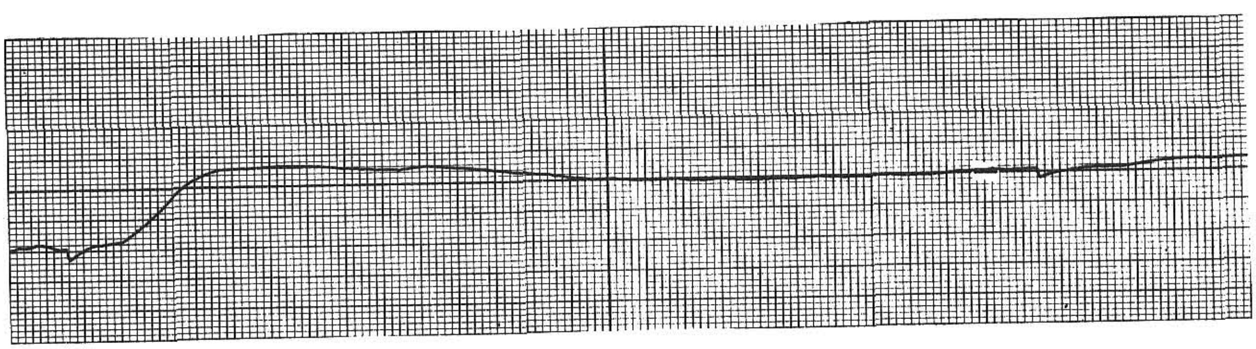

Figure 58. Acceleration From 1600 to 2000 rpm at 10.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

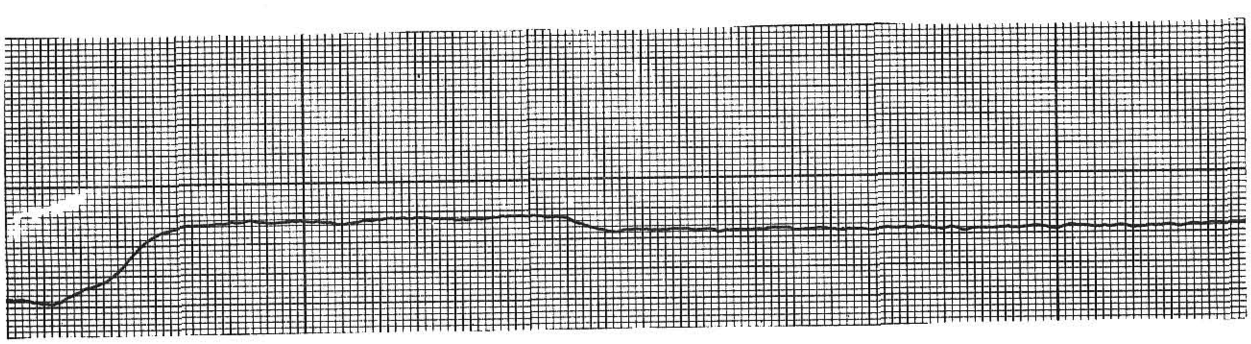

Figure 59. Acceleration From 1200 to 1600 rpm at 10.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

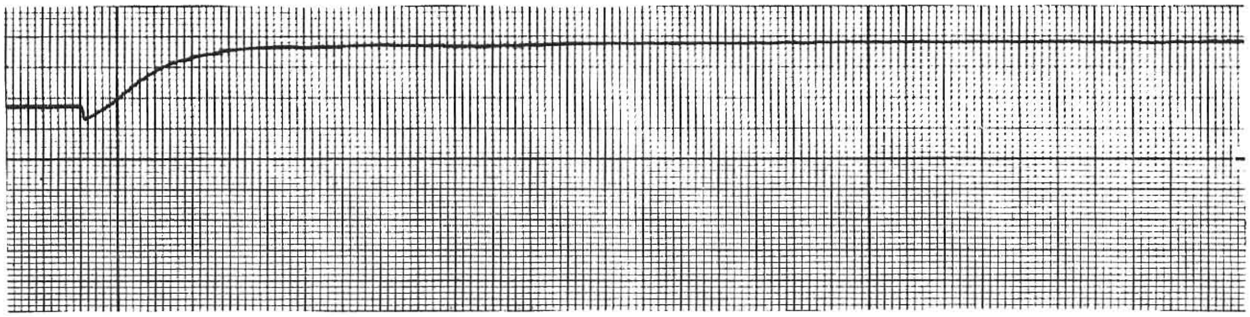

Figure 60. Acceleration From 2400 to 2800 rpm at 25.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

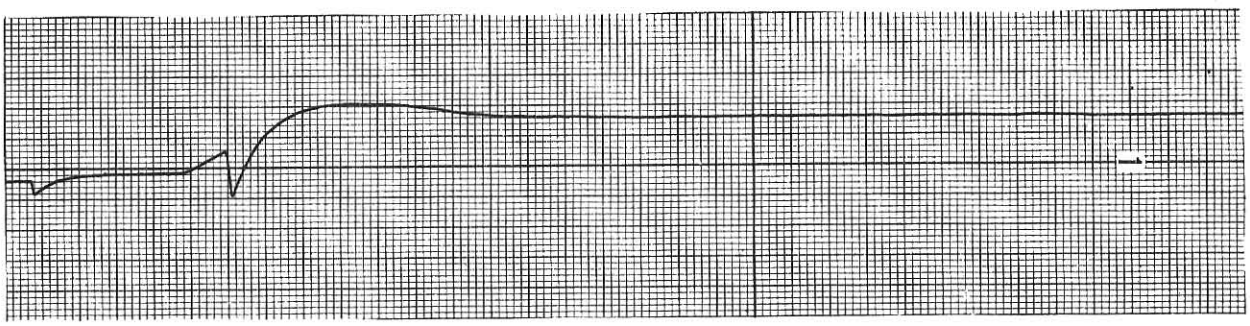

Figure 61. Acceleration From 2000 to 2400 rpm at 25.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

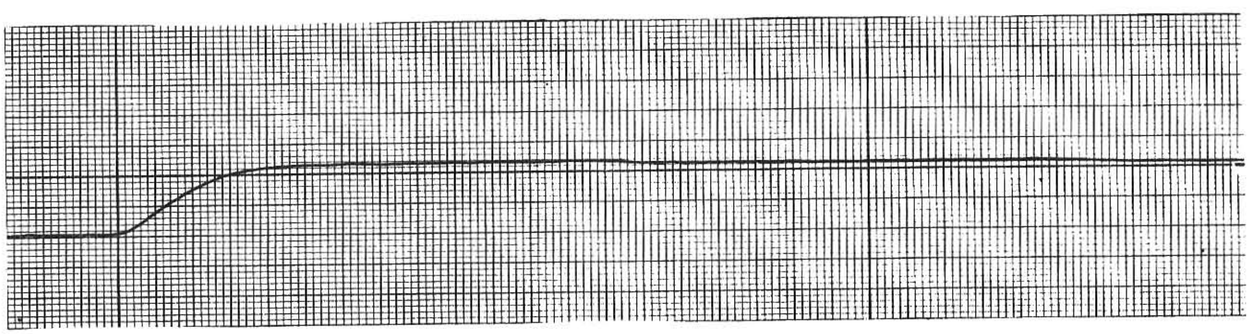

Figure 62. Acceleration From 1600 to 2000 rpm at 25.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

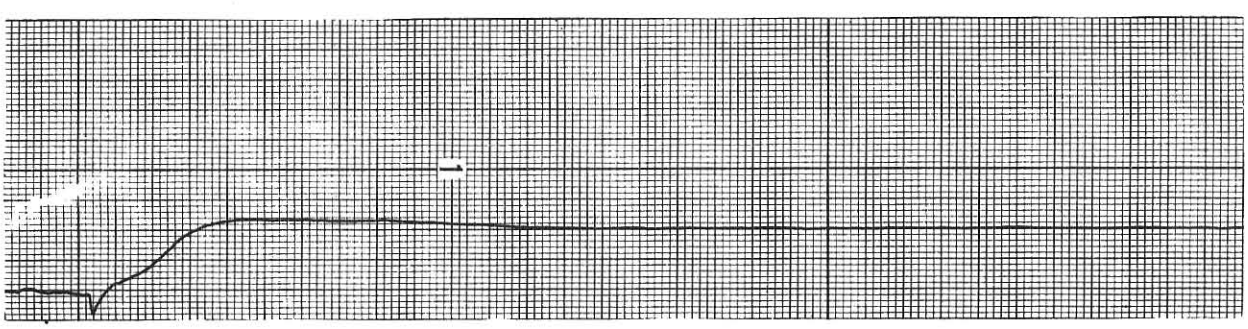

Figure 63. Acceleration From 1200 to 1600 rpm at 25.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

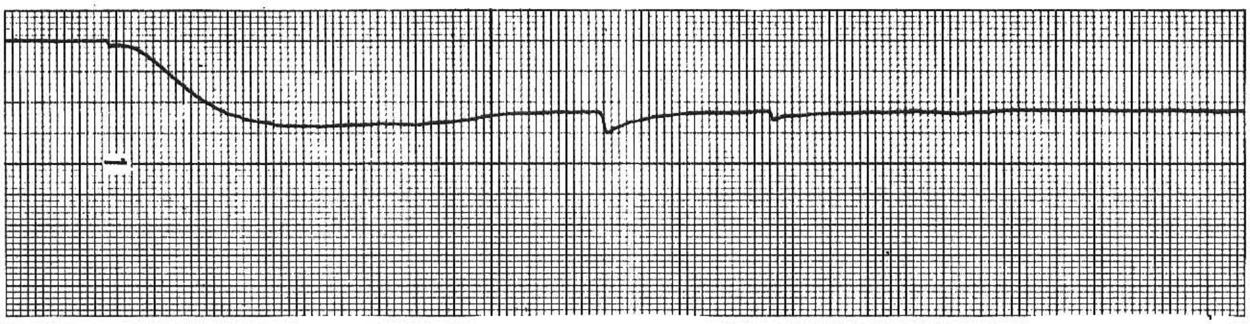

Figure 64. Deceleration From 2800 to 2400 rpm at 10.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

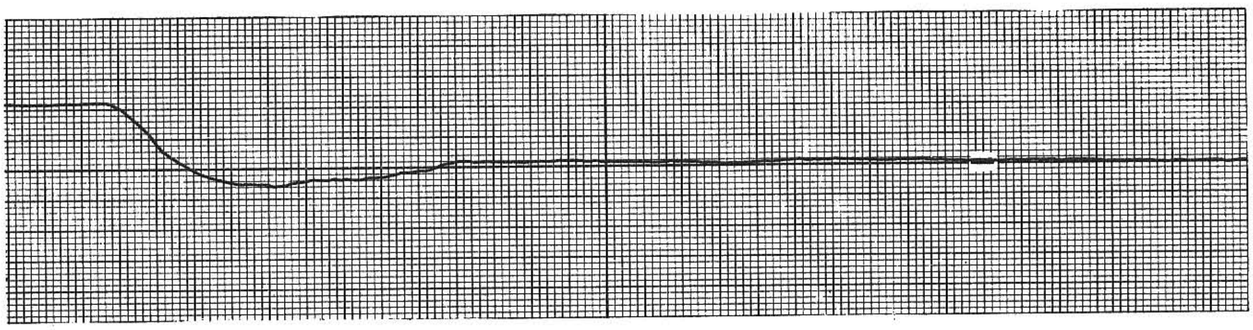

Figure 65. Deceleration From 2400 to 2000 rpm at 10.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

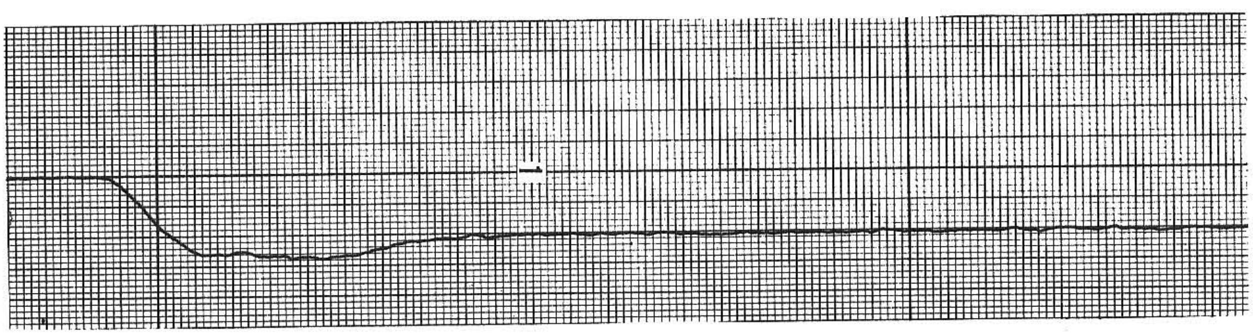

Figure 66. Deceleration From 2000 to 1600 rpm at 10.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

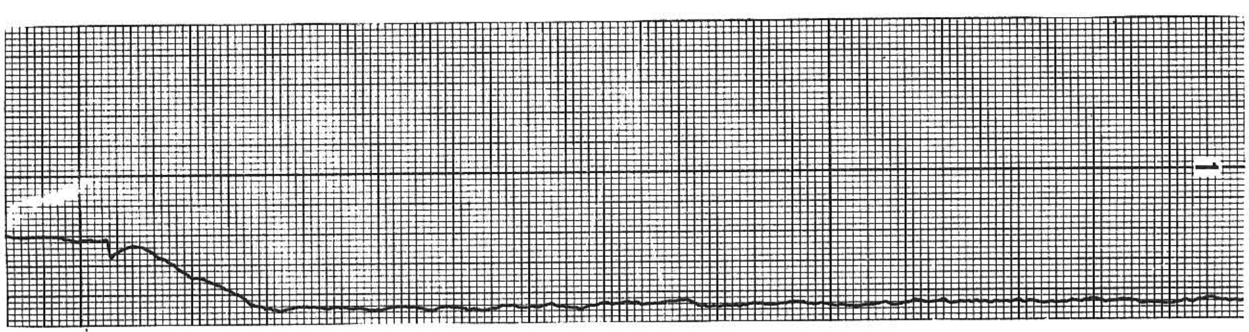

Figure 67. Deceleration from 1600 to 1200 rpm at 10.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

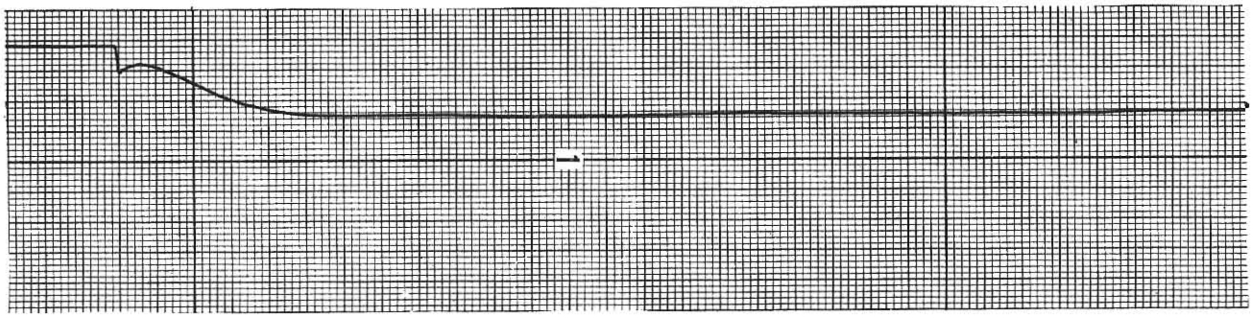

Figure 68. Deceleration From 2800 to 2400 rpm at 25.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

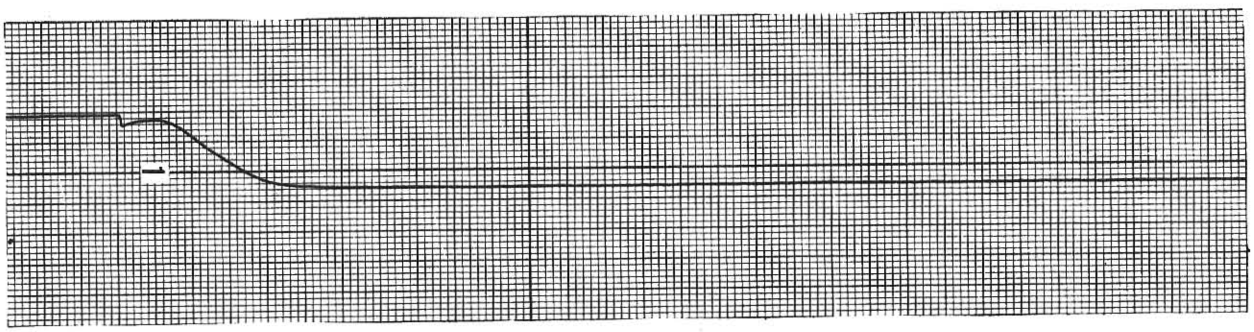

Figure 69. Deceleration From 2400 to 2000 rpm at 25.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

