MICROPROCESSOR CONTROL OF AN ENGINE-HYDROSTATIC TRANSMISSION SYSTEM

By

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NOMENCLATURE

a	rolling resistance coefficient
A	front area of vehicle, in.^{2}
b	velocity correction coefficient, in./sec
B	bulk modulus of hydraulic oil, psi
C_a	air resistance coefficient
C_{dm}	motor viscous drag coefficient
C_{dp}	pump viscous drag coefficient
C_{fm}	motor dry friction coefficient
C_{fp}	pump dry friction coefficient
C_{sm}	motor slip coefficient
C_{sp}	pump slip coefficient
C_1	proportional gain for throttle PI controller
C_1^*	optimum proportional gain for throttle PI controller
C_2	proportional gain for displacement PI controller
C_2^*	optimum proportional gain for displacement PI controller
D_c	crossover point of crossover controller, amp
D_m	motor displacement, in.^{3}/rad
$\tilde{D}_m$	dummy motor displacement, in.^{3}/rad
D_{mm}	maximum motor displacement, in.^{3}/rad
D_p	pump displacement, in.^{3}/rad
D_{pm}	maximum pump displacement, in.^{3}/rad
D_r	displacement control signal (output of amplifier), amp

D_{rh}	displacement control signal (output of zero order hold), volt
D_{ra}	displacement control signal (output of D/A converter), volt
D_{rd}	displacement control signal (output of PI controller)
D_{rmax}	maximum value of D_r, amp
D_{rm}	motor displacement control signal (output of crossover controller), amp
D_{rp}	pump displacement control signal (output of crossover controller), amp
DI	integrator output of the displacement PI controller
DI_{max}	upper limit of DI
DI_{min}	lower limit of DI
f	total fuel consumption, lbm
$\dot{f}$	fuel consumption rate, lbm/sec
$\tilde{f}$	fuel consumption per unit of distance, lbm/in.
F_a	air resistance, lbf
F_g	road grade resistance, lbf
F_p	vehicle propulsive force, lbf
F_r	rolling resistance, lbf
G	road grade
G_m	motor gear ratio
G_p	pump gear ratio
HPE_{max}	maximum engine horsepower, hp
J	performance criterion
J_c	moment of inertia of the engine-gear-pump unit, lb-in.-sec^2
J_e	engine moment of inertia, lbf-in.-sec^2
J_m	motor moment of inertia, lbf-in.-sec^2
J_{mg}	motor gear moment of inertia, lbf-in.-sec^2

J_p	pump moment of inertia, lbf-in.-sec^2
J_{pg}	pump gear moment of inertia, lbf-in.-sec^2
K_1	engine throttle gain, in.-lbf/rad
K_2	engine damping coefficient, in.-lbf-sec/rad
K_3	engine transport delay constant, rad
ℓ_1	slope for function LIMIT
ℓ_2	slope for function DEADSP
L	traveled distance, in.
M	vehicle inertia mass, lbm
M_c	inertia mass of the motor-gear-vehicle unit, lbf-sec^2/in.
P	hydraulic pressure, psi
P_e	engine power, in.-lbf/sec
P_e^*	engine power at a particular load point, in.-lbf/sec
P_ℓ	load power, in.-lbf/sec
P_ℓ^*	load power at a particular load point, in.-lbf/sec
P_m	motor pressure drop, psi
P_p	pump pressure drop, psi
P_{max}	maximum working pressure, psi
Q_m	motor flowrate, in.^{3}/sec
Q_p	pump flowrate, in.^{3}/sec
Q_{st}	total leakage flow, in.^{3}/sec
R	wheel radius, in.
S_c	command vehicle speed, rad/sec
S_{cd}	digitized command vehicle speed
S_e	engine speed, rad/sec
$\dot{S}_e$	rate of change of engine speed, rad/sec^2
S_e^*	optimum engine speed at a particular load point, rad/sec