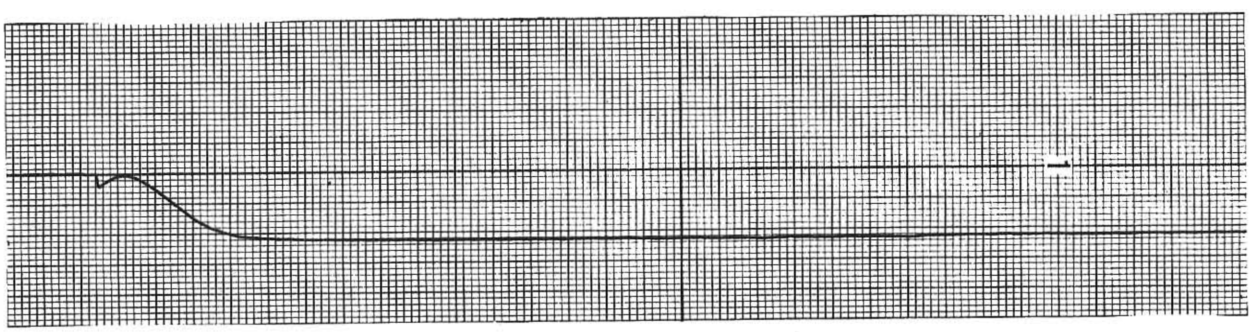

Figure 70. Deceleration From 2000 to 1600 rpm at 25.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

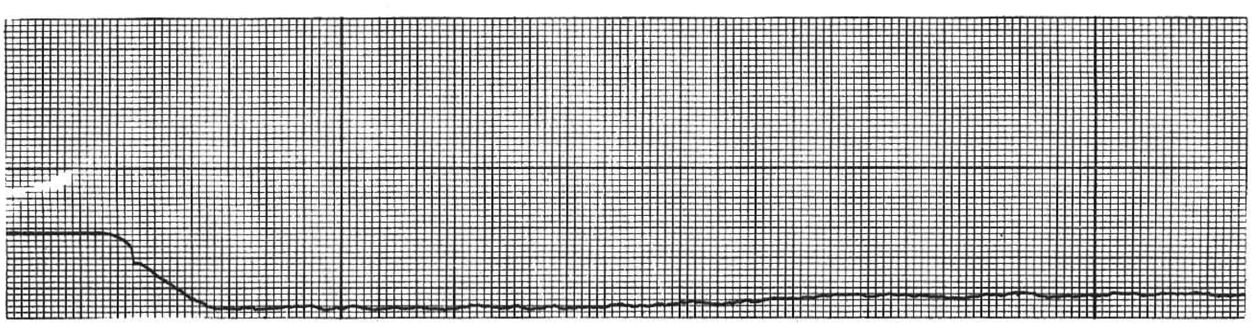

Figure 71. Deceleration From 1600 to 1200 rpm at 25.0 lb-ft Load; Microcomputer Injection; 5 mm/sec

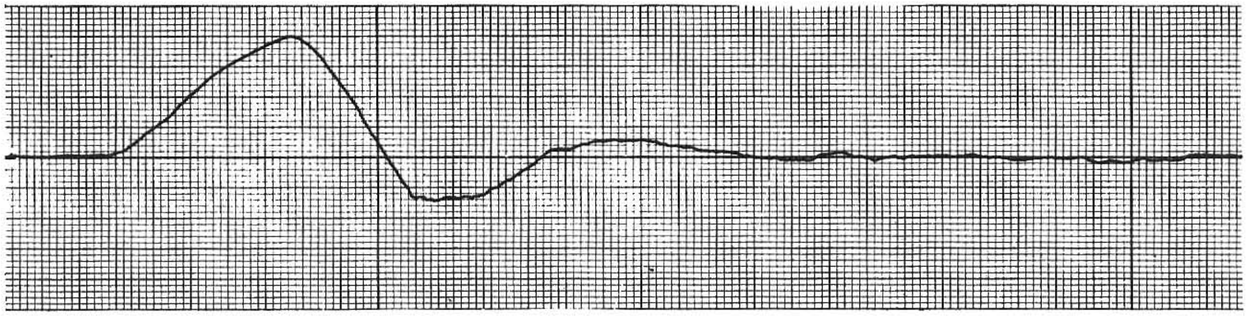

Figure 72. Set Speed of 2000 rpm; Load Disturbance From 25.0 lb-ft to 10.0 lb-ft; Bosch Injection; 5 mm/sec

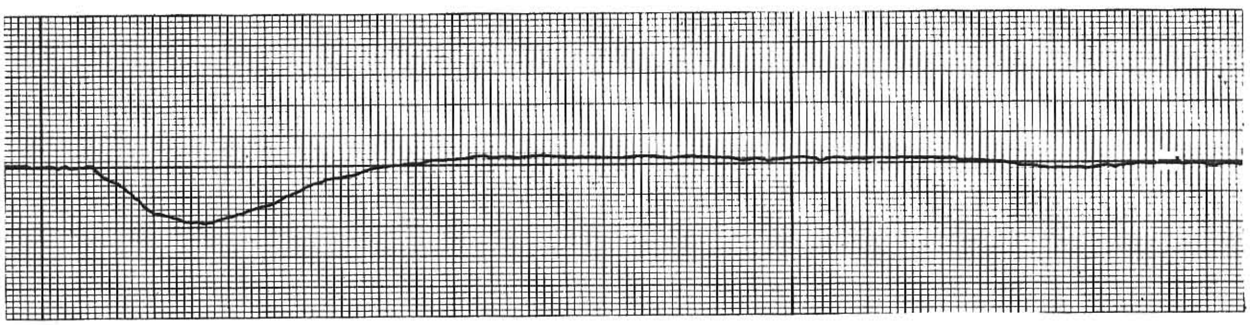

Figure 73. Set Speed of 2000 rpm; Load Disturbance From 10.0 to 25.0 lb-ft; Bosch Injection; 5 mm/sec

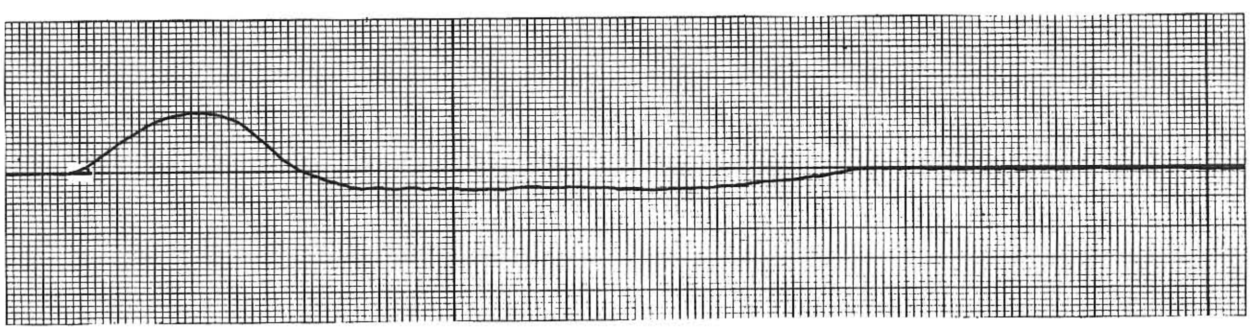

Figure 74. Set Speed of 2000 rpm; Load Disturbance From 40.0 to 25.0 lb-ft; Bosch Injection; 5 mm/sec

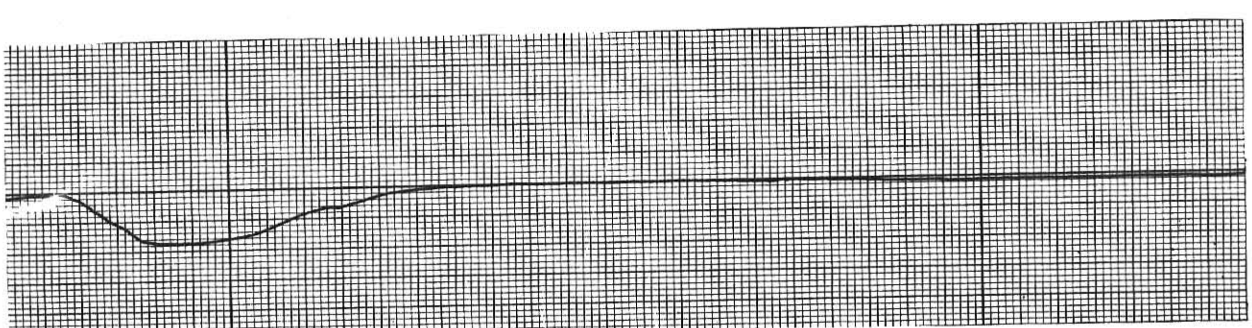

Figure 75. Set Speed of 2000 rpm; Load Disturbance From 25.0 to 40.0 lb-ft; Bosch Injection; 5 mm/sec

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7-1 Introduction

The first chapter of this thesis provided an introduction to the work that was conducted in this research and a description of the objective. Chapters 2 and 3 provided descriptions of the systems involved in the air-fuel ratio and speed controllers. The fourth chapter presented the software developed for the microcomputer control systems, while chapter 5 described the procedures and testing performed on the engine. Chapter 6 presented the results of these tests in full. This chapter will provide a summary of this work. Recommendations for further study will also be given in this chapter.

7-2 Summary and Conclusions

Engine performance tests were conducted to determine the characteristics of the microcomputer air-fuel ratio and speed control systems. These tests were run over an operating range of the engine of 1000 to 3000 rpm and loads of 10.0 to 40.0 lb-ft. The microprocessor was programmed to control the air-fuel ratio at four different values: 11.2-1, 12.8-1, 14.4-1, and 16.0-1. Speed controller performance was determined by acceleration and deceleration tests over the operating range of speed and load. Tests were also performed by operating the engine at a constant speed and then introducing a sudden disturbance, consisting of an increase or decrease in the load.

The results of this testing showed that:

1. The air-fuel ratio could be maintained within a percentage standard

deviation from the mean between 5.3% and 11.5%. The limit of error for these measurements was calculated to be 3.3%.

2. The actual, measured air-fuel ratios differed from the desired air-fuel ratios by a minimum of 0.85% at a desired air-fuel ratio of 14.4-1 to a maximum of 7.42% at a desired air-fuel ratio of 11.2-1.
3. The table look-up method used in the air-fuel ratio controller performed adequately throughout the testing with few complications, although this method of control required a large amount of memory for storage of injection time data, which in turn required considerable time to be programmed into the computer.
4. Changes in air temperature and atmospheric pressure may have had an effect on the air-fuel ratio control system, since these parameters were not sensed or adjusted for in the injection time look-up tables.
5. The mathematical model of the engine and control system proved to be adequate for performing a frequency response analysis of the microcomputer speed controller. The ease with which parameters of the controller can be changed should allow further tests to be made that could result in more accurate values of the parameters being used for each combination of speed and load, with a resulting improvement in the transient response.
6. Stable acceleration and deceleration results could be obtained while operating the speed control system over the entire operating range of speed and load, although the response was nearly unstable at a load of 10.0 lb-ft and between the range of 1600 to 2400 rpm. The microcomputer also corrected for disturbances that were applied to the system, maintaining the engine at a constant speed after a reasonable period during which corrections were made.

7. Some problems were encountered while operating the engine with both microcomputer speed and fuel injection control systems operating. This was due mostly to the awkwardness of switching to the microcomputer system from the original system after an interrupt had been demanded by the operator to vary the desired speed. The relative slowness with which the microcomputer speed control system operated, mainly due to the excessive length of time it took to perform the one main division in the speed control algorithm, also caused problems within the speed control system.
8. It has been shown in this research that it is possible to control both the air-fuel ratio and speed of an electronically fuel injected internal combustion engine using a KIM-1 microcomputer and additional memory. The limitations of peripheral devices supplied with the microcomputer added numerous complications to the programming of the system as a whole, which could have been avoided had certain peripheral devices been added. However, these complications were dealt with and successfully overcome.

7-3 Recommendations

There are several recommendations which can be made to improve upon the research conducted for this thesis, and to expand upon the system for further research. One physical device which could be added to the microcomputer system that would improve the ease with which it could be programmed would be a 6530 Peripheral Interface Adapter containing additional input-output pins and another programmable interval timer. The restrictions and complications that arose from the fact that only one interval timer was available on this microcomputer were numerous, although not insurmountable. A few restrictions were encountered because only 15 input-output pins were available, although these too were overcome by increased software complexity.

Improvements may be made on the system if a different method were used to determine engine speed. The counting circuitry used for this research proved to be adequate in the laboratory in which the distributor signal was simulated by the output of a function generator. However, during actual engine testing the output data simply was not stable enough at times to provide reliable speed values for the control systems employed in this research. Additional problems arose due to the non-linearity associated with the counting network over the speed range utilized in this research. Although this counting circuit provided for good resolution over lower speed ranges, at the higher range of speeds the resolution decreased greatly. This property may have further contributed to errors in the speed control system.

Improved resolution could also be obtained in the speed control system through additional gearing of the stepping motor. Because the rotational span of the throttle is so small, the stepping motor must be geared down by a large ratio. For this system, the gearing was to be sufficient to allow for a resolution of 10 rpm. This could easily be improved upon simply by further gearing down the stepping motor.

For this research most of the external electronics, including the TTL and analog-to-digital conversion circuitry, was mounted on circuit design breadboards. This circuitry could be restructured into a more compact design that would make it easier to transport it from one testing laboratory to another. An improved layout would also improve the ease with which A/D and D/A components could be utilized in further testing.

An analysis might be made to determine if the existing program structure could be refined to provide improved control. For this research the air-fuel ratio control was accomplished through a table look-up system, while speed control utilized a division routine to evaluate a mathematical algorithm. The table look-up method provided a fast means for injection time determination - 106 microseconds maximum, including the checks made to verify that the look-up values remained within the confines of the table. The problem associated with this method was the large amount of memory required for storage of the injection time data 7680 words. One way that this memory requirement could be reduced would be through the development of an interpolation algorithm that would allow fewer data points to be stored in memory while retaining the speed and accuracy of the present system. Another way in which the memory requirement could be reduced would be through utilization of a mathematical algorithm, evaluated with multiplication and division routines. An analysis should be made to determine the feasibility of this method, in particular.

The multiplication and division routines developed for this thesis could probably be improved somewhat for additional research. Such an effort would particularly be worthwhile if these routines were used to calculate the injection times as suggested. The present multiplication subroutine requires at least 270 μsec for execution and at most 490 μsec, depending on the branches taken during execution of the routine. The division subroutine requires 50 μsec during the initialization process and sign fix-up. Each subtraction loop requires 40 μsec. Therefore, for a division in which the dividend is 110 and the divisor is 50, the division routine would require about 150 μsec execution time. However, for a division in which the divisor is 5, the division routine requires about 930 msec to be executed with the same dividend as before. This characteristic can be a major drawback in an engine control system such as the one developed for this research, in which the cycle length is quite short.

Another aspect of this research that was largely an inconvenience, but that could be a major handicap in further research, was lack of a provision for operator interaction with the microcomputer during control operations. During this research, whenever the demand speed was to be changed the engine control had to be switched back to the Bosch control unit, the computer operation reset and speed value changed, then engine control switched back to the microcomputer. Elimination of this drawback would expedite the alteration or examination of parameter values during on line control.

A provision to compensate for ambient temperature and pressure changes in the air-fuel ratio control could possibly improve these results, and may be necessary for operation over a wider range of these variables than was encountered during this research. It is now felt that the fuel injector calibration was the primary cause of the offset in the air-fuel ratio results. These injectors should be calibrated again to determine if the calibration curve used during this research can be duplicated.

The research conducted in this thesis was conducted over a limited range of engine speeds with the engine fully warmed up. During additional research the control capabilities would be broadened if the microcomputer were programmed to run the engine during cold-starting and warm-up periods. This would entail sensing the oil temperature or head temperature and adjusting the air-fuel ratio accordingly. The incorporation of this control strategy would be relatively simple if a computational algorithm was used.

Another aspect of engine control that might be researched in conjunction with fuel injection control is ignition timing. An optimal control system incorporating both ignition timing and injection control would maximize performance of the engine. The use of feedback elements to provide closed-loop control would minimize the dependence of such a system on the calibrations of open loop sensing devices.

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APPENDICES

APPENDIX A

ENGINE SPECIFICATIONS

Model	1968 Volkswagen, Electronic Fuel Injection
Number of Cylinders	4
Displacement	96.9 cu. in. (1.584 1)
Compression Ratio	8.8:1
Torque (SAE)	86.8 ft-lb 2800 rpm
Output (SAE)	65 bhp @ 4600 rpm
Bore	3.36 in (85.5 mm)
Stroke	2.72 in (69 mm)
Valve Clearance	.006 in (.15 mm) intake & exhaust
Ignition Timing	0^{o} TDC @ 850 rpm with vacuum hose disconnected
Spark Plug Type	Bosch W 145 T 1
Spark Plug Gap	.028 in (.7 mm)
Breaker Point Gap	.016 in (.4 mm)
Engine Oil	between 40^{o}F and 86^{o}F SAE 30 (MS)

APPENDIX B

MICROCOMPUTER SPECIFICATIONS

Manufacturer	MOS Technology, Inc.
Model	KIM-1 Microcomputer System
MPU	8-Bit 6502 Microprocessor Array
Address Range	65 K (65,536 bytes)
No. of Addressing Modes	13
Available ROM	2048 bytes
Available RAM	1152 bytes
Available I/0	15 bits
Interrupt Modes	Non-Maskable (NMI) and Interrupt Request (IRQ)
Available Interval Timers	1

Additional Memory

Manufacturer	The Digital Group
Available RAM	8 K (8192 bytes)

APPENDIX C

UNCERTAINTY ANALYSIS

The equations of Sprague and Nash (20) will be used to calculate the uncertainty in each of the performance parameters. For a variable which is a function of various independently measured values

$$H = f(Y_1, Y_2, Y_3, \ldots, Y_n),$$

the uncertainty in H is

$$\lambda_H = \sqrt{S_1^2\lambda_1^2 + S_2^2\lambda_2^2 + \ldots + S_n^2\lambda_n^2} \tag{15}$$

where S_n is defined as

$$S_n = \frac{\partial f}{\partial Y_n} \frac{Y_n}{f(Y_1, Y_2, \ldots, Y_n)} \tag{16}$$

and where λ_n is the uncertainty in the n'th measured value.

For a variable which is a function of variously measured dependent values, the equation for the uncertainty is

$$\lambda_H = \sqrt{(S_1\lambda_1 + S_2\lambda_2 + S_3\lambda_3 + \ldots + S_n\lambda_n)^2} \tag{17}$$

For this uncertainty analysis λ will be calculated in percent of reading wherever possible. The uncertainties will be calculated using the smallest measured values in order to determine the largest uncertainties involved. In cases where manufacturer's literature was not available for the instruments used, the resolution was assumed equal to ½ of the smallest scale division of the particular instrument. Also, it was assumed that the instrument uncertainty and the resolution would be nearly equal.

Air Flow Sensor Calibration Uncertainty

The primary variables involved in determining the air flow sensor calibration were the air flow sensor output voltage and the corresponding mass air flow rate. To calculate the mass air flow rate uncertainty, the uncertainty in CFM and DENAIR must first be found. These two quantities in turn require the uncertainty in TDB, TWB, ATMPR, PNSD, and PMN to be computed.

The uncertainty in TDB and TWB are found by assuming the instrument uncertainty equals the resolution uncertainty of 0.5°F. The smallest value of TDB during calibration was 82°F, while the smallest value of TWB was 68°F. The uncertainties then are:

$$\lambda_{TDB} = \sqrt{(\lambda^2)\text{ linearity} + (\lambda^2)\text{ resolution}}$$

$$= \sqrt{\left[\frac{0.5}{82}\right]^2 + \left[\frac{0.5}{82}\right]^2}$$

$$= 0.862\%$$

$$\lambda_{TWB} = \sqrt{(\lambda^2)\text{ linearity} + (\lambda^2)\text{ resolution}}$$

$$= \sqrt{\left[\frac{0.5}{68}\right]^2 + \left[\frac{0.5}{68}\right]^2}$$

$$= 1.040\%$$

The uncertainty in the barometric pressure is to be calculated with the instrument uncertainty and resolution uncertainty equal to the smallest scale division on the barometer, since a vernier scale was incorporated in the readings. The smallest division was 0.01 in. Hg. and the smallest pressure reading was 28.68 in. Hg. The uncertainty in ATMPR is:

$$\lambda_{ATMPR} = \sqrt{(\lambda^2)\text{ linearity} + (\lambda^2)\text{ resolution}}$$

$$= \sqrt{\left[\frac{0.01}{28.68}\right]^2 + \left[\frac{0.01}{28.68}\right]^2}$$

$$= 0.0493\%$$

Once the sensitivities of TDB, TWB, and ATMPR are determined, the uncertainty in DENAIR can be computed. From equation 16:

$$S_{TDB} = \frac{\frac{\partial\ DENAIR}{\partial\ TDB}\ TDB}{DENAIR}$$

$$S_{TDB} = \frac{-1.33\ \frac{ATMPR}{TDB} + 1.03\ \frac{PW}{TDB} + 0.00019\ \frac{TWB}{TDB}\ ATMPR}{1.33\ \frac{ATMPR}{TDB} - 1.03\ \frac{PW}{TDB} + 0.00019\ ATMPR - 0.00019\ \frac{TWB}{TDB}\ ATMPR}\ .$$

This provides an equation representing the sensitivity for the dry bulb temperature with respect to the air density. Calculating the sensitivity for TWB:

$$S_{TWB} = \frac{\frac{\partial\ DENAIR}{\partial\ TWB}\ TWB}{DENAIR}$$

$$S_{TWB} = \frac{-0.00019\ \frac{TWB}{TDB}\ ATMPR}{1.33\ \frac{ATMPR}{TDB} - 1.03\ \frac{PW}{TDB} + 0.00019\ ATMPR - 0.00019\ \frac{TWB}{TDB}\ ATMPR}$$

Next calculate the sensitivity of ATMPR:

$$S_{ATMPR} = \frac{\frac{\partial\ DENAIR}{\partial\ ATMPR}\ ATMPR}{DENAIR}$$

$$= \frac{\frac{\partial}{\partial\ ATMPR}\ \frac{1.33}{TDB} + 0.00019 - 0.00019\ \frac{TWB}{TDB}\ ATMPR - 1.03\ \frac{PW}{TDB}\ ATMPR}{1.33\ \frac{ATMPR}{TDB} - 1.03\ \frac{PW}{TDB} + 0.00019\ ATMPR - 0.00019\ \frac{TWB}{TDB}\ ATMPR}$$

$$= \frac{\frac{1.33}{TDB} + 0.00019 - 0.00019\ \frac{TWB}{TDB}}{\frac{1.33}{TDB} - \frac{1.03\ PW}{ATMPR(TDB)} + 0.00019 - 0.00019\ \frac{TWB}{TDB}}\ .$$

The values of TDB, TWB, ATMPR, and PW to be substituted into the above sensitivity equations just derived will be the corresponding values previously used in this analysis. These values are:

TDB = $82^{o}F$

TWB = $68^{o}F$

PW = 0.33889 psi

ATMPR = 28.68 in. Hg

When these values are substituted into the sensitivity equations, the result is:

$S_{TDB} = -0.998$

$S_{TWB} = -0.0098$

$S_{ATMPR} = 1.010$

The uncertainty in DENAIR can now be found.

$$\lambda_{DENAIR} = \sqrt{(S^2\lambda^2)_{TDB} + (S^2\lambda^2)_{TWB} + (S^2\lambda^2)_{ATMPR}}$$

$$= \sqrt{(-.998)^2(.00862)^2 + (-.0098)^2(.0104)^2 + (1.010)^2(.000493)^2}$$

$$= 0.86\%$$

Next, the uncertainty in PNSD and CFM must be found so that the uncertainty in the air mass flow rate can be obtained. Since

$$PNSD = \frac{PMN(.075)}{DENAIR},$$

the uncertainty in PMN must be calculated before the PNSD uncertainty can be found. The uncertainty associated with PMN measurements was the resolution and linearity of the micromanometer. Again, these two uncertainties are assumed equal to ½ the smallest scale division, or 0.0005. The uncertainty is:

$$\lambda_{PMN} = \sqrt{(\lambda^2)\text{ linearity} + (\lambda^2)\text{ resolution}}$$

$$= \sqrt{\left[\frac{.0005}{.024}\right]^2 + \left[\frac{.0005}{.024}\right]^2}$$

$$= 2.95\%$$

The sensitivities of PMN and DENAIR with respect to PNSD are:

$$S_{PMN} = \frac{\frac{\partial\ PNSD}{\partial\ PMN}\ PMN}{PNSD}$$

$$= \frac{\frac{\partial}{\partial\ PMN}\ \frac{.075\,(PMN)}{DENAIR}\ PMN}{\frac{.075\,(PMN)}{DENAIR}}$$

$$= 1$$

$$S_{DENAIR} = \frac{\frac{\partial\ PNSD}{\partial\ DENAIR}\ DENAIR}{PNSD}$$

$$= \frac{\frac{\partial}{\partial\ DENAIR}\ \frac{.075\ PMN}{DENAIR}\ DENAIR}{\frac{.075\ PMN}{DENAIR}}$$

$$= 1$$

Therefore, the uncertainty in PNSD is

$$\lambda_{PNSD} = \sqrt{(S^2\lambda^2)_{PMN} + (S^2\lambda^2)_{DENAIR}}$$

$$= \sqrt{(0.0295)^2 + (0.0086)^2}$$

$$= 3.07\%$$

To calculate the uncertainty in CFM the sensitivity of PNSD must be found.

$$S_{PNSD} = \frac{\frac{\partial\ CFM}{\partial\ PNSD}\ PNSD}{CFM}$$

$$= \frac{\frac{\partial}{\partial\ PNSD}\ (62.0524)(PNSD)^{.5014}(PNSD)}{(62.0524)(PNSD)^{.5014}}$$

$$= \frac{(62.0524)(.5014)(PNSD)}{(62.0524)(PNSD)^{.5014}}\ (PNSD)$$

$$= 0.5014$$

The uncertainty in CFM now can be calculated as:

$$\lambda_{CFM} = \sqrt{(S^2\lambda^2)_{PNSD}}$$

$$= (0.0307)(0.5014)$$

$$= 1.54\%$$

The sensitivities of DENAIR and CFM with respect to the mass air flow rate are:

$$S_{DENAIR} = \frac{\frac{\partial\ AMFR}{\partial\ DENAIR}\ DENAIR}{AMFR}$$

$$= \frac{\frac{\partial}{\partial \text{ DENAIR}} (\text{CFM})(\text{DENAIR})}{(\text{CFM})(\text{DENAIR})} \text{ DENAIR}$$

$$= 1$$

Likewise, the sensitivity of CFM is 1. Therefore, the uncertainty in AMFR is calculated as:

$$\lambda_{AMFR} = \sqrt{(S^2\lambda^2)_{CFM} + (S^2\lambda^2)_{DENAIR}}$$

$$= \sqrt{(0.0154)^2 + (0.0086)^2}$$

$$= 1.76\%$$

The uncertainty involved in measuring the air flow sensor voltage lies in the uncertainty of the Fluke digital multimeter that was used for these measurements. This uncertainty is due to the linearity and resolution parameters:

$$\lambda_{Multimeter} = \pm \text{ (0.1\% of reading + 1 digit)}$$

$$= \sqrt{(0.001)^2 + \left[\frac{.01}{0.70}\right]^2} = 1.43\%$$

<u>Fuel Injector Calibration Uncertainty</u>

The primary variables involved in the electromagnetic fuel injector calibration were the mass of fuel consumed by the engine per injection and the corresponding injection length in milliseconds. The mass of fuel consumed per injection was calculated from the equation:

$$\text{INJECT} = \frac{(\text{DELGAS})(120)}{(\text{RPM})(\text{DELTIM})}$$

where RPM is the engine speed in revolutions per minute, DELGAS is the mass of fuel consumed per test, and DELTIM is the elapsed time of the test period in seconds. Therefore to calculate the uncertainty in INJECT the uncertainties in RPM, DELGAS, and DELTIM must first be calculated.

The sensitivities of these parameters will be calculated first. The sensitivity of DELGAS is:

$$S_{DELGAS} = \frac{\frac{\partial\ INJECT}{\partial\ DELGAS}\ DELGAS}{INJECT}$$

$$= \frac{\frac{\partial}{\partial\ DELGAS}\ \frac{(DELGAS)(120)}{(RPM)(DELTIM)}}{\frac{(DELGAS)(120)}{(RPM)(DELTIM)}}\ DELGAS$$

$$= \frac{\frac{120}{(RPM)(DELTIM)}}{\frac{(DELGAS)(120)}{(RPM)(DELTIM)}}\ DELGAS$$

$$= 1$$

In the same manner, the sensitivities of RPM and DELTIM are found to be -1.

A mass balance with a smallest scale division of 0.01 lb_m was used to determine DELGAS. This allows the uncertainty to be calculated for this parameter as:

$$\lambda_{DELGAS} = \sqrt{\lambda^2\ linearity + \lambda^2\ resolution}$$

$$= \sqrt{\left[\frac{.005}{.40}\right]^2 + \left[\frac{.005}{.40}\right]^2}$$

$$= 1.77\%$$

A stopwatch was used to measure DELTIM. The uncertainty for this parameter is:

$$\lambda_{DELTIM} = \sqrt{\lambda^2\ linearity + \lambda^2\ resolution}$$

$$= \sqrt{\left[\frac{.05}{163.9}\right]^2 + \left[\frac{.05}{163.9}\right]^2} = 0.043\%$$

A Daytronic Instrument Module was used to measure engine speed. The accuracy of the speed measurement module is 0.05 percent of scale for the speed output derived from the frequency-to-voltage converter. There is also a 0.02 percent $\pm$ one digit accuracy associated with the display of this quantity.

Since full scale of the engine speed was 5000 rpm, the uncertainty in the speed can be changed to percent of reading as follows:

$$\lambda_{rpm} = \sqrt{(\lambda)^2 \text{ linearity} + (\lambda)^2 \underset{\text{of display}}{\text{accuracy}} + (\lambda)^2 \text{ resolution}}$$

$$= \sqrt{(.0005)^2 + (.0002)^2 + \left[\frac{5}{5000}\right]^2}$$

$$= 0.114\%$$

Now then:

$$\lambda_{RPM} = (.114)(5000) = 5.68 \text{ rpm}$$

$$= \frac{5.68}{1200} = 0.473\%$$

The uncertainty in INJECT can now be calculated as:

$$\lambda_{INJECT} = \sqrt{(S^2\lambda^2)_{DELGAS} + (S^2\lambda^2)_{DELTIM} + (S^2\lambda^2)_{RPM}}$$

$$= \sqrt{(.0177)^2 + (.00043)^2 + (0.00114)^2}$$

$$= 1.77\%$$

For this calibration injection length also had to be measured. This was accomplished with a Tektronix Type 564 Storage Oscilloscope equipped with a Type 2B67 Time-Base plug in unit. Specifications for this instrument specify that the calibrated sweep rates are within 3% of the step switch setting. Resolution accuracy will be taken as ½ the smallest scale division. Therefore, the uncertainty associated with the injection pulse length measurement is:

$$\lambda_{PULSTIM} = \sqrt{(\lambda^2) \text{ linearity} + (\lambda^2) \text{ resolution}}$$

$$= \sqrt{(.03)^2 + \left[\frac{.05}{2.10}\right]^2}$$

$$= 3.83\%$$

Air-Fuel Ratio Uncertainty

The next parameter for which the uncertainty must be computed is the air-fuel ratio. Air-fuel ratio is defined as:

$$AFR = \frac{AIRIN}{DELGAS}$$

where AIRIN and DELGAS have been previously defined as the consumed masses of air and fuel per test, respectively.

The mass of air consumed was calculated from the equation:

$$AIRIN = \frac{(DELTIM)(AMFR)}{60}$$

To calculate the uncertainty in AIRIN, the uncertainties in DELTIM and AMFR must be found first. The limit of error for AMFR has already been calculated in the air flow sensor uncertainty calculations. While the basic equations used in the intermediate calculations leading to the total uncertainty in AMFR still hold, the values of TDB, TWB, ATMPR, PW, and PMN that apply to these equations are different for this analysis. These values will be:

$TDB = 78^{o}F$

$TWB = 63^{o}F$

$ATMPR = 28.76$ in. Hg.

$PW = 0.28495$ psi

$PMN = 0.030$ in. H_2O

Therefore:

$$\lambda_{TDB} = \sqrt{\left[\frac{.5}{78}\right]^2 + \left[\frac{.5}{78}\right]^2} = 0.907\%$$

$$\lambda_{TWB} = \sqrt{\left[\frac{.5}{63}\right]^2 + \left[\frac{.5}{63}\right]^2} = 1.122\%$$

$$\lambda_{ATMPR} = \sqrt{\left[\frac{.01}{28.76}\right]^2 + \left[\frac{.01}{28.76}\right]^2} = 0.0492\%$$

$S_{TDB} = -0.989$

$S_{TWB} = -0.0091$

$S_{ATMPR} = 1.008$

$$\lambda_{DENAIR} = \sqrt{(.00907)^2(-.989)^2 + (.01122)^2(-.0091)^2 + (.000492)^2(1.008)^2}$$

$$= 0.90\%$$

$$\lambda_{PMN} = \sqrt{\left[\frac{.0005}{.030}\right]^2 + \left[\frac{.0005}{.030}\right]^2} = 2.36\%$$

$S_{PMN} = 1$

$S_{DENAIR} = 1$

$$\lambda_{PNSD} = \sqrt{(.0090)^2 + (.0236)^2} = 2.53\%$$

$S_{PNSD} = 0.5014$

$$\lambda_{CFM} = \sqrt{(.0253)^2(.5014)^2} = 1.27\%$$

$\lambda_{DENAIR} = 1$

$\lambda_{CFM} = 1$

$$\lambda_{AMFR} = \sqrt{(.0127)^2 + (.0090)^2} = 1.56\%$$

The uncertainty in DELTIM, the length of the test in seconds, must now be calculated. This measurement was made using an arrangement consisting of a micro-switch latching device and a Hewlett Packard model 519C Electronic Counter. The specifications on the Hewlett Packard instrument state the counter accuracy is equal to $\pm$ 1 count $\pm$ the time base accuracy. During testing, DELTIM was measured to the hundredth of a second. Also, the time base accuracy is stated to be .0002% of the range used. Therefore, the Counter uncertainty is found to be:

$$\lambda_{COUNTER} = \sqrt{\left[\frac{.01}{104.52}\right]^2 + (.0002)^2}$$

$$= 0.022\%$$

Another precision error component due to the mechanical action of the micro-switch and vibration of the platform scale during testing added to the uncertainty in the measurement of DELTIM. A statistical analysis was made on this aspect of the data-taking procedure to determine this precision error component. A series of 21 tests were performed while the engine was operating at 2000 rpm and 25.0 ft-lb of load. The throttle was controlled manually, while the microcomputer controlled injection time so that it was as constant as possible throughout the data-taking procedure. The time required for the engine to consume 0.4 lb of gasoline was recorded for each test, resulting in a mean value of 162.89 seconds for the 21 tests. The standard deviation was 4.17 seconds, or 2.56%.