S_{ed}	digitized engine speed
S_{emax}	maximum engine speed, rad/sec
S_{idle}	engine idling speed, rad/sec
S_{ℓ}	load speed, rad/sec
S_{ℓ}^{*}	load speed at a particular load point, rad/sec
$S_{\ell d}$	digitized load speed
$S_{\ell max}$	maximum load speed, rad/sec
S_m	motor speed, rad/sec
S_p	pump speed, rad/sec
t	time, sec
t_1	engine transport delay, sec
T_a	engine accelerating torque, in.-lbf
T_d	engine damping torque, in.-lbf
T_e	engine loading torque, in.-lbf
T_e^{*}	optimum engine loading torque at a particular load point, in.-lbf
T_{ed}	digitized engine loading torque
T_{emax}	maximum engine loading torque, in.-lbf
T_{full}	engine full throttle torque, in.-lbf
T_{idle}	engine idling torque, in.-lbf
T_{ℓ}	load torque, in.-lbf
T_{ℓ}^{*}	load torque at a particular load point, in.-lbf
$T_{\ell d}$	digitized load torque
$T_{\ell max}$	maximum load torque, in.-lbf
T_m	motor torque, in.-lbf
T_{op}	optimum engine loading torque, in.-lbf
T_{out}	delayed engine output torque, in.-lbf

T_p	pump torque, in.-lbf
T_s	sampling time interval, ms
T_y	engine input torque, in.-lbf
v	total volume under compression, in.^{3}
V	vehicle velocity, in./sec
$\dot{V}$	vehicle acceleration, in./sec
V_{150}	vehicle velocity after 150 seconds, in./sec
V_{max}	maximum vehicle velocity, in./sec
V_w	head wind velocity, in./sec
W	vehicle weight, lbf
Y	engine throttle position, rad
Y_d	digitized engine throttle position
Y_{idle}	idling throttle position, rad
Y_{max}	maximum throttle position, rad
Y_r	throttle control signal (output of amplifier), amp
Y_{rh}	throttle control signal (output of zero order hold), volt
Y_{ra}	throttle control signal (output of D/A converter), volt
Y_{rd}	throttle control signal (output of PI controller)
Y_s	delayed engine throttle position (output of function YSHIFT)
YI	integrator output of the throttle PI controller
YI_{max}	upper limit of YI
YI_{min}	lower limit of YI

Greek Symbols

μ	hydraulic oil viscosity, lbf-sec/in.^{2}
η_e	engine efficiency
η_s	overall system efficiency

η_t	transmission efficiency
λ	upper limit for implicit constraint
ϕ	slope of terrain, rad
ρ	air density, lbf-sec^2/in.^{4}
τ_d	displacement servo time constant, sec
τ_y	throttle servo time constant, sec
τ_1	integral time constant for throttle PI controller, sec
τ_1^*	optimum integral time constant for throttle PI controller, sec
τ_2	integral time constant for displacement PI controller, sec
τ_2^*	optimum integral time constant for displacement PI controller, sec
ΔD	total change of pump and motor displacements, in.^{3}/rad
ΔD_m	total change of motor displacement, in.^{3}/rad
ΔD_p	total change of pump displacement, in.^{3}/rad
ΔS	vehicle speed error
ΔT	engine loading torque error

Acronyms

A/D	analog to digital
CPU	central processing unit
D/A	digital to analog
FG	function generator
HST	hydrostatic transmission
IC	internal combustion
ITAE	integral of the time weighted absolute value of the error
I/O	input/output

ms	minisecond
PI	proportional-integral
PROM	programmable read-only memory
RAM	random access memory
SI	spark ignition
μC	microcomputer
μP	microprocessor
μs	microsecond

CHAPTER I

INTRODUCTION

1.1 General

Generally, vehicle prime movers have torque-speed characteristics which are not well matched to the vehicle load as reflected through the wheels. A transmission is used to convert the engine output to the desired combination of torque and speed.

The hydrostatic transmission (HST) has the attactive advantage of providing a continuously variable, stepless gear ratio between the engine and the driving wheels. With a continuous variance, an HST can be controlled to maximize any reasonable performance criterion for the engine-transmission power train, e.g., maximum engine efficiency, maximum overall system efficiency, maximum vehicle acceleration, etc. However, in order to accomplish the control function, it is necessary to devise a good controller which can relate the engine throttle, pump and motor displacements in an appropriate manner.

During the past years, a lot of such control systems have been designed based on different control schemes, e.g., mechanical, hydraulic, electronic, fluidic controls and a combination of these. Today, the microprocessor provides a new approach to the engine-transmission control due to its considerable potential of low cost, flexibility, and computational power.

The microprocessor (μP) has already found many applications. In the automotive area, the μP has been used in ignition control and fuel injection control. However, in engine-HST control, so far there is no literature published. The objective of this study was to conduct a conceptual design of a high performance μP-based controller for a vehicle propulsion system comprising an internal combustion engine and an hydrostatic transmission.

1.2 Literature Survey

A literature survey was done in the areas of HST control technology and μP implementation. In the area of HST control technology, the literature was reviewed according to performance criteria used and control schemes used.

1.2.1 Performance Criteria

The performance criteria that have been established in the past are maximum engine efficiency, maximum overall system efficiency, and maximum vehicle acceleration. Wilson et al. [1], Reid et al. [2], Svoboda [3], and Cunningham et al. [4] have developed controllers which can be used to vary the load on the engine to maximize engine efficiency and, therefore, minimize fuel consumption. Taking into account the transmission efficiency, Reid et al. [5] and Bowns et al. [6] have presented controllers, by which the system overall efficiency was optimized by varying the engine speed, and the pump and motor displacements for the power required. Wilson [7] proposed to govern engine speed to produce maximum power output while controlling the pump displacement to give maximum vehicle acceleration (motor displacement varied by operator). A controller proposed by Howard et al. [8] adjusts the speed ratio to give maximum load at maximum engine throttle. This type of controller would find its best application in a situation like a farm tractor where maximum load and maximum throttle are simultaneously and continuously required.

1.2.2 Control Schemes

Mechanical controls for HST's fulfilled the industry needs satisfactorily for a long time. For the simple mechanical control, the control lever is connected to the internal mechanism which makes the pump and motor variable through a hydraulic boost [9]. Reid et al. [2] discussed a General Electric Company mechanical controller, which schedules the engine speed and the pump and motor displacements according to the power requirements. The variable to be controlled by the operator is the load speed via the accelerator pedal. Cams are arranged to schedule engine speed as a function of throttle angle and sensed engine speed. Any deviation from the engine speed schedule is accompanied by an appropriate change in pump and motor displacements. In the last few years, electrohydraulic devices have become available for stroking pump and motor displacements with small electrical signals. This capability creates possibilities for improved control of mobile vehicles, ranging from simple remote control to sophisticated automatic control [10, 11]. Numerous papers deal with electronic-based control systems. The works of Svoboda [3] and Cunningham et al. [4] are representative. For the control system generated by Cunningham et al., the driver adjusts the setting of the engine speed governor via an accelerator pedal. Engine speed is sensed and converted into an engine torque reference signal, which is combined with a signal proportional to transmission pressure difference to generate the correcting pump displacement signal. For the control system developed by Svoboda [3], the driver controls the vehicle velocity by operating the motor swashplate. The engine throttle and pump displacement are governed by a multiloop electronic controller via electrohydraulic servoactuators. The feasibility of fluidic-based controllers have been studied by Reid et al. [5] and Howard et al. [8]. Reid et al. chose to implement the controller with fluidic circuits for the various sensing, logic and control functions required in military vehicle propulsion systems. Several different control concepts were developed.

1.2.3 Microprocessor Implementation

Since their introduction in 1971, μPs have spurred interest in process control, automotive, aerospace, biomedical, instrumentation, data acquisition and consumer electronics applications as well as other industrial, commercial and military applications. In automotive applications, the use of a microprocessor to control an automotive engine has become a reality. Binder et al. [12], Toelle [13], Marley [14], and many others investigated the μP control on such existing functions as air/fuel-ratio, ignition-timing and exhaust-gas-recirculation control to obtain fuel economy, low emissions and driveability. Hosey et al. [15] have designed a μP-based spark timing controller based on measurements of cylinder pressure to extract maximum energy from the fuel while minimizing pollutants. Generally, all the μP-based controllers respond with suitable engine adjustments on the basis of the stored information together with concurrent operating conditions sensed from the engine. All the applications for μPs in the automobile focused on the fuel-flow, spark-advance and emission control. There appears to be no direct transfer of implementation strategies used to the engine-HST drive system control problem in this study, except in techniques for function generation.

The various control concepts used for HST control are compared in Table I.

1.3 Objectives of Study

The primary objectives of this study include:

1. Design a power transmission circuit and size its components. Develop a generalized steady-state mathematical model for the HST power train and code a program which can be used to search the optimum system operating conditions based on different performance criterion, e.g., optimum fuel economy. Some of these optimum system variable relationships will be selected for the generation of the function generator.

2. Design a microprocessor-based controller for the engine-HST system. Entails the design of the control circuit, the μP configuration and the derivation of the digital control algorithms. The preliminary system design is followed by optimum adjustment of the controller parameters. A simplex optimization method is used.

3. Derive the linearized model and transfer function for the engine-HST system, and calculate the highest system frequency, which will be used to check whether the sampling requirement is met.