The parameter that has been used in calculating uncertainties thus far has been the limit of error, λ, that inculdes 95% of all expected errors. For the above analysis the 95% confidence interval must be found in order to meet this specification. Sprague and Nash state that this can be found using the equation

$$\lambda_{95\%} = \frac{1.96\sigma}{n} = \frac{(1.96)(4.17)}{3}$$

$$= 4.72$$

$$= 2.90\%$$

For this calculation n=3 because there were three samples taken at each data point during the original data-taking procedure.

The total uncertainty associated with DELTIM may now be calculated as:

$$\lambda_{DELTIM} = \sqrt{(.00022)^2 + (.0290)^2}$$

$= 2.90\%$

The sensitivities of DELTIM and AMFR with respect to AIRIN are both +1, therefore the uncertainty of AIRIN is found to be:

$$\lambda_{AIRIN} = \sqrt{(.0156)^2 + (0.029)^2}$$

$$= 3.29\%$$

A 0.4 lb weight was used for the determination of DELGAS, therefore the uncertainty in DELGAS lies in the certainty with which the 0.40 lb weight could be measured. This measurement was done using a Sartorius Model 2253-AL Balance. The uncertainty in this measurement is calculated as:

$$\lambda_{DELGAS} = \sqrt{(\lambda)^2 \text{ linearity} + (\lambda)^2 \text{ resolution}}$$

$$= \sqrt{\left[\frac{.05}{181.4}\right]^2 + \left[\frac{0.10}{181.4}\right]^2}$$

$$= 0.062\%$$

The sensitivity of AIRIN with respect to AFR is +1, while the sensitivity of DELGAS is -1. Therefore, the uncertainty in AFR is:

$$\lambda_{AFR} = \sqrt{(S^2\lambda^2)_{AIRIN} + (S^2\lambda^2)_{DELGAS}}$$

$$= \sqrt{(.0329)^2 + (.00062)^2}$$

$$= 3.29\%$$

APPENDIX D

DETAILED CIRCUIT DIAGRAMS

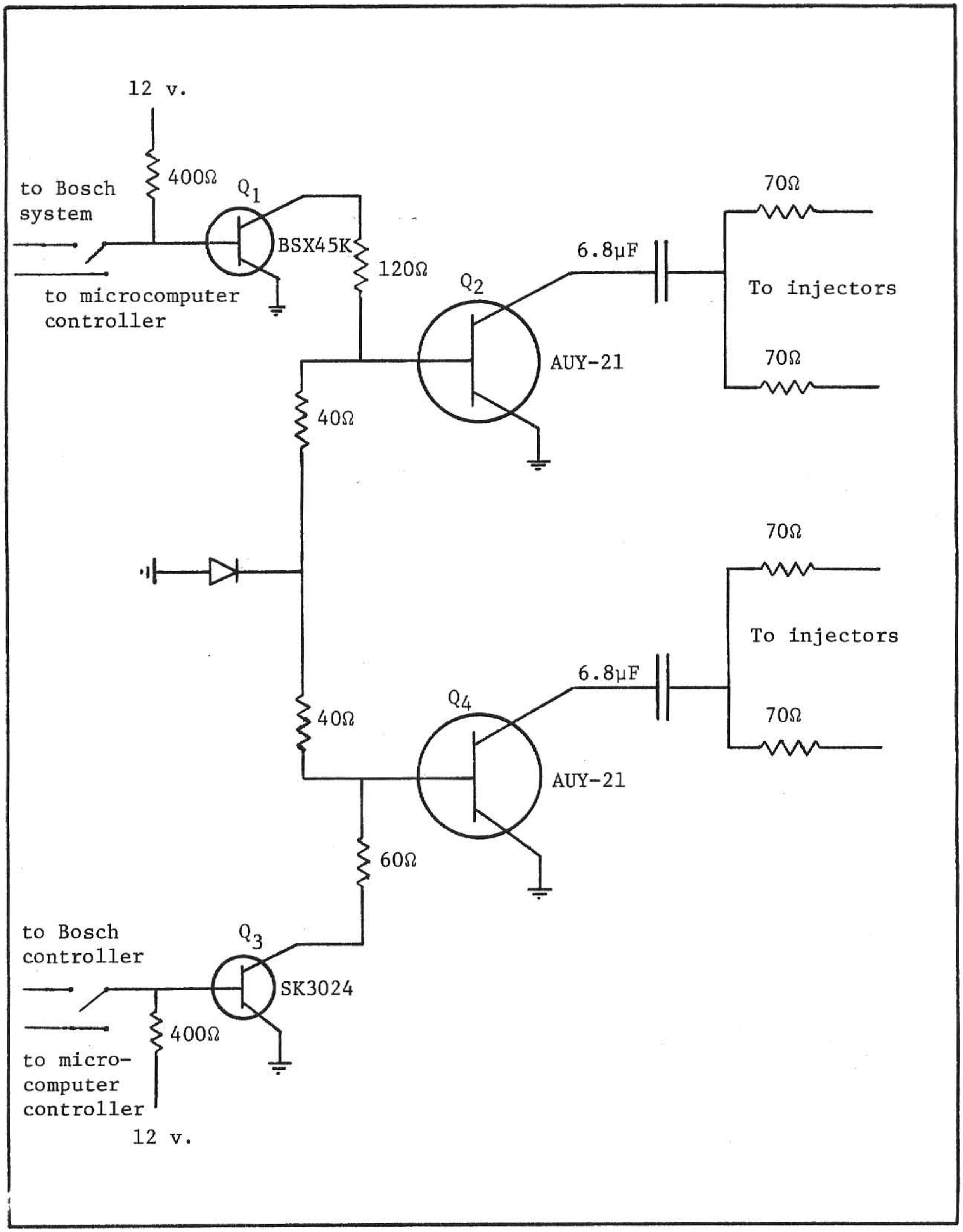

Figure D-1. Injector Driving Circuitry

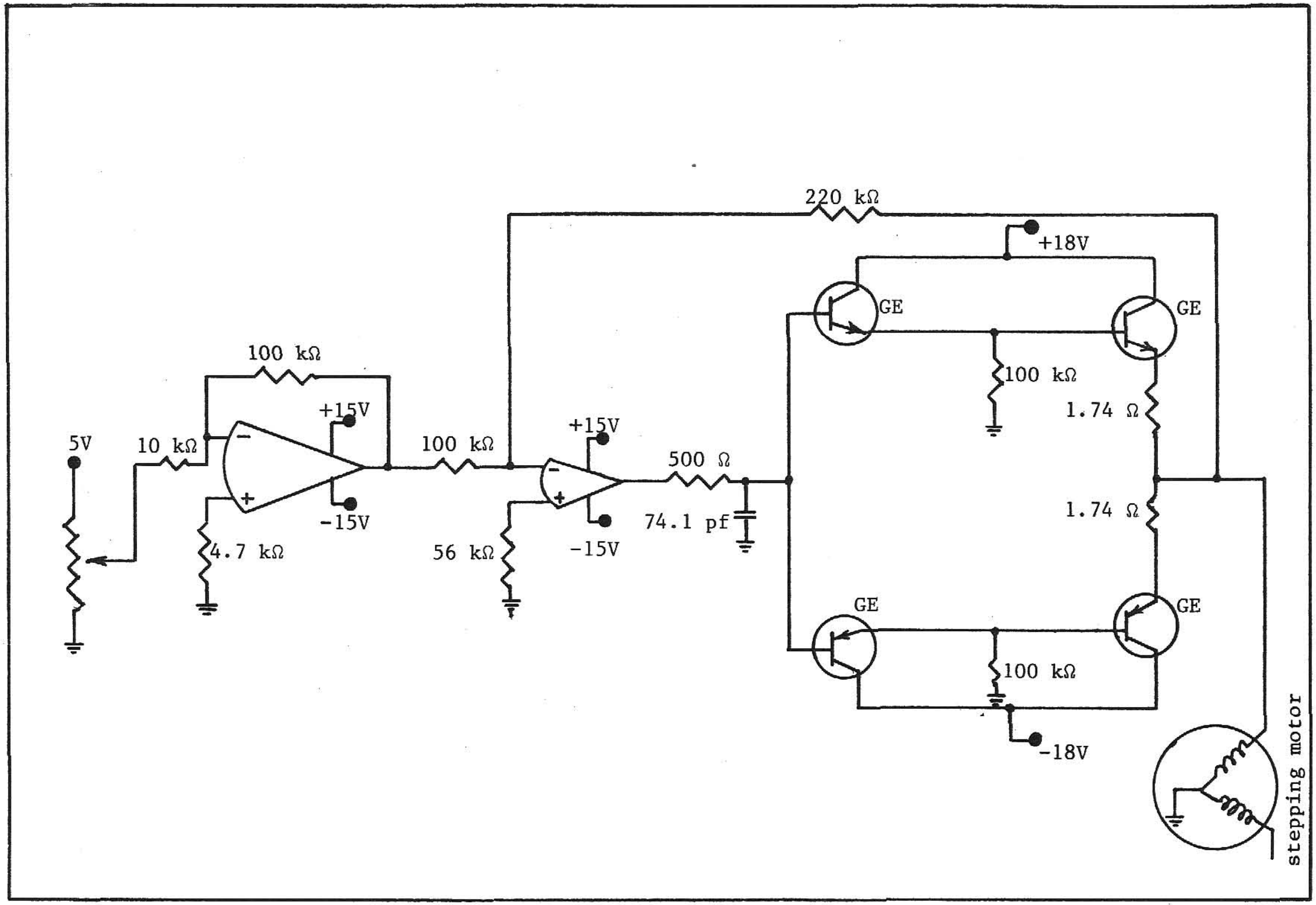

Figure D-2. Stepping Motor Amplifiers

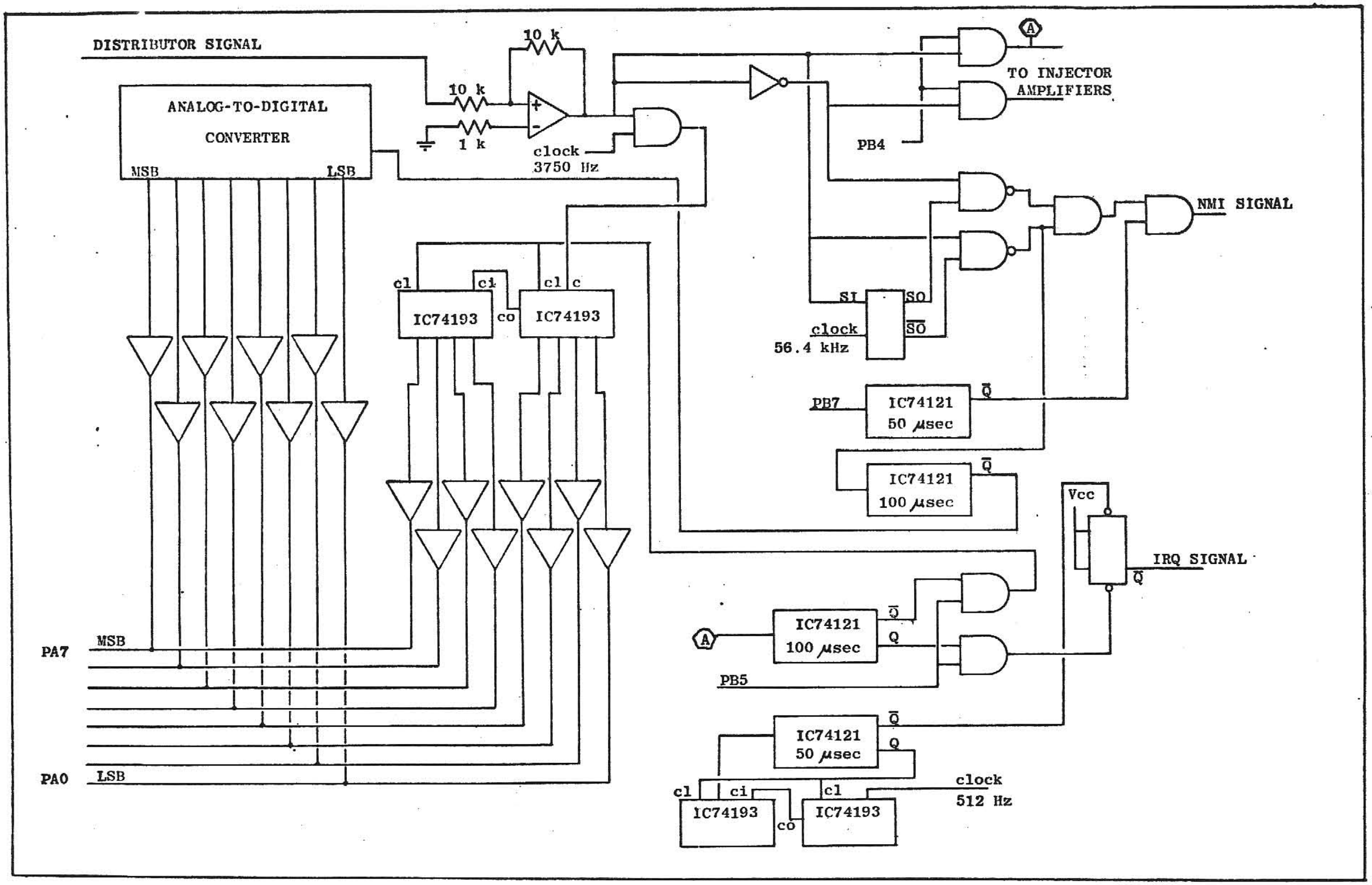

FIGURE D-3. TTL Peripheral Circuitry

APPENDIX E

MICROCOMPUTER PROGRAM LISTING

Memory Location	OP Code	Assembly Lang. Form	Addressing Mode	No. Cycles	Comments
					INITIALIZATION
0200	A2 FF	LDX	IMMEDIATE	2	INITIALIZE STACK POINTER
0202	9A	TXS	IMPLIED	2	
0203	78	SEI	IMPLIED	2	SET INTERRUPT DISABLE FLAG
0204	A9 00	LDA	IMMEDIATE	2	DEFINE DATA DIRECTION REGISTER A
0206	8D 01 17	STA	ABSOLUTE	4	
0209	A9 3C	LDA	IMMEDIATE	2	DEFINE DATA DIRECTION REGISTER B
020B	8D 03 17	STA	ABSOLUTE	4	
020E	D8	CLD	IMPLIED	2	SPECIFY BINARY MODE
020F	A9 90	LDA	IMMEDIATE	2	SPECIFY IRQ VECTOR
0211	8D FE 17	STA	ABSOLUTE	4	
0214	A9 3F	LDA	IMMEDIATE	2	
0216	8D FF 17	STA	ABSOLUTE	4	
0219	A9 80	LDA	IMMEDIATE	2	SPECIFY NMI VECTOR
021B	8D FA 17	STA	ABSOLUTE	4	
021E	A9 17	LDA	IMMEDIATE	2	
0220	8D FB 17	STA	ABSOLUTE	4	
0223	A9 0A	LDA	IMMEDIATE	2	INITIALIZE SPEED CONTROL
0225	85 08	STA	ZERO PAGE	3	
0227	A9 1F	LDA	IMMEDIATE	2	INITIALIZE INC-DEC REGISTERS
0229	8D 00 20	STA	ABSOLUTE	4	
022C	A9 20	LDA	IMMEDIATE	2	
022E	8D 01 20	STA	ABSOLUTE	4	
0231	58	CLI	IMPLIED	2	CLEAR INTERRUPT DISABLE FLAG
0232	4C 0A 00	JMP	ABSOLUTE	4	
0249-02FF					SPEED LOOK-UP TABLE FOR INJ VALUE ARRAY
					INJECTION TIME PROGRAM
0000					DESIRED RPM
0001					A/F RATIO VALUE
0002					RPM COUNT
0003					AFS COUNT
0004					AFS VALUE
0005					RPM VALUE 1
0006					INJ. VALUE
0007					RPM VALUE 2

```
0008                                                 ΔRPM CURRENT
0009                                                 ΔRPM PREVIOUS
000A  A5 03       LDA   ZERO PAGE    3               TEST IF AFS COUNT IS OUT OF RANGE
000C  C9 38       CMP   IMMEDIATE    2
000E  30 11       BMI   RELATIVE     3
0010  A9 C6       LDA   IMMEDIATE    2
0012  C5 03       CMP   ZERO PAGE    3
0014  30 0B       BMI   RELATIVE     3
0016  A5 03       LDA   ZERO PAGE    3               SCALE AFS COUNT
0018  85 1B       STA   ZERO PAGE    3
001A  AD __ 03    LDA   ABSOLUTE     4
001D  85 46       STA   ZERO PAGE    3
001F  85 04       STA   ZERO PAGE    3               SAVE AFS VALUE IN INTERMEDIATE REGISTER
0021  A5 02       LDA   ZERO PAGE    3               TEST IF RPM COUNT IS OUT OF RANGE
0023  C9 49       CMP   IMMEDIATE    2
0025  30 1D       BMI   RELATIVE     3
0027  A5 02       LDA   ZERO PAGE    3               SCALE RPM COUNT
0029  85 2C       STA   ZERO PAGE    3
002B  AD __ 02    LDA   ABSOLUTE     4
002E  85 EE       STA   ZERO PAGE    3
0030  A5 01       LDA   ZERO PAGE    3               CORRECT FOR AF RATIO VALUE:
0032  C9 01       CMP   IMMEDIATE    2                                           16-1
0034  FO 1F       BEQ   RELATIVE     3
0036  C9 02       CMP   IMMEDIATE    2                                           18-1
0038  FO 25       BEQ   RELATIVE     3
003A  C9 03       CMP   IMMEDIATE    2                                           20-1
003C  FO 2B       BEQ   RELATIVE     3
003E  A5 EE       LDA   ZERO PAGE    3
0040  85 45       STA   ZERO PAGE    3
0042  85 05       STA   ZERO PAGE    3               SAVE RPM VALUE IN INTERMEDIATE REGISTER
0044  AD __ __    LDA   ABSOLUTE     4               LOOK UP INJECTION TIME VALUE
0047  C9 00       CMP   IMMEDIATE    2               TEST IF OUT OF TABLE
0049  FO 02       BEQ   RELATIVE     3
004B  85 06       STA   ZERO PAGE    3               SAVE INJ. VALUE IN INTERMEDIATE REGISTER
004D  4C 7D 00    JMP   ABSOLUTE     4

0055  A5 EE       LDA   ZERO PAGE    3               CORRECT INJ. VALUE FOR 16-1 A-F RATIO
0057  18          CLC   IMPLIED      2
0058  69 40       ADC   IMMEDIATE    2
```

```
005A   85 45      STA   ZERO PAGE   3
005C   4C 42 00   JMP   ABSOLUTE    4
005F   A5 EE      LDA   ZERO PAGE   3   CORRECT INJ. VALUE FOR 18-1 A-F RATIO
0061   18         CLC   IMPLIED     2
0062   69 80      ADC   IMMEDIATE   2
0064   85 45      STA   ZERO PAGE   3
0066   4C 42 00   JMP   ABSOLUTE    4
0069   A5 EE      LDA   ZERO PAGE   3   CORRECT INJ. VALUE FOR 20-1 A-F RATIO
006B   18         CLC   IMPLIED     2
006C   69 00      ADC   IMMEDIATE   2
006E   85 45      STA   ZERO PAGE   3
0070   4C 42 00   JMP   ABSOLUTE    4

0075   A9 66      LDA   IMMEDIATE   2   SET FLAG
0077   85 9E      STA   ZERO PAGE   3
0079   4C 0A 00   JMP   ABSOLUTE    4   JUMP TO START OF INJ. VALUE ROUTINE

007D   A5 9E      LDA   ZERO PAGE   3   CHECK STATUS OF FLAG
007F   C9 66      CMP   IMMEDIATE   2
0081   F0 03      BEQ   RELATIVE    3
0083   4C 0A 00   JMP   ABSOLUTE    4   JUMP TO START OF INJ. VALUE ROUTINE
0086   A9 00      LDA   IMMEDIATE   2   RESET FLAG
0088   85 9E      STA   ZERO PAGE   3
008A   4C DB 03   JMP   ABSOLUTE    4   RETURN FROM INTERRUPT


                                              ***STEPTIME ROUTINE***
0300                                              STEPTIME LOB
0301                                              STEPTIME HOB
0302   A5 9A      LDA   ZERO PAGE   3   FETCH STEPTIME FROM INTERMEDIATE REGISTERS
0304   8D 00 03   STA   ABSOLUTE    4
0307   A5 9B      LDA   ZERO PAGE   3
0309   29 7F      AND   IMMEDIATE   2   STRIP OFF SIGN BIT
030B   8D 01 03   STA   ABSOLUTE    4
030E   C9 00      CMP   IMMEDIATE   2
0310   F0 22      BEQ   RELATIVE    3   BRANCH IF STEPTIME < 255 to 0334
0312   38         SEC   IMPLIED     2
0313   AD 00 03   LDA   ABSOLUTE    4
```

0316	E9 FF	SBC	IMMEDIATE	2	SUBTRACT 255 FROM STEPTIME
0318	8D 00 03	STA	ABSOLUTE	4	
031B	AD 01 03	LDA	ABSOLUTE	4	
031E	E9 00	SBC	IMMEDIATE	2	
0320	8D 01 03	STA	ABSOLUTE	4	
0323	A5 9C	LDA	ZERO PAGE	3	
0325	C9 22	CMP	IMMEDIATE	2	
0327	F0 08	BEQ	RELATIVE	3	IF FLAG = 22 BRANCH TO 0331
0329	A9 FF	LDA	IMMEDIATE	2	LOAD 255 INTO INTERVAL TIMER REGISTER
032B	8D 0F 17	STA	ABSOLUTE	4	
032E	4C AE 21	JMP	ABSOLUTE	4	
0331	4C E3 21	JMP	ABSOLUTE	4	
0334	4C D5 21	JMP	ABSOLUTE	4	
0337-03C6					AFS LOOK-UP TABLE FOR INJ VALUE ARRAY
03C7	AD 00 03	LDA	ABSOLUTE	4	LOAD STEPTIME INTO INTERVAL TIMER REGISTER
03CA	8D 0F 17	STA	ABSOLUTE	4	
03CD	A9 88	LDA	IMMEDIATE	2	RESET FLAG
03CF	8D DF 03	STA	ABSOLUTE	4	
03D2	A9 00	LDA	IMMEDIATE	2	CLEAR STEPTIME REGISTERS
03D4	8D 00 03	STA	ABSOLUTE	4	
03D7	A9 00	LDA	ZERO PAGE	3	
03D9	85 9F	STA	ZERO PAGE	3	
03DB	68	PLA	IMPLIED	4	
03DC	AA	TAX	IMPLIED	2	
03DD	68	PLA	IMPLIED	4	
03DE	40	RTI	IMPLIED	6	RETURN FROM INTERRUPT
					INCREMENT-DECREMENT SUBROUTINE
2000					INC-DEC REGISTER A
2001					INC-DEC REGISTER B
2002					
2003	EE 00 20	INC	ABSOLUTE	4	INCREMENT REGISTER A
2006	AD 00 20	LDA	ABSOLUTE	4	
2009	29 02	AND	IMMEDIATE	2	ISOLATE OUTPUT BIT A
200B	0A	ASL	ACCUMULATOR	2	
200C	0A	ASL	ACCUMULATOR	2	

200D	8D 40 20	STA	ABSOLUTE	4	STORE BIT IN INTERMEDIATE REGISTER
2010	EE 01 20	INC	ABSOLUTE	4	INCREMENT REGISTER B
2013	AD 01 20	LDA	ABSOLUTE	4	
2016	29 02	AND	IMMEDIATE	2	ISOLATE OUTPUT BIT B
2018	0A	ASL	ACCUMULATOR	2	
2019	0D 40 20	ORA	ABSOLUTE	4	COMBINE OUTPUT BITS
201C	8D 41 20	STA	ABSOLUTE	4	
201F	AD 00 20	LDA	ABSOLUTE	4	
2022	CD 01 20	CMP	ABSOLUTE	4	TEST THAT BITS ARE UNEQUAL
2025	F0 07	BEQ	RELATIVE	3	IF BITS ARE EQUAL BRANCH TO 202E
2027	AD 41 20	CDA	ABSOLUTE	4	STORE OUTPUT BITS IN OUTPUT PORTS
202A	8D 02 17	STA	ABSOLUTE	4	
202D	60	RTS	IMPLIED	6	RETURN FROM SUBROUTINE
202E	EE 01 20	INC	ABSOLUTE	4	
2031	4C 03 20	JMP	ABSOLUTE	4	
2049-20FF					SPEED LOOK-UP TABLE FOR SPEED CONTROLLER
3FC0	CE 00 20	DEC	ABSOLUTE	4	DECREMENT REGISTER A
3FC3	AD 00 20	LDA	ABSOLUTE	4	
3FC6	29 02	AND	IMMEDIATE	2	ISOLATE OUTPUT BIT A
3FC8	0A	ASL	ACCUMULATOR	2	
3FC9	0A	ASL	ACCUMULATOR	2	
3FCA	8D 44 20	STA	ABSOLUTE	4	STORE BIT IN INTERMEDIATE REGISTER
3FCD	CE 01 20	DEC	ABSOLUTE	4	DECREMENT REGISTER B
3FD0	AD 01 20	LDA	ABSOLUTE	4	
3FD3	29 02	AND	IMMEDIATE	2	ISOLATE OUTPUT BIT B
3FD5	0A	ASL	ACCUMULATOR	2	
3FD6	0D 44 20	ORA	ABSOLUTE	4	COMBINE OUTPUT BITS
3FD9	8D 45 20	STA	ABSOLUTE	4	
3FDC	AD 00 20	LDA	ABSOLUTE	4	
3FDF	CD 01 20	CMP	ABSOLUTE	4	TEST THAT BITS ARE UNEQUAL
3FE2	F0 07	BEQ	RELATIVE	3	IF BITS ARE EQUAL BRANCH TO 3FEB
3FE4	AD 45 20	LDA	ABSOLUTE	4	
3FE7	8D 02 17	STA	ABSOLUTE	4	STORE OUTPUT BITS IN OUTPUT PORTS
3FEA	60	RTS	IMPLIED	6	RETURN FROM SUBROUTINE
3FEB	CE 00 20	DEC	ABSOLUTE	4	
3FEE	4C C0 3F	JMP	ABSOLUTE	4	

NMI PROGRAM

```
1780   48         PHA   IMPLIED     3
1781   8A         TXA   IMPLIED     2
1782   48         PHA   IMPLIED     3
1783   AD 02 17   LDA   ABSOLUTE    4
1786   8D E9 17   STA   ABSOLUTE    4
1789   29 01      AND   IMMEDIATE   2
178B   F0 3B      BEQ   RELATIVE    3   BRANCH TO 17C8 IF NMI GENERATED BY INTERVAL TIMER
178D   AD 06 17   LDA   ABSOLUTE    4
1790   18         CLC   IMPLIED     2
1791   6D 00 03   ADC   ABSOLUTE    4
1794   8D 00 03   STA   ABSOLUTE    4   SAVE UNUSED PORTION OF STEPTIME
1797   AD 01 03   LDA   ABSOLUTE    4
179A   69 00      ADC   IMMEDIATE   2
179C   8D 01 03   STA   ABSOLUTE    4
179F   38         SEC   IMPLIED     2
17A0   AD 00 03   LDA   ABSOLUTE    4
17A3   E9 05      SBC   IMMEDIATE   2   CORRECT STEPTIME FOR INJECTION TIME
17A5   8D 00 03   STA   ABSOLUTE    4
17A8   AD 01 03   LDA   ABSOLUTE    4
17AB   E9 00      SBC   IMMEDIATE   2
17AD   8D 01 03   STA   ABSOLUTE    4
17B0   90 33      BCC   RELATIVE    3   IF RESULT IS NEGATIVE BRANCH TO 17E5
17B2   A5 06      LDA   ZERO PAGE   3   FETCH INJECTION TIME VALUE
17B4   8D 0E 17   STA   ABSOLUTE    4   STORE IN INTERVAL TIMER REGISTER
17B7   AD E9 17   LDA   ABSOLUTE    4
17BA   09 10      ORA   IMMEDIATE   2   LOAD 1 INTO INJECTION OUTPUT PORT
17BC   8D 02 17   STA   ABSOLUTE    4
17BF   A9 22      LDA   IMMEDIATE   2   SET FLAG
17C1   85 9C      STA   ZERO PAGE   3
17C3   4C 75 00   JMP   ABSOLUTE    4   JUMP TO INJECTION TIME PROGRAM

17C8   A9 00      LDA   IMMEDIATE   2
17CA   8D 06 17   STA   ABSOLUTE    4
17CD   A5 9C      LDA   ZERO PAGE   3
17CF   C9 22      CMP   IMMEDIATE   2
17D1   D0 0F      BNE   RELATIVE    3   BRANCH TO 17E2 IF STEPTIME = 00
17D3   AD E9 17   LDA   ABSOLUTE    4
```

17D6	29 EF	AND	IMMEDIATE	2	LOAD 0 INTO INJECTOR OUTPUT PORT
17D8	8D 02 17	STA	ABSOLUTE	4	
17DB	A9 00	LDA	IMMEDIATE	2	RESET FLAG
17DD	85 9C	STA	ZERO PAGE	3	
17DF	4C A0 00	JMP	ABSOLUTE	4	
17E2	4C E0 03	JMP	ABSOLUTE	4	
17E5	4C B0 3F	JMP	ABSOLUTE	4	
00A0	AD 02 17	LDA	ABSOLUTE	4	
00A3	29 02	AND	IMMEDIATE	2	
00A5	F0 10	BEQ	RELATIVE	3	BRANCH TO 00B7 IF DISTRIBUTOR SIGNAL IS HIGH
00A7	AD 00 17	LDA	ABSOLUTE	4	SAMPLE RPM COUNT
00AA	85 02	STA	ZERO PAGE	3	STORE IN INTERMEDIATE REGISTER
00AC	AD 02 17	LDA	ABSOLUTE	4	INITIATE PULSE TO ZERO COUNTERS
00AF	09 20	ORA	IMMEDIATE	2	
00B1	8D 02 17	STA	ABSOLUTE	4	
00B4	4C BC 00	JMP	ABSOLUTE	4	
00B7	AD 00 17	LDA	ABSOLUTE	4	SAMPLE AIR FLOW SENSOR COUNT
00BA	85 03	STA	ZERO PAGE	3	STORE IN INTERMEDIATE REGISTER
00BC	AD 02 17	LDA	ABSOLUTE	4	
00BF	29 DF	AND	IMMEDIATE	2	
00C1	8D 02 17	STA	ABSOLUTE	4	TURN OFF PULSE TO ZERO COUNTERS
00C4	AD 01 03	LDA	ABSOLUTE	4	
00C7	4C 0E 03	JMP	ABSOLUTE	4	JUMP TO STEPTIME ROUTINE
03E0	AD DF 03	LDA	ABSOLUTE	4	
03E3	C9 88	CMP	IMMEDIATE	2	
03E5	F0 06	BEQ	RELATIVE	3	BRANCH TO 03ED IF STEPTIME = 00 00
03E7	AD 01 03	LDA	ABSOLUTE	4	LOAD REMAINDER OF STEPTIME INTO REGISTER
03EA	4C 0E 03	JMP	ABSOLUTE	4	JUMP TO STEPTIME ROUTINE
03ED	A5 9B	LDA	ZERO PAGE	3	
03EF	30 06	BMI	RELATIVE	3	BRANCH TO 03F7 IF STEP NO. IS NEGATIVE
03F1	20 03 20	JSR	ABSOLUTE	4	JUMP TO INCREMENT SUBROUTINE
03F4	4C 02 03	JMP	ABSOLUTE	4	
03F7	20 C0 3F	JSR	ABSOLUTE	4	JUMP TO DECREMENT SUBROUTINE
03FA	4C 02 03	JMP	ABSOLUTE	4	

IRQ PROGRAM

```
3F90    48          PHA    IMPLIED        3
3F91    8A          TAX    IMPLIED        2
3F92    48          PHA    IMPLIED        3
3F93    AD 02 17    LDA    ABSOLUTE       4    INITIATE PULSE TO ACKNOWLEDGE INTERRUPT
3F96    09 20       ORA    IMMEDIATE      2
3F98    8D 02 17    STA    ABSOLUTE       4
3F9B    EA          NOP    IMPLIED        2
3F9C    EA          NOP    IMPLIED        2
3F9D    EA          NOP    IMPLIED        2
3F9E    EA          NOP    IMPLIED        2
3F9F    EA          NOP    IMPLIED        2
3FA0    AD 02 17    LDA    ABSOLUTE       4    TURN OFF PULSE TO INTERRUPT DEVICE
3FA3    29 DF       AND    IMMEDIATE      2
3FA5    8D 02 17    STA    ABSOLUTE       4
3FA8    A5 02       LDA    ZERO PAGE      3    FETCH RPM COUNT
3FAA    8D 1B 21    STA    ABSOLUTE       4
3FAD    4C 1A 21    JMP    ABSOLUTE       4    JUMP TO 211A
3FB0    A9 01       LDA    IMMEDIATE      2
3FB2    8D 00 03    STA    ABSOLUTE       4    DELAY TIMER INTERRUPT TILL END OF INJECTION
3FB5    A9 00       LDA    IMMEDIATE      2
3FB7    8D 01 03    STA    ABSOLUTE       4
3FBA    4C B2 17    JMP    ABSOLUTE       4

211A    AD __ 20    LDA    ABSOLUTE       4    LOOK UP RPM VALUE 2
211D    85 07       STA    ZERO PAGE      3    STORE IN INTERMEDIATE REGISTER
211F    A5 08       LDA    ZERO PAGE      3
2121    85 09       STA    ZERO PAGE      3
2123    38          SEC    IMPLIED        2
2124    A5 00       LDA    ZERO PAGE      3    DETERMINE ε
2126    E5 07       SBC    ZERO PAGE      3
2128    85 08       STA    ZERO PAGE      3    STORE IN INTERMEDIATE REGISTER
212A    E5 09       SBC    ZERO PAGE      3    DETERMINE Δε
212C    30 04       BMI    RELATIVE       3    BRANCH TO 2132 IF RESULT IS NEGATIVE
212E    4A          LSR    ACCUMULATOR    2    DETERMINE Δε/2
212F    4C 35 21    JMP    ABSOLUTE       4
2132    4A          LSR    ACCUMULATOR    2
2133    09 80       ORA    IMMEDIATE      2
```