TABLE I

COMPARISON OF VARIOUS CONTROL CONCEPTS USED FOR HST CONTROL

Performance Criterion \ Control Scheme	*	Mechanical Control	Electronic Control	Fluidic Control	Microprocessor Control
*		Houk [9]	Cornell [10]		
Maximum Engine Efficiency	Wilson [1]	Reid [2]	Svoboda [3] Cunningham [4]		
Maximum System Efficiency		Bowns [6]		Reid [5]	†
Maximum Vehicle Acceleration	Wilson [7]				
Maximum Load				Howard [8]	

*Indicates that no performance criterion was used or no control scheme was mentioned in the control technology.

†Indicates the control technology studied in this thesis.

4. Derive a closed-loop dynamic model for the engine-HST vehicle drive system, and code a computer program. By utilizing manufacturers' data for individual components whenever possible as an example, a discrete system simulation is carried out to evaluate the dynamic performance and the fuel economy of the vehicle propulsion system, and to demonstrate the feasibility of the μP-based control system.

CHAPTER II

FUEL ECONOMY STRATEGY

In view of the apparent decreasing availability and increasing cost of liquid petroleum, fuel economy is one of the most important considerations in modern engineering design. For an engine-HST system, substantially reduced fuel consumption may be achieved by scheduling the engine loading torque and the pump and motor displacements according to the power requirements.

2.1 Engine Loading

Proper engine loading can improve system fuel economy. Before illustrating this idea, it is useful to define a performance criteron as:

$$J = \frac{\text{Load speed X load torque}}{\text{Rate of fuel consumption}} = \frac{S_\ell \, T_\ell}{\dot{f}} \tag{2.1}$$

The engine efficiency is defined as

$$\eta_e = \frac{S_e \, T_e}{\dot{f}} \tag{2.2}$$

Inserting this expression yields

$$J = \frac{S_\ell \, T_\ell}{S_e \, T_e} \eta_e \tag{2.3}$$

Furthermore, the transmission efficiency may be defined as

$$\eta_t = \frac{S_\ell \; T_\ell}{S_e \; T_e} \tag{2.4}$$

so that the performance criterion becomes

$$J = \eta_e \; \eta_t \tag{2.5}$$

Therefore, minimum fuel consumption (i.e. maximum performance criterion) can be accomplished by maximizing the product of the engine and transmission efficiencies, i.e. the system efficiency η_s.

Engine loading affects fuel economy, and speed ratio affects the system efficiency. For illustration consider the case of an ideal transmission (i.e. $\eta_t = 1$). The problem is to find the speed ratio which maximizes the performance criterion η_e. Consider a particular load point (S_ℓ*, T_ℓ*) on the lowest grade curve (nominal load line) of Figure 1. This load requires a power P_ℓ* to be delivered by the engine. For an ideal transmission, the engine supplied power, P_e* equals the load requirement, P_ℓ*. Reference to Figure 2 reveals that the engine power P_e* can be developed by various combinations of throttle positions and engine speeds (see horizontal line drawn at power level P_e*). However, there is only one combination that will deliver this power while maximizing the engine efficiency. Operation either to the left or right of the point (S_e*, T_e*) will be at lower efficiency. By considering different loading points the same procedure can be extended to develop the locus of points which maximizes engine efficiency. This locus is shown in Figure 2 by the dashed line labeled "optimum engine efficiency". For a real transmission, the load power requires $P_e{*} = P_\ell{*}/\eta_t$ from the engine. Since the transmission efficiency η_t is variable with loading, the power requirement from the engine is not a constant horizontal line as before, but is a function of speed as shown in Figure 3. However, there does exist an operating point (S_e^*, T_e^*) that maximizes the overall system efficiency. By considering other points along a nominal load line, the engine curve for optimum nominal operation is obtained (see the heavy solid line in Figure 4.) The consideration of all loading conditions experienced by the vehicle leads to the range of optimum operation indicated by the shaded region in Figure 4.

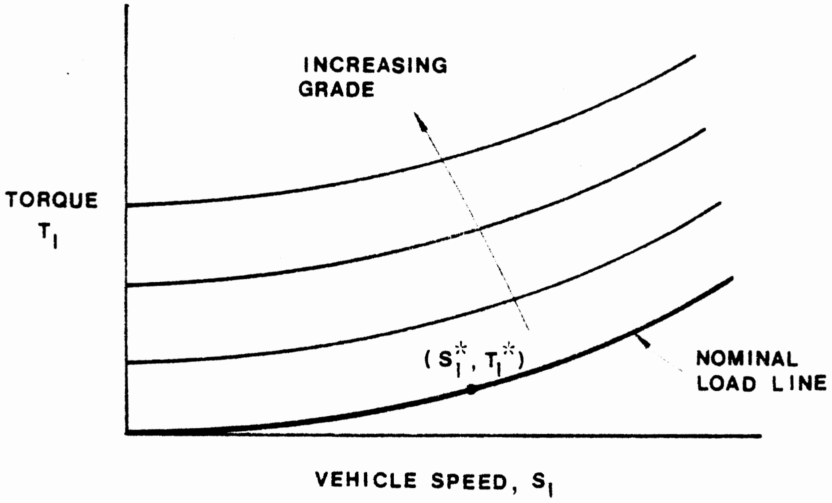


Figure 1. Load Characteristics for a Typical Vehicle

From the above discussion, it can be seen that only through the use of a wide ratio range continuously variable transmission, such as an HST,

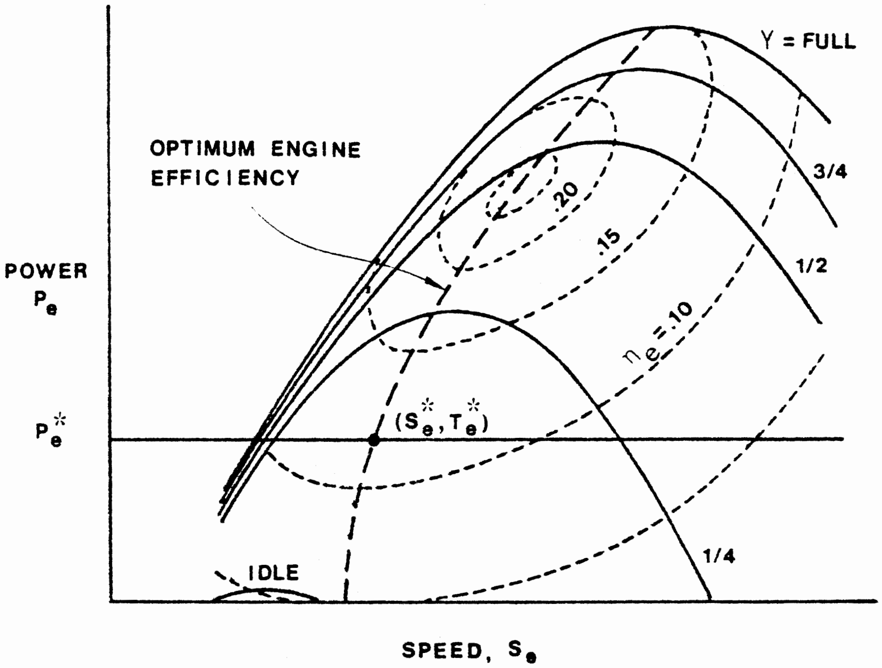


Figure 2. Typical IC Engine Performance Map Showing Optimum Operation [16, p. 93]

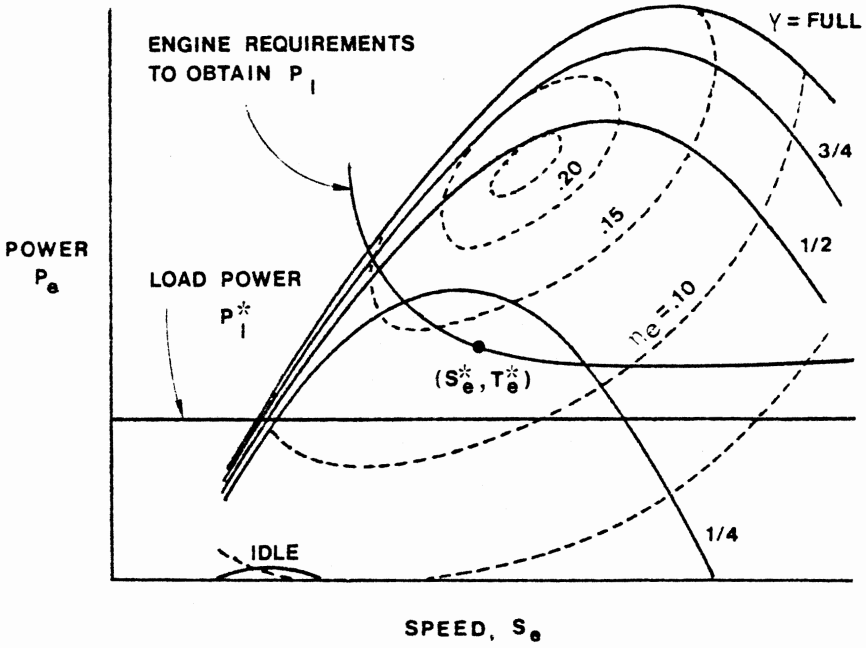


Figure 3. Typical IC Engine Performance Map Showing Optimum Operation With a HST [16, p. 95]