2135	18	CLC	IMPLIED	2	
2136	65 08	ADC	ZERO PAGE	3	DETERMINE $\varepsilon + \Delta\varepsilon/2$ (STEP NO.)
2138	30 03	BMI	RELATIVE	3	BRANCH TO 213D IF RESULT IS NEGATIVE
213A	4C 55 21	JMP	ABSOLUTE	4	
213D	4C F8 21	JMP	ABSOLUTE	4	
2155	C9 03	CMP	IMMEDIATE	2	
2157	30 24	BMI	RELATIVE	3	BRANCH TO 217D IF STEP NO. < 3
2159	85 E9	STA	ZERO PAGE	3	
215B	A9 00	LDA	IMMEDIATE	2	
215D	85 E8	STA	ZERO PAGE	3	SET UP DIVIDE REGISTERS
215F	A9 08	LDA	IMMEDIATE	2	
2161	85 E6	STA	ZERO PAGE	3	
2163	A9 48	LDA	IMMEDIATE	2	
2165	85 E7	STA	ZERO PAGE	3	
2167	20 40 3F	JSR	ABSOLUTE	4	JUMP TO DIVISION SUBROUTINE
216A	4C 9D 21	JMP	ABSOLUTE	4	
2170	C9 03	CMP	IMMEDIATE	2	
2172	30 09	BMI	RELATIVE	3	IF STEP NO. < 3 BRANCH TO 217D
2174	85 E9	STA	ZERO PAGE	3	
2176	A9 80	LDA	IMMEDIATE	2	SET NEGATIVE BIT IN DIVISION REGISTER
2178	85 E8	STA	ZERO PAGE	3	
217A	4C 5F 21	JMP	ABSOLUTE	4	
217D	4C 95 21	JMP	ABSOLUTE	4	
2195	A9 20	LDA	IMMEDIATE	2	LOAD 20XX INTO STEPTIME REGISTER.
2197	85 9B	STA	ZERO PAGE	3	
2199	58	CLI	IMPLIED	2	
219A	4C DB 03	JMP	ABSOLUTE	4	JUMP TO STEPTIME ROUTINE
219D	A5 EB	LDA	ZERO PAGE	3	LOAD DIVISION RESULT INTO INTERMEDIATE REGISTER
219F	85 9A	STA	ZERO PAGE	3	
21A1	A5 EA	LDA	ZERO PAGE	3	
21A3	85 9B	STA	ZERO PAGE	3	
21A5	4C DB 03	JMP	ABSOLUTE	4	RETURN FROM INTERRUPT
21AE	A9 FF	LDA	IMMEDIATE	2	SET FLAG
21B0	8D DF 03	STA	ABSOLUTE	4	
21B3	4C DB 03	JMP	ABSOLUTE	4	RETURN FROM INTERRUPT

21D5	A5 9C	LDA	ZERO PAGE	3	CHECK STATUS OF FLAG
21D7	C9 22	CMP	IMMEDIATE	2	
21D9	F0 04	BEQ	RELATIVE	3	BRANCH TO 21DF IF FLAG IS SET
21DB	4C C7 03	JMP	ABSOLUTE	4	JUMP TO STEPTIME ROUTINE
21DF	4C DB 03	JMP	ABSOLUTE	4	RETURN FROM INTERRUPT
21E3	18	CLC	IMPLIED	2	
21E4	AD 00 03	LDA	ABSOLUTE	4	FIX UP STEPTIME FOR RTI
21E7	69 FF	ADC	IMMEDIATE	2	
21E9	8D 00 03	STA	ABSOLUTE	4	
21EC	AD 01 03	LDA	ABSOLUTE	4	
21EF	69 00	ADC	IMMEDIATE	2	
21F1	8D 01 03	STA	ABSOLUTE	4	
21F4	4C DB 03	JMP	ABSOLUTE	4	RETURN FROM INTERRUPT
21F8	49 FF	EOR	IMMEDIATE	2	TAKE COMPLEMENT OF STEP NO.
21FA	18	CLC	IMPLIED	2	
21FB	69 01	ADC	IMMEDIATE	2	ADD 1 TO COMPLEMENT
21FD	4C 70 21	JMP	ABSOLUTE	4	

MULTIPLY SUBROUTINE

3F00	A2 08	LDX	IMMEDIATE	2	INITIALIZATION
3F02	A9 00	LDA	IMMEDIATE	2	SET COUNTER to 8
3F04	85 03	STA	ZERO PAGE	3	
3F06	85 E4	STA	ZERO PAGE	3	
3F08	A5 E0	LDA	ZERO PAGE	3	TAKE CARE OF SIGN
3F0A	30 1F	BMI	RELATIVE	3	BRANCH TO 3F2B
3F0C	18	CLC	ZERO PAGE	3	CHECK LOW ORDER BYTE
3F0D	A5 E2	LDA	ZERO PAGE	3	
3F0F	4A	LSR	ACCUMULATOR	2	
3F10	90 0D	BCC	RELATIVE	3	IF MULTIPLIER LOB IS ZERO BRANCH TO 3F1F
3F12	18	CLC	IMPLIED	2	ADD MULTIPLICAND TO PARTIAL PRODUCT
3F13	A5 E1	LDA	ZERO PAGE	3	
3F15	65 E4	ADC	ZERO PAGE	3	
3F17	85 E4	STA	ZERO PAGE	3	
3F19	A5 E0	LDA	ZERO PAGE	3	
3F1B	65 E3	ADC	ZERO PAGE	3	

```
3F1D    85 E3       STA   ZERO PAGE   3
3F1F    CA          DEX   IMPLIED     2   DECREMENT COUNTER
3F20    F0 17       BEQ   RELATIVE    3   BRANCH TO 3F39 IF COUNTER IS 0
3F22    46 E2       LSR   ZERO PAGE   3   SHIFT MULTIPLIER RIGHT 1 BIT
3F24    06 E1       ASL   ZERO PAGE   3   SHIFT MULTIPLICAND LEFT 1 BIT
3F26    26 E0       ROL   ZERO PAGE   3
3F28    4C 0C 3F    JMP   ABSOLUTE    4
3F2B    A9 80       LDA   IMMEDIATE   2   FIX PRODUCT SIGN FOR NEGATIVE RESULT
3F2D    18          CLC   IMPLIED     2
3F2E    85 E3       STA   ZERO PAGE   3
3F30    A5 E0       LDA   ZERO PAGE   3
3F32    29 7F       AND   IMMEDIATE   2   STRIP SIGN BIT OFF OF MULTIPLICAND
3F34    85 E0       STA   ZERO PAGE   3
3F36    4C 0C 3F    JMP   ABSOLUTE    4
3F39    60          RTS   IMPLIED     6   RETURN FROM SUBROUTINE


                                              ***DIVISION SUBROUTINE***
3F40    A9 00       LDA   IMMEDIATE   2   ZERO PARTIAL QUOTIENT
3F42    85 EA       STA   ZERO PAGE   3
3F44    85 EB       STA   ZERO PAGE   3
3F46    A5 E6       LDA   ZERO PAGE   3   ISOLATE MSB OF DIVIDEND
3F48    29 80       AND   IMMEDIATE   2
3F4A    85 EC       STA   ZERO PAGE   3
3F4C    A5 E6       LDA   ZERO PAGE   3   ISOLATE MSB OF DIVISOR
3F4E    29 7F       AND   IMMEDIATE   2
3F50    85 E6       STA   ZERO PAGE   3
3F52    A5 E8       LDA   ZERO PAGE   3
3F54    29 80       AND   IMMEDIATE   2
3F56    C5 EC       CMP   ZERO PAGE   3   ARE BITS EQUAL?
3F58    F0 05       BEQ   RELATIVE    3   BRANCH TO 3F5F IF BITS ARE EQUAL
3F5A    18          CLC   IMPLIED     2
3F5B    A9 80       LDA   IMMEDIATE   2   FIX SIGN BIT IN QUOTIENT
3F5D    85 EA       STA   ZERO PAGE   3
3F5F    A5 E8       LDA   ZERO PAGE   3
3F61    29 7F       AND   IMMEDIATE   2
3F63    85 E8       STA   ZERO PAGE   3
```

3F65	38	SEC	IMPLIED	2	SUBTRACT DIVISOR FROM DIVIDEND
3F66	A5 E7	LDA	ZERO PAGE	3	
3F68	E5 E9	SBC	ZERO PAGE	3	
3F6A	85 E7	STA	ZERO PAGE	3	STORE RESULT IN DIVIDEND
3F6C	A5 E6	LDA	ZERO PAGE	3	
3F6E	E5 E8	SBC	ZERO PAGE	3	
3F70	85 E6	STA	ZERO PAGE	3	
3F72	90 16	BCC	RELATIVE	3	BRANCH TO 3F8A ON NEGATIVE RESULT
3F74	18	CLC	IMPLIED	2	
3F75	A9 01	LDA	IMMEDIATE	2	
3F77	65 EB	ADC	ZERO PAGE	3	ADD 1 TO PARTIAL QUOTIENT
3F79	85 EB	STA	ZERO PAGE	3	
3F7B	B0 03	BCS	RELATIVE	3	BRANCH TO 3F80 ON OVERFLOW
3F7D	4C 65 3F	JMP	ABSOLUTE	4	RETURN TO START OF SUBTRACTION LOOP
3F80	18	CLC	IMPLIED	2	
3F81	A9 01	LDA	ZERO PAGE	3	FIX UP FOR OVERFLOW
3F83	65 EA	ADC	ZERO PAGE	3	
3F85	85 EA	STA	ZERO PAGE	3	
3F87	4C 65 3F	JMP	ABSOLUTE	4	RETURN TO START OF SUBTRACTION LOOP
3F8A	60	RTS	IMPLIED	6	RETURN FROM SUBROUTINE

APPENDIX F

FORTRAN PROGRAM LISTINGS

```
C      THIS PROGRAM CALCULATES INJECTION TIME VALUES TO BE STORED IN
C      THE INJECTION TIME ARRAY, PAGES 21-3E OF THE MICROCOMPUTER
C      OUTPUT VALUES JM, KM, AND NTIME ARE IN HEXADECIMAL FORMAT
C      AIRFLO IS IN LB/MIN, RPM IS IN REV/MIN, TIME IS IN MSEC
       DIMENSION J(30),K(64)
   100 FORMAT(30I2)
   101 FORMAT(40I2)
   103 FORMAT(24I2)
       READ(5,100)(J(I),I=1,30)
       READ(5,101) (K(I),I=1,40)
       READ(5,103) (K(I),I=41,64)
       DO 200 IFR=14,20,2
       AIRFLO=0.600
       DO 300 I=1,30
       JM=J(I)
       RPM=900
       DO 400 M=1,64
       KM=K(M)
       TIME=(((AIRFLO/(2*RPM*IFR))*10**5)+0.5061)/0.823
       YYYY=TIME/0.064
       NTIME=TIME/0.064
       ZZZZ=YYYY-NTIME
       IF(ZZZZ.GT.0.5)NTIME=NTIME+1
   102 FORMAT(4X,I2,4X,F4.2,4X,F9.4,4X,F9.6,4X,Z4,2X,Z4,2X,Z4)
       WRITE(6,102)IFR,AIRFLO,RPM,TIME,JM,KM,NTIME
   400 RPM=RPM+34.375
   300 AIRFLO=AIRFLO+0.1
   200 CONTINUE
       STOP
       END
```

```
C      AIR FLOW SENSOR CALIBRATION
C      THIS PROGRAM CALCULATES MASS AIR FLOW RATES WHERE:
C      TWB IS WET BULB TEMP IN °RANKINE; TDB IS DRY BULB TEMP IN °RANKINE;
C      PW IS VAPOR PRESSURE OF AIR AT WET BULB TEMP IN PSI; ATMPR IS
C      ATMOSPHERIC PRESSURE IN INCHES HG; PMN IS PRESSURE DROP ACROSS NOZZLE
C      IN INCHES H20
       DIMENSION TWB(165), TDB(165), ATMPR(165), PW(165), PMN(165)
   100 FORMAT(I3)
       READ(5,100) N
   101 FORMAT(5F10.5 )
       READ(5,101) (TWB(I),TDB(I),ATMPR(I),PW(I),PMN(I),I=1,N)
```

```
      DO 200 I=1,12
      DENAIR=((ATMPR(I)*.491)-.38*(PW(I)-((ATMPR(I)*.491)*
     1(TDB(I)-TWB(I))/2700)))/(.37*TDB(I))
C     DENAIR IS THE AIR DENSITY IN LB/CU.FT.
      PNSD=PMN(I)*(.075/DENAIR)
C     PNSD IS THE STANDARD DENSITY PRESSURE DROP ACROSS NOZZLE IN IN. H20
      CFM=(62.0524*PNSD**.5014)
C     CFM IS THE CU. FT./MIN INTO THE ENGINE
      AMFR1=CFM*DENAIR
C     AMFR1 IS THE MASS FLOW RATE OF AIR IN LB/MIN
      PRINT,DENAIR, PNSD, CFM, AMFR1
  200 CONTINUE
      STOP
      END
```

```
C     SPEED SENSOR CALIBRATION
      DO 200 NO=70,250
      RPM=225000/NO
  200 PRINT,NO,RPM
      STOP
      END
```

```
C     THIS PROGRAM CALCULATES AIR-FUEL RATIOS
C     VARIABLES ARE DEFINED AS IN THE AIR-FLOW SENSOR CALIBRATION, WITH
C     THE ADDITION OF:  DELTIM: ELAPSED TIME OF TEST IN SECONDS;
C     DELGAS:  MASS OF FUEL CONSUMED DURING TEST
      DIMENSION TWB(165),TDB(165), ATMPR(165),PW(165),PMN(165)
      DIMENSION DELGAS(165),DELTIM(165)
  100 FORMAT(I3)
      READ(5,100) N
  101 FORMAT(7F10.5)
      READ(5,101) (TWB(I),TDB(I),ATMPR(I),PW(I),PMN(I),DELGAS(I),
     1DELTIM(I),I=1,N)
      DO 200 I=1,N
      DENAIR=((ATMPR(I)*.491)-.38(PW(I)-((ATMPR(I)*.491)*
     2(TDB(I)-TWB(I))/2700)))/(.37*TDB(I))
      PNSD=PMN(I)*(.075/DENAIR)
      CFM=(62.0524*PNSD**.5014)
      AMFR1=CFM*DENAIR
      AIRIN=DELTIM(I)*AMFR1/60.0
      AFR=AIRIN/DELGAS(I)
      PRINT,DENAIR,PNSD,CFM,AMFR1,AIRIN,AFR
  200 CONTINUE
      STOP
      END
```

APPENDIX G

AIR-FUEL RATIO TESTING RAW DATA

AF	RPM	LOAD	TDB	TWB	PW	ATMPR	PMN	DELTIM	DEL-GAS	AFS	TIM
11.2	1200.	10.	538.0	524.0	.29497	28.84	.044	296.02	.40	2.76	4.40
11.2	1200.	10.	538.0	524.0	.29497	28.84	.044	299.22	.40	2.75	4.40
11.2	1200.	10.	538.0	524.0	.29497	28.84	.044	320.46	.40	2.76	4.40
11.2	1600.	10.	539.0	523.0	.28495	28.84	.051	268.93	.40	3.00	3.70
11.2	1600.	10.	539.0	523.0	.28495	28.84	.052	253.12	.40	3.02	3.70
11.2	1600.	10.	539.0	523.0	.28495	28.84	.057	243.55	.40	3.10	3.70
11.2	2000.	10.	539.0	523.0	.28495	28.84	.071	227.79	.40	3.37	3.50
11.2	2000.	10.	539.0	523.0	.28495	28.84	.071	229.34	.40	3.38	3.50
11.2	2000.	10.	539.0	523.0	.28495	28.84	.071	228.11	.40	3.38	3.50
11.2	2400.	10.	542.0	524.0	.29497	28.84	.098	191.18	.40	3.83	3.45
11.2	2400.	10.	542.0	524.0	.29497	28.84	.098	201.47	.40	3.83	3.45
11.2	2400.	10.	542.0	524.0	.29497	28.84	.098	190.23	.40	3.83	3.45
11.2	2800.	10.	542.0	524.0	.29497	28.84	.142	168.81	.40	4.47	3.45
11.2	2800.	10.	542.0	524.0	.29497	28.84	.138	162.93	.40	4.47	3.45
11.2	2800.	10.	542.0	524.0	.29497	28.84	.141	161.14	.40	4.69	3.45
11.2	1200.	25.	538.0	524.0	.29497	28.84	.062	210.15	.40	3.18	5.28
11.2	1200.	25.	538.0	524.0	.29497	28.84	.057	276.89	.40	3.10	5.28
11.2	1200.	25.	538.0	524.0	.29497	28.84	.059	277.18	.40	3.12	5.28
11.2	1600.	25.	539.0	523.0	.28495	28.84	.085	216.43	.40	3.59	4.40
11.2	1600.	25.	539.0	523.0	.28495	28.84	.086	210.31	.40	3.62	4.40
11.2	1600.	25.	539.0	523.0	.28495	28.84	.086	223.51	.40	3.62	4.40
11.2	2000.	25.	539.0	523.0	.28495	28.84	.147	156.79	.40	4.65	4.55
11.2	2000.	25.	539.0	523.0	.28495	28.84	.148	154.09	.40	4.66	4.55
11.2	2000.	25.	539.0	523.0	.28495	28.84	.148	171.53	.40	4.66	4.55
11.2	2400.	25.	542.0	524.0	.29497	28.84	.190	138.25	.40	5.16	4.55
11.2	2400.	25.	542.0	524.0	.29497	28.84	.202	143.13	.40	5.20	4.55
11.2	2400.	25.	542.0	524.0	.29497	28.84	.195	138.58	.40	5.20	4.55
11.2	2800.	25.	542.0	524.0	.29497	28.84	.312	105.81	.40	5.72	4.65
11.2	2800.	25.	542.0	524.0	.29497	28.84	.312	115.84	.40	5.72	4.65
11.2	2800.	25.	542.0	524.0	.29497	28.84	.314	104.52	.40	5.73	4.65
11.2	1200.	40.	539.0	524.0	.29497	28.84	.088	230.65	.40	3.57	5.75
11.2	1200.	40.	539.0	524.0	.29497	28.84	.088	230.20	.40	3.59	5.75
11.2	1200.	40.	539.0	524.0	.29497	28.84	.088	225.69	.40	3.59	5.75
11.2	1600.	40.	539.0	524.0	.29497	28.84	.143	189.14	.40	4.57	5.20
11.2	1600.	40.	539.0	524.0	.29497	28.84	.143	188.32	.40	4.50	5.20
11.2	1600.	40.	539.0	524.0	.29497	28.84	.141	196.02	.40	4.44	5.20
11.2	2000.	40.	539.0	523.0	.28495	28.84	.236	129.01	.40	5.35	5.70
11.2	2000.	40.	539.0	523.0	.28495	28.84	.242	121.29	.40	5.38	5.70
11.2	2000.	40.	539.0	523.0	.28495	28.84	.240	131.50	.40	5.37	5.70
11.2	2400.	40.	542.0	524.0	.29497	28.84	.355	114.49	.40	5.90	5.30
11.2	2400.	40.	542.0	524.0	.29497	28.84	.355	115.18	.40	5.90	5.30
11.2	2400.	40.	542.0	524.0	.29497	28.84	.341	114.29	.40	5.80	5.30
11.2	2800.	40.	542.0	524.0	.29497	28.84	.498	109.94	.40	6.28	4.65
11.2	2800.	40.	542.0	524.0	.29497	28.84	.487	109.33	.40	6.20	4.65
11.2	2800.	40.	542.0	524.0	.29497	28.84	.482	109.30	.40	6.19	4.65

12.8	1200.	10.	541.0	526.0	.31626	28.76	.038	377.71	.40	2.36	3.20
12.8	1200.	10.	541.0	526.0	.31626	28.76	.033	408.68	.40	2.40	3.20
12.8	1200.	10.	541.0	526.0	.31626	28.76	.032	416.04	.40	2.37	3.20
12.8	1600.	10.	543.0	524.0	.29497	28.76	.057	259.32	.40	3.11	3.30
12.8	1600.	10.	543.0	524.0	.29497	28.76	.057	249.60	.40	3.11	3.30
12.8	1600.	10.	543.0	524.0	.29497	28.76	.057	252.26	.40	3.10	3.30
12.8	2000.	10.	543.0	525.0	.30561	28.76	.080	215.60	.40	3.53	3.35
12.8	2000.	10.	543.0	525.0	.30561	28.76	.080	220.53	.40	3.53	3.35
12.8	2000.	10.	543.0	525.0	.30561	28.76	.080	211.32	.40	3.54	3.35
12.8	2400.	10.	546.0	527.0	.32757	28.76	.098	200.02	.40	3.81	3.05
12.8	2400.	10.	546.0	527.0	.32757	28.76	.098	198.14	.40	3.83	3.05
12.8	2400.	10.	546.0	527.0	.32757	28.76	.098	199.24	.40	3.83	3.05
12.8	2800.	10.	545.0	526.0	.31626	28.76	.146	179.58	.40	4.79	3.20
12.8	2800.	10.	545.0	526.0	.31626	28.76	.146	171.51	.40	4.79	3.20
12.8	2800.	10.	545.0	526.0	.31626	28.76	.146	253.89	.60	4.79	3.20
12.8	1200.	25.	541.0	526.0	.31626	28.76	.056	313.43	.40	3.04	4.15
12.8	1200.	25.	541.0	526.0	.31626	28.76	.055	313.59	.40	3.03	4.15
12.8	1200.	25.	541.0	526.0	.31626	28.76	.055	321.54	.40	3.03	4.15
12.8	1600.	25.	543.0	524.0	.29497	28.76	.083	237.17	.40	3.56	4.10
12.8	1600.	25.	543.0	524.0	.29497	28.76	.083	238.72	.40	3.57	4.10
12.8	1600.	25.	543.0	524.0	.29497	28.76	.083	233.07	.40	3.56	4.10
12.8	2000.	25.	543.0	525.0	.30561	28.76	.151	167.60	.40	4.74	4.10
12.8	2000.	25.	543.0	525.0	.30561	28.76	.132	223.06	.40	4.28	3.70
12.8	2000.	25.	543.0	525.0	.30561	28.76	.131	210.97	.40	4.30	3.70
12.8	2400.	25.	546.0	527.0	.32757	28.76	.203	148.14	.40	5.22	4.15
12.8	2400.	25.	546.0	527.0	.32757	28.76	.203	142.86	.40	5.23	4.15
12.8	2400.	25.	546.0	527.0	.32757	28.76	.207	145.10	.40	5.26	4.15
12.8	2800.	25.	545.0	526.0	.31626	28.76	.298	119.06	.40	5.66	4.15
12.8	2800.	25.	545.0	526.0	.31626	28.76	.312	115.25	.40	5.71	4.15
12.8	2800.	25.	545.0	526.0	.31626	28.76	.308	125.39	.40	5.70	4.15
12.8	1200.	40.	543.0	525.0	.30561	28.76	.087	260.11	.40	3.57	5.05
12.8	1200.	40.	543.0	525.0	.30561	28.76	.084	259.36	.40	3.54	5.05
12.8	1200.	40.	543.0	525.0	.30561	28.76	.084	260.84	.40	3.54	5.05
12.8	1600.	40.	543.0	525.0	.30561	28.76	.144	217.43	.40	4.49	4.80
12.8	1600.	40.	543.0	525.0	.30561	28.76	.140	221.26	.40	4.38	4.80
12.8	1600.	40.	543.0	525.0	.30561	28.76	.141	209.70	.40	4.49	4.80
12.8	2000.	40.	543.0	525.0	.30561	28.76	.236	160.02	.40	5.37	3.85
12.8	2000.	40.	543.0	525.0	.30561	28.76	.242	168.65	.40	5.40	3.85
12.8	2000.	40.	543.0	525.0	.30561	28.76	.240	149.55	.40	5.39	3.85
12.8	2400.	40.	546.0	527.0	.32757	28.76	.354	129.03	.40	5.90	4.10
12.8	2400.	40.	546.0	527.0	.32757	28.76	.358	121.68	.40	5.90	4.10
12.8	2400.	40.	546.0	527.0	.32757	28.76	.358	125.66	.40	5.90	4.10
12.8	2800.	40.	545.0	526.0	.31626	28.84	.458	122.97	.40	6.16	4.25
12.8	2800.	40.	545.0	526.0	.31626	28.84	.458	123.37	.40	6.15	4.25
12.8	2800.	40.	545.0	526.0	.31626	28.84	.455	123.36	.40	6.15	4.25

14.4	1200.	10.	540.0	524.0	.29497	28.88	.030	480.24	.40	2.27
14.4	1200.	10.	540.0	524.0	.29497	28.88	.030	467.74	.40	2.25
14.4	1200.	10.	540.0	524.0	.29497	28.88	.030	455.14	.40	2.25
14.4	1600.	10.	541.0	524.0	.29497	28.88	.048	314.91	.40	3.00
14.4	1600.	10.	541.0	524.0	.29497	28.88	.050	289.68	.40	3.00
14.4	1600.	10.	541.0	524.0	.29497	28.88	.051	301.59	.40	3.00
14.4	2000.	10.	543.0	524.0	.29497	28.88	.067	277.95	.40	3.32
14.4	2000.	10.	543.0	524.0	.29497	28.88	.067	262.87	.40	3.31
14.4	2000.	10.	543.0	524.0	.29497	28.88	.068	260.44	.40	3.32
14.4	2400.	10.	545.0	524.0	.29497	28.80	.095	218.34	.40	3.86
14.4	2400.	10.	545.0	524.0	.29497	28.80	.096	218.46	.40	3.86
14.4	2400.	10.	545.0	524.0	.29497	28.80	.096	228.33	.40	3.86
14.4	2800.	10.	544.0	524.0	.29497	28.80	.141	172.01	.40	4.78
14.4	2800.	10.	544.0	524.0	.29497	28.80	.141	177.69	.40	4.78
14.4	2800.	10.	544.0	524.0	.29497	28.80	.142	173.62	.40	4.84
14.4	1200.	25.	540.0	524.0	.29497	28.88	.052	361.21	.40	2.98
14.4	1200.	25.	540.0	524.0	.29497	28.88	.052	346.53	.40	2.98
14.4	1200.	25.	540.0	524.0	.29497	28.88	.053	330.30	.40	3.01
14.4	1600.	25.	541.0	524.0	.29497	28.88	.080	265.25	.40	3.54
14.4	1600.	25.	541.0	524.0	.29497	28.88	.080	268.54	.40	3.54
14.4	1600.	25.	541.0	524.0	.29497	28.88	.080	265.78	.40	3.54
14.4	2000.	25.	543.0	524.0	.29497	28.88	.135	221.19	.40	4.28
14.4	2000.	25.	543.0	524.0	.29497	28.88	.135	218.58	.40	4.28
14.4	2000.	25.	543.0	524.0	.29497	28.88	.135	217.82	.40	4.28
14.4	2400.	25.	545.0	524.0	.29497	28.80	.194	152.56	.40	5.20
14.4	2400.	25.	545.0	524.0	.29497	28.80	.194	155.73	.40	5.20
14.4	2400.	25.	545.0	524.0	.29497	28.80	.194	155.46	.40	5.20
14.4	2800.	25.	544.0	524.0	.29497	28.80	.301	127.77	.40	5.73
14.4	2800.	25.	544.0	524.0	.29497	28.80	.304	119.30	.40	5.78
14.4	2800.	25.	544.0	524.0	.29497	28.80	.302	122.69	.40	5.76
14.4	1200.	40.	540.0	524.0	.29497	28.88	.083	259.47	.40	3.55
14.4	1200.	40.	540.0	524.0	.29497	28.88	.083	261.61	.40	3.54
14.4	1200.	40.	540.0	524.0	.29497	28.88	.083	286.04	.40	3.54
14.4	1600.	40.	541.0	524.0	.29497	28.88	.142	225.62	.40	4.57
14.4	1600.	40.	541.0	524.0	.29497	28.88	.140	233.39	.40	4.46
14.4	1600.	40.	541.0	524.0	.29497	28.88	.140	225.29	.40	4.46
14.4	2000.	40.	543.0	524.0	.29497	28.88	.226	157.24	.40	5.35
14.4	2000.	40.	543.0	524.0	.29497	28.88	.226	162.97	.40	5.36
14.4	2000.	40.	543.0	524.0	.29497	28.88	.229	156.97	.40	5.37
14.4	2400.	40.	545.0	524.0	.29497	28.80	.434	132.73	.40	5.79
14.4	2400.	40.	545.0	524.0	.29497	28.80	.434	135.26	.40	5.79
14.4	2400.	40.	545.0	524.0	.29497	28.80	.434	137.10	.40	5.79
14.4	2700.	40.	544.0	524.0	.29497	28.80	.484	137.55	.40	6.28
14.4	2700.	40.	544.0	524.0	.29497	28.80	.491	132.79	.40	6.30
14.4	2700.	40.	544.0	524.0	.29497	28.80	.509	132.42	.40	6.32

16.0	1200.	10.	540.0	523.0	.28495	28.86	.031	425.51	.40	2.41	2.95
16.0	1200.	10.	540.0	523.0	.28495	28.86	.029	501.99	.40	2.31	2.95
16.0	1200.	10.	540.0	523.0	.28495	28.86	.029	493.87	.40	2.27	2.95
16.0	1600.	10.	541.0	524.0	.29497	28.86	.048	347.98	.40	2.93	2.70
16.0	1600.	10.	541.0	524.0	.29497	28.86	.048	380.52	.40	2.94	2.70
16.0	1600.	10.	541.0	524.0	.29497	28.86	.048	374.30	.40	2.94	2.70
16.0	2000.	10.	541.0	524.0	.29497	28.86	.066	328.12	.40	3.25	2.55
16.0	2000.	10.	541.0	524.0	.29497	28.86	.066	335.54	.40	3.26	2.55
16.0	2000.	10.	541.0	524.0	.29497	28.86	.066	321.27	.40	3.26	2.55
16.0	2400.	10.	541.0	524.0	.29497	28.86	.099	248.65	.40	3.71	2.40
16.0	2400.	10.	541.0	524.0	.29497	28.86	.099	277.93	.40	3.71	2.40
16.0	2400.	10.	541.0	524.0	.29497	28.86	.099	268.03	.40	3.71	2.40
16.0	2800.	10.	541.0	524.0	.29497	28.86	.134	243.48	.40	4.50	2.40
16.0	2800.	10.	541.0	524.0	.29497	28.86	.134	250.12	.40	4.54	2.40
16.0	2800.	10.	541.0	524.0	.29497	28.86	.134	243.84	.40	4.54	2.40
16.0	1200.	25.	540.0	523.0	.28495	28.86	.054	348.65	.40	2.99	3.45
16.0	1200.	25.	540.0	523.0	.28495	28.86	.054	357.57	.40	2.99	3.45
16.0	1200.	25.	540.0	523.0	.28495	28.86	.054	335.38	.40	2.99	3.45
16.0	1600.	25.	541.0	524.0	.29497	28.86	.078	304.39	.40	3.47	3.25
16.0	1600.	25.	541.0	524.0	.29497	28.86	.078	312.41	.40	3.47	3.25
16.0	1600.	25.	541.0	524.0	.29497	28.86	.078	311.76	.40	3.47	3.25
16.0	200.	25.	541.0	524.0	.29497	28.86	.142	225.13	.40	4.39	3.20
16.0	2000.	25.	541.0	524.0	.29497	28.86	.142	238.14	.40	4.39	3.20
16.0	2000.	25.	541.0	524.0	.29497	28.86	.142	237.68	.40	4.39	3.20
16.0	2400.	25.	541.0	524.0	.29497	28.86	.198	185.91	.40	5.10	3.30
16.0	2400.	25.	541.0	524.0	.29497	28.86	.198	180.24	.40	5.10	3.30
16.0	2400.	25.	541.0	524.0	.29497	28.86	.198	174.16	.40	5.10	3.30
16.0	2800.	25.	541.0	524.0	.29497	26.66	.280	156.13	.40	5.59	3.30
16.0	2800.	25.	541.0	524.0	.29497	28.86	.275	173.06	.40	5.56	3.30
16.0	2800.	25.	541.0	524.0	.29497	28.86	.275	171.13	.40	5.56	3.30