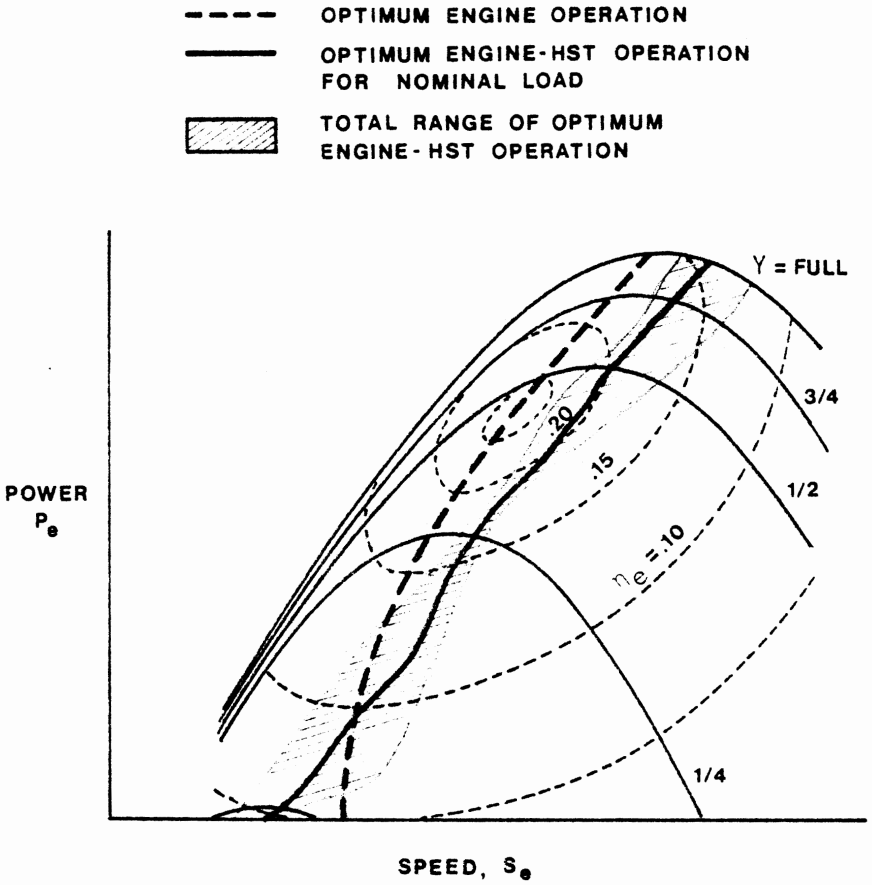


Figure 4. Comparison of Optimum Engine and System [16, p. 96]

it is possible to vary both engine torque and speed over a wide range and results in maximum fuel economy. With a mechanical transmission incorporating, say, a four-speed gearbox, a load torque and speed demand can only be met at four engine torque levels.

2.2 Determination of Optimum Engine Operation Schedule

In order to obtain the best fuel efficiency, the engine must run at its best operating point. The optimum engine operation schedule was generated based on the concept of optimum fuel consumption just described in the last section. The optimization requires knowledge of the loading conditions of interest, the coefficients for the HST mathematical model, and engine performance data. With this information, a search for optimality was carried out as follows: Select a load point of interest. For this load point, try different transmission displacements to find the one giving the speed ratio for maximum system efficiency; that is, select trial values of displacements and observe the corresponding system operating point. Knowing the speed and torque of the load point and the transmission displacements, the engine speed and torque can be computed using the transmission equations (see Appendix A). Since an engine operating efficiency is associated with each engine operating point, and the transmission efficiency is computed from the ratio of the load power to the computed engine power, then, the system efficiency is computed from Equation (2.5) for these trial displacements. Searching for the values of the displacements which give maximum system efficiency finally yields the optimum operating point for all system variables; e.g., throttle position, engine speed and torque, displacements, etc. By extending this search procedure to every load point of interest, the scheduling of optimum engine operation for the load map of interest can be determined.

A computer program was developed to facilitate the search. A listing of this program and results on the example system (see section 4.1) are given in Appendix G.2. From the obtained optimum operating conditions some variable relationships can be selected to generate a function generator. In this study, the engine loading torque versus throttle position for different load torques was chosen to be a function generator (Table II). It could be stored in a programmable read-only memory chip (see section 6.1) and used along with sampled data to determine the optimum engine loading torque.

TABLE II

OPTIMUM ENGINE LOADING TORQUE VERSUS THROTTLE POSITION AND LOAD TORQUE

TAU	OPTE1	OPTE2	OPTE3	OPTE4	OPTE5	OPTE6	OPTE7
0.1	2.3	2.3	2.3	2.3	2.3	2.3	2.3
3.6	51.4	62.5	63.1	63.2	63.0	60.0	51.4
7.1	111.4	111.9	106.7	107.1	107.6	107.9	111.4
10.6	149.4	148.3	151.1	172.7	175.0	176.0	176.4
14.1	178.7	187.6	189.1	196.2	205.2	205.4	207.8
17.6	206.4	211.1	208.0	210.2	212.9	213.8	217.8
21.1	220.9	227.0	226.1	226.7	226.2	227.5	231.8
24.6	227.5	238.5	238.4	237.0	238.0	237.3	235.5
28.1	234.5	239.4	239.6	239.0	239.7	238.6	236.6
31.6	238.0	239.8	242.2	239.5	241.7	242.4	239.0
35.1	242.8	242.6	245.0	239.8	246.9	247.8	244.3
38.5	245.0	245.4	246.9	240.9	251.4	252.2	248.7
42.0	246.1	248.0	247.0	242.7	255.7	255.0	252.8
45.5	246.9	250.4	248.6	246.6	257.3	255.6	256.7
49.0	247.5	252.8	252.0	250.6	258.0	258.4	260.5
52.5	247.9	246.6	250.3	254.6	258.8	262.0	264.3
56.0	248.2	246.1	250.0	258.5	259.6	265.8	269.3
59.5	248.4	245.0	249.8	254.1	260.3	269.7	272.3
63.0	248.6	244.0	249.1	253.9	261.4	272.0	273.3
66.5	248.7	243.3	246.4	248.3	261.6	272.6	273.8
70.0	248.7	243.0	243.0	242.7	261.9	272.9	274.0

CHAPTER III

ENGINE-HYDROSTATIC TRANSMISSION POWER TRAIN CONTROL STUDY

This chapter is presented to describe the power circuit and control concept of the engine-hydrostatic transmission power train.

3.1 Power Circuit Configuration

The power circuit diagram of the proposed engine-transmission system is shown in Figure 5. An internal combustion (IC) engine (1) drives an axial-piston variable-displacement pump (3) through a pump gear (2), thus generating hydraulic power. The power is converted into mechanical power in an axial-piston variable-displacement motor (4), which through a motor gear (5) drives the vehicle load (6).

The axial-piston units (3) and (4), selected for their high efficiency, require a pressurized intake line to prevent cavitation. A boost pump (8) serves this purpose.

A strainer (7) prevents contamination from entering the power circuit. An airblast cooler (6), placed in the drain line, maintains the oil temperature within the operating range.

Shock loads are, to a certain extent, taken up by bleeding some of the high pressure to the low pressure side via check valve (12 or 13), relief valve (10), and check valve (14 or 11). The main relief valve (15) gives overload protection for transmission and prime mover. So,