APPENDIX H

AIR-FUEL RATIO TESTING COMPUTED RESULTS

AF	RPM	LOAD	CFM	AMFRI	DELTIM	AIRIN	DEL-GAS	AFR
11.2	1200.	10.	13.3475	0.9439	296.02	4.6566	.40	11.6416
11.2	1200.	10.	13.3475	0.9439	299.22	4.7070	.40	11.7675
11.2	1200.	10.	13.3475	0.9439	320.46	5.0411	.40	12.6028
11.2	1600.	10.	14.3825	1.0157	268.93	4.5526	.40	11.3815
11.2	1600.	10.	14.5232	1.0256	253.12	4.3269	.40	10.8172
11.2	1600.	10.	15.2073	1.0740	243.55	4.3594	.40	10.8985
11.2	2000.	10.	16.9777	1.1990	227.79	4.5520	.40	11.3799
11.2	2000.	10.	16.9777	1.1990	229.34	4.5829	.40	11.4573
11.2	2000.	10.	16.9777	1.1990	228.11	4.5583	.40	11.3959
11.2	2400.	10.	20.0108	1.4054	191.18	4.4780	.40	11.1951
11.2	2400.	10.	20.0108	1.4054	201.47	4.7190	.40	11.7976
11.2	2400.	10.	20.0108	1.4054	190.23	4.4558	.40	11.1394
11.2	2800.	10.	24.1002	1.6926	168.81	4.7621	.40	11.9053
11.2	2800.	10.	23.7574	1.6685	162.93	4.5308	.40	11.3271
11.2	2800.	10.	24.0149	1.6866	161.14	4.5297	.40	11.3241
11.2	1200.	25.	15.8518	1.1209	210.15	3.9261	.40	9.8152
11.2	1200.	25.	15.1974	1.0747	276.89	4.9594	.40	12.3985
11.2	1200.	25.	15.4625	1.0934	277.18	5.0512	.40	12.6279
11.2	1600.	25.	18.5809	1.3122	216.43	4.7334	.40	11.8334
11.2	1600.	25.	18.6902	1.3199	210.31	4.6266	.40	11.5665
11.2	1600.	25.	18.6902	1.3199	223.51	4.9170	.40	12.2924
11.2	2000.	25.	24.4540	1.7270	156.79	4.5129	.40	11.2822
11.2	2000.	25.	24.5373	1.7329	154.09	4.4503	.40	11.1257
11.2	2000.	25.	24.5373	1.7329	171.53	4.9540	.40	12.3849
11.2	2400.	25.	27.8688	1.9587	138.25	4.5131	.40	11.2828
11.2	2400.	25.	28.7585	2.0198	143.13	4.8181	.40	12.0453
11.2	2400.	25.	28.2544	1.9843	138.58	4.5832	.40	11.4580
11.2	2800.	25.	35.7628	2.5117	105.81	4.4293	.40	11.0733
11.2	2800.	25.	35.7628	2.5117	115.84	4.8492	.40	12.1230
11.2	2800.	25.	35.8776	2.5197	104.52	4.3894	.40	10.9735
11.2	1200.	40.	18.9108	1.3350	230.65	5.1318	.40	12.8295
11.2	1200.	40.	18.9108	1.3350	230.20	5.1218	.40	12.8045
11.2	1200.	40.	18.9108	1.3350	225.69	5.0215	.40	12.5536
11.2	1600.	40.	24.1231	1.7029	189.14	5.3681	.40	13.4203
11.2	1600.	40.	24.1231	1.7029	188.32	5.3448	.40	13.3621
11.2	1600.	40.	23.9533	1.6909	196.02	5.5242	.40	13.8106
11.2	2000.	40.	31.0052	2.1896	129.01	4.7081	.40	11.7702
11.2	2000.	40.	31.3980	2.2174	121.29	4.4824	.40	11.2060
11.2	2000.	40.	31.2677	2.2082	131.50	4.8396	.40	12.0989
11.2	2400.	40.	38.1547	2.6797	114.49	5.1132	.40	12.7831
11.2	2400.	40.	38.1547	2.6797	115.18	5.1440	.40	12.8601
11.2	2400.	40.	37.3926	2.6261	114.29	5.0024	.40	12.5059
11.2	2800.	40.	45.2120	3.1753	109.94	5.8182	.40	14.5455
11.2	2800.	40.	44.7085	3.1399	109.33	5.7215	.40	14.3037
11.2	2800.	40.	44.4778	3.1237	109.30	5.6904	.40	14.2260

12.8	1200.	10.	12.4564	0.8731	377.71	5.4964	.40	13.7411
12.8	1200.	10.	11.6057	0.8135	408.68	5.5410	.40	13.8525
12.8	1200.	10.	11.4280	0.8010	416.04	5.5544	.40	13.8860
12.8	1600.	10.	15.2841	1.0686	259.32	4.6185	.40	11.5462
12.8	1600.	10.	15.2841	1.0686	249.60	4.4454	.40	11.1135
12.8	1600.	10.	15.2841	1.0686	252.26	4.4928	.40	11.2319
12.8	2000.	10.	18.1195	1.2663	215.60	4.5502	.40	11.3756
12.8	2000.	10.	18.1195	1.2663	220.53	4.6543	.40	11.6357
12.8	2000.	10.	18.1195	1.2663	211.32	4.4599	.40	11.1498
12.8	2400.	10.	20.1204	1.3978	200.02	4.6597	.40	11.6493
12.8	2400.	10.	20.1204	1.3978	198.14	4.6159	.40	11.5398
12.8	2400.	10.	20.1204	1.3978	199.24	4.6415	.40	11.6038
12.8	2800.	10.	24.5457	1.7089	179.58	5.1146	.40	12.7865
12.8	2800.	10.	24.5457	1.7089	171.51	4.8848	.40	12.2119
12.8	2800.	10.	24.5457	1.7089	253.89	7.2310	.60	12.0517
12.8	1200.	25.	15.1297	1.0605	313.43	5.5399	.40	13.8497
12.8	1200.	25.	14.9936	1.0510	313.59	5.4929	.40	13.7322
12.8	1200.	25.	14.9936	1.0510	321.54	5.6321	.40	14.0803
12.8	1600.	25.	18.4531	1.2902	237.17	5.0998	.40	12.7495
12.8	1600.	25.	18.4531	1.2902	238.72	5.1331	.40	12.8328
12.8	1600.	25.	18.4531	1.2902	233.07	5.0116	.40	12.5291
12.8	2000.	25.	24.9159	1.7413	167.60	4.8639	.40	12.1599
12.8	2000.	25.	23.2912	1.6277	223.06	6.0514	.40	15.1284
12.8	2000.	25.	23.2026	1.6215	210.97	5.7016	.40	14.2540
12.8	2400.	25.	28.9877	2.0138	148.14	4.9720	.40	12.4301
12.8	2400.	25.	28.9877	2.0138	142.86	4.7948	.40	11.9871
12.8	2400.	25.	29.2727	2.0336	145.10	4.9179	.40	12.2947
12.8	2800.	25.	35.1028	2.4438	119.06	4.8494	.40	12.1234
12.8	2800.	25.	35.9202	2.5007	115.25	4.8035	.40	12.0087
12.8	2800.	25.	35.6885	2.4846	125.39	5.1924	.40	12.9810
12.8	1200.	40.	18.8978	1.3207	260.11	5.7254	.40	14.3136
12.8	1200.	40.	18.5683	1.2977	259.36	5.6094	.40	14.0234
12.8	1200.	40.	18.5683	1.2977	260.84	5.6414	.40	14.1034
12.8	1600.	40.	24.3299	1.7003	217.43	6.1617	.40	15.4042
12.8	1600.	40.	23.9886	1.6765	221.26	6.1823	.40	15.4556
12.8	1600.	40.	24.0744	1.6825	209.70	5.8802	.40	14.7005
12.8	2000.	40.	31.1684	2.1782	160.02	5.8094	.40	14.5234
12.8	2000.	40.	31.5633	2.2058	168.65	6.2002	.40	15.5005
12.8	2000.	40.	31.4322	2.1967	149.55	5.4752	.40	13.6880
12.8	2400.	40.	38.3094	2.6614	129.03	5.7233	.40	14.3082
12.8	2400.	40.	38.5258	2.6764	121.68	5.4278	.40	13.5694
12.8	2400.	40.	38.5258	2.6764	125.66	5.6053	.40	14.0132
12.8	2800.	40.	43.4828	3.0357	122.97	6.2217	.40	15.5543
12.8	2800.	40.	43.4828	3.0357	123.37	6.2420	.40	15.6049
12.8	2800.	40.	43.3397	3.0257	123.36	6.2209	.40	15.5523

14.4	1200.	10.	11.0267	0.7782	480.24	6.2283	.40	15.5709
14.4	1200.	10.	11.0267	0.7782	467.74	6.0662	.40	15.1656
14.4	1200.	10.	11.0267	0.7782	455.14	5.9028	.40	14.7570
14.4	1600.	10.	13.9689	0.9841	314.91	5.1651	.40	12.9127
14.4	1600.	10.	14.2578	1.0045	289.68	4.8495	.40	12.1238
14.4	1600.	10.	14.4000	1.0145	301.59	5.0993	.40	12.7482
14.4	2000.	10.	16.5395	1.1612	277.95	5.3794	.40	13.4486
14.4	2000.	10.	16.5395	1.1612	262.87	5.0876	.40	12.7190
14.4	2000.	10.	16.6629	1.1699	260.44	5.0781	.40	12.6954
14.4	2400.	10.	19.7655	1.3792	216.34	5.0188	.40	12.5470
14.4	2400.	10.	19.8696	1.3864	218.46	5.0480	.40	12.6200
14.4	2400.	10.	19.8696	1.3864	228.33	5.2761	.40	13.1902
14.4	2800.	10.	24.0728	1.6826	172.01	4.8237	.40	12.0591
14.4	2800.	10.	24.0728	1.6826	177.69	4.9829	.40	12.4573
14.4	2800.	10.	24.1582	1.6885	173.62	4.8861	.40	12.2152
14.4	1200.	25.	14.5285	1.0253	361.21	6.1723	.40	15.4308
14.4	1200.	25.	14.5285	1.0253	346.53	5.9215	.40	14.8037
14.4	1200.	25.	14.6679	1.0351	330.30	5.6983	.40	14.2458
14.4	1600.	25.	18.0467	1.2714	265.25	5.6206	.40	14.0514
14.4	1600.	25.	18.0467	1.2714	268.54	5.6903	.40	14.2257
14.4	1600.	25.	18.0467	1.2714	265.78	5.6318	.40	14.0795
14.4	2000.	25.	23.5006	1.6500	221.19	6.0826	.40	15.2066
14.4	2000.	25.	23.5006	1.6500	218.58	6.0109	.40	15.0272
14.4	2000.	25.	23.5006	1.6500	217.82	5.9900	.40	14.9749
14.4	2400.	25.	28.2736	1.9728	152.56	5.0163	.40	12.5407
14.4	2400.	25.	28.2736	1.9728	155.73	5.1205	.40	12.8013
14.4	2400.	25.	28.2736	1.9728	155.46	5.1116	.40	12.7791
14.4	2800.	25.	35.2096	2.4610	127.77	5.2407	.40	13.1017
14.4	2800.	25.	35.3851	2.4733	119.30	4.9176	.40	12.2941
14.4	2800.	25.	35.2682	2.4651	122.69	5.0407	.40	12.6017
14.4	1200.	40.	18.3671	1.2962	259.47	5.6053	.40	14.0132
14.4	1200.	40.	18.3671	1.2962	261.61	5.6515	.40	14.1288
14.4	1200.	40.	18.3671	1.2962	286.04	6.1793	.40	15.4482
14.4	1600.	40.	24.0627	1.6952	225.62	6.3746	.40	15.9364
14.4	1600.	40.	23.8922	1.6832	233.39	6.5474	.40	16.3684
14.4	1600.	40.	23.8922	1.6832	225.29	6.3201	.40	15.8003
14.4	2000.	40.	30.4284	2.1364	157.24	5.5987	.40	13.9969
14.4	2000.	40.	30.4284	2.1364	162.97	5.8028	.40	14.5069
14.4	2000.	40.	30.6303	2.1506	156.97	5.6262	.40	14.0655
14.4	2400.	40.	42.3365	2.9541	132.73	6.5350	.40	16.3374
14.4	2400.	40.	42.3365	2.9541	135.26	6.6595	.40	16.6488
14.4	2400.	40.	42.3365	2.9541	137.10	6.7501	.40	16.8753
14.4	2700.	40.	44.6776	3.1227	137.55	7.1589	.40	17.8972
14.4	2700.	40.	45.0004	3.1453	132.79	6.9611	.40	17.4027
14.4	2700.	40.	45.8201	3.2026	132.42	7.0682	.40	17.6704

16.0	1200.	10.	11.2111	0.7909	425.51	5.6092	.40	14.0230
16.0	1200.	10.	10.8424	0.7649	501.99	6.3998	.40	15.9994
16.0	1200.	10.	10.8424	0.7649	493.87	6.2963	.40	15.7406
16.0	1600.	10.	13.9738	0.9838	347.98	5.7055	.40	14.2637
16.0	1600.	10.	13.9738	0.9838	380.52	6.2390	.40	15.5975
16.0	1600.	10.	13.9738	0.9838	374.30	6.1370	.40	15.3426
16.0	2000.	10.	16.3930	1.1541	328.12	6.3113	.40	15.7782
16.0	2000.	10.	16.3930	1.1541	335.54	6.4540	.40	16.1349
16.0	2000.	10.	16.3930	1.1541	321.27	6.1795	.40	15.4488
16.0	2400.	10.	20.0887	1.4143	248.65	5.8609	.40	14.6522
16.0	2400.	10.	20.0887	1.4143	277.93	6.5510	.40	16.3776
16.0	2400.	10.	20.0887	1.4143	268.03	6.3177	.40	15.7942
16.0	2800.	10.	23.3814	1.6461	243.48	6.6797	.40	16.6993
16.0	2800.	10.	23.3814	1.6461	250.12	6.8619	.40	17.1547
16.0	2800.	10.	23.3814	1.6461	243.84	6.6896	.40	16.7240
16.0	1200.	25.	14.8082	1.0447	348.65	6.0707	.40	15.1766
16.0	1200.	25.	14.8082	1.0447	357.57	6.2260	.40	15.5649
16.0	1200.	25.	14.8082	1.0447	335.38	5.8396	.40	14.5990
16.0	1600.	25.	17.8253	1.2549	304.39	6.3663	.40	15.9159
16.0	1600.	25.	17.8253	1.2549	312.41	6.5341	.40	16.3352
16.0	1600.	25.	17.8253	1.2549	311.76	6.5205	.40	16.3012
16.0	2000.	25.	24.0712	1.6946	225.13	6.3585	.40	15.8962
16.0	2000.	25.	24.0712	1.6946	238.14	6.7259	.40	16.8149
16.0	2000.	25.	24.0712	1.6946	237.68	6.7130	.40	16.7824
16.0	2400.	25.	28.4373	2.0020	165.91	6.2032	.40	15.5080
16.0	2400.	25.	28.4373	2.0020	160.24	6.0140	.40	15.0350
16.0	2400.	25.	28.4373	2.0020	174.16	5.8111	.40	14.5278
16.0	2800.	25.	33.8333	2.3819	156.13	6.1981	.40	15.4951
16.0	2800.	25.	33.5290	2.3605	173.06	6.8083	.40	17.0209
16.0	2800.	25.	33.5290	2.3605	171.13	6.7324	.40	16.8311

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VITA

Gary A. Schneck

Candidate for the Degree of

Master of Science

Thesis: DESIGN, IMPLEMENTATION, AND TESTING OF A REAL-TIME MICROCOMPUTER AIR-FUEL RATIO AND SPEED CONTROLLER FOR AN ELECTRONICALLY FUEL INJECTED INTERNAL COMBUSTION ENGINE

Major Field: Mechanical Engineering

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DESIGN, IMPLEMENTATION, AND TESTING OF A REAL-TIME MICROCOMPUTER AIR-FUEL RATIO AND SPEED CONTROLLER FOR AN ELECTRONICALLY FUEL INJECTED INTERNAL COMBUSTION ENGINE

by

GARY ALAN SCHNECK

B.S., Kansas State University, 1975

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

Abstract

The advent of governmental emission standards in 1968 resulted in the requirement that the automobile engine have more precision in metering and mixing the fuel and air to maintain an air-fuel ratio that would reduce exhaust emissions, yet still meet the driver's demands and the engine's operating needs. Today this precision is an even more important requirement because those emission limits have become more severe and the motoring public is demanding vastly improved performance in terms of driveability and economy. The only way these divergent requirements can be reconciled is through extremely accurate control. The power and versatility of the microcomputer make it an ideal candidate for the task at hand because it can provide that high degree of accuracy in computation and control.

The objective of this thesis was to develop and test a microcomputer air-fuel ratio and speed control system operating in conjunction with an electronically fuel injected internal combustion engine. The microcomputer was programmed to control the engine at 4 different air-fuel ratios: 11.2-1, 12.8-1, 14.4-1, and 16.-1 over a range of 1000-3000 rpm and 10.0-40.0 lb-ft of load. Furthermore, the computer was programmed to control the acceleration, deceleration, or maintenance of constant engine speed within the previously defined operating range. The air-fuel ratio controller was an open-loop, nonfeedback control system, utilizing a table look-up procedure and stored injection time data. Measured inputs to the computer were engine speed and mass air flow rate. The speed controller was a closed-loop type control system using a TTL speed sensor as the feedback element. A stepping motor was utilized to control the position

of the throttle.

Testing was performed on an engine mounted on a test block in a laboratory of the Mechanical Engineering Department. The engine was a 1968 model, 96.6 cubic inch displacement, four cylinder, horizontally opposed, air cooled, spark ignition, internal combustion, Volkswagen engine equipped with a Bosch pulse-timed gasoline injection system. Data for the air-fuel ratio testing was taken, following an engine warm-up period, at combinations of five engine speeds between 1200-2800 rpm, three loads between 10-40 lb-ft, and four different air fuel ratios. Three sets of data were taken at each test point. Speed control tests were run over this same range of parameters, with the exception that the microcomputer controller was set to maintain an air-fuel ratio of 12.8-1. Acceleration and deceleration tests were made to compare the Bosch fuel injection control and the microcomputer injection control system. Tests were also made to determine speed control characteristics when a sudden load disturbance was induced.

The results of the testing made on the air-fuel ratio controller showed that an offset ranging from 0.85% to 7.42% existed between the computed air-fuel ratios and the desired air-fuel ratios. Inaccuracies involved in the fuel injector calibration are believed to be major causes for this offset. The percent standard deviation from the mean for tests at a specific load and air-fuel ratio ranged from a low of 3.83% to a high of 8.79%. For the air-fuel ratio tests as a whole the percent standard deviation ranged from 5.33% to 16.59%. The uncertainty associated with the air-fuel ratio results was calculated to be a limit of error of 3.3%.

The speed control tests, recorded using a strip chart recorder, resulted in the determination of certain response parameters, namely time response, percent overshoot, and settling time for the varied operating conditions. The speed control system was shown to react adequately to load disturbances, although some difficulty was encountered while running the tests in conjunction with the microcomputer air-fuel ratio controller due to the switching involved in changing from one system to the next.