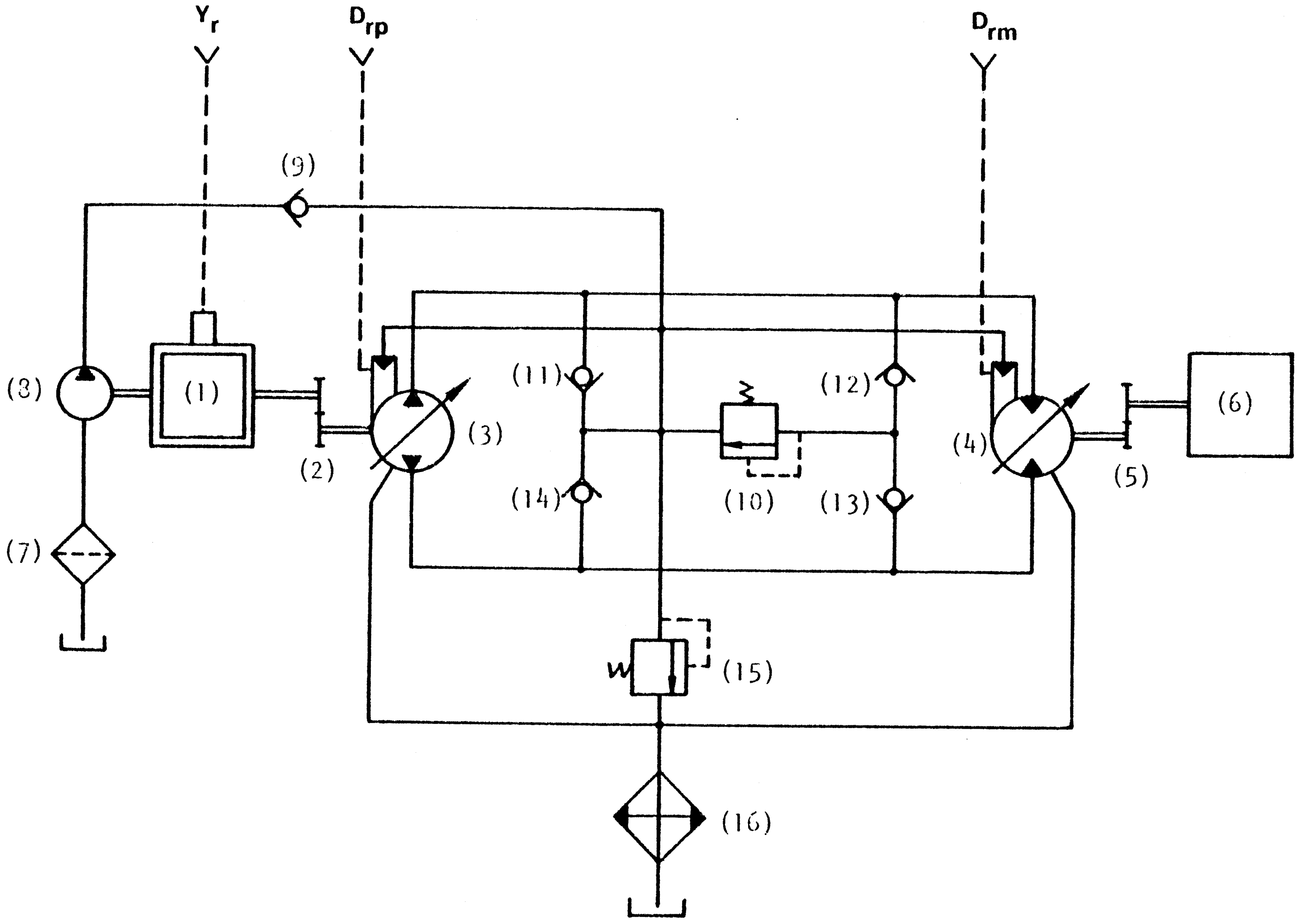


Figure 5. Power Circuit Diagram

for more severe shocks, shock loads will dissipate through relief valves (10 and 15). Check valve (9) prevents dissipation of shock loads through the boost pump.

An electric analog signal Y_r controls the engine throttle by means of an electric servoactuator, and electric analog signals D_{rp} and D_{rm} control the pump displacement and motor displacement, respectively, through the use of electro-hydraulic servos. All of these signals are generated in a microprocessor-based controller, whose design concept is discussed in the next section.

3.2 Control System Concept

Figure 6 illustrates the essential features of a control system which might be used for an engine-HST propulsion system.

The control system includes two feedback loops. They are the vehicle speed control loop and the power train control loop. In the vehicle speed control loop, the command vehicle speed, S_{cd}, is compared with the actual vehicle speed, $S_{\ell d}$. The speed error, ΔS, which represents the discrepancy between the engine power supply and the vehicle power need is converted in a discrete proportional-plus-integral (PI) controller into the reference throttle position signal, Y_r; this signal regulates the engine throttle setting Y via an electric servodrive. The PI controller is used to reduce the steady-state speed error. Ideally, the PI controller provides a zero steady-state error and the accuracy of the speed control depends only upon the accuracy of the speed transducer.

Proper engine loading can improve fuel economy. The optimum engine loading schedule is controlled by the power train control loop, which is incorporated within the speed control loop. In this loop, the measured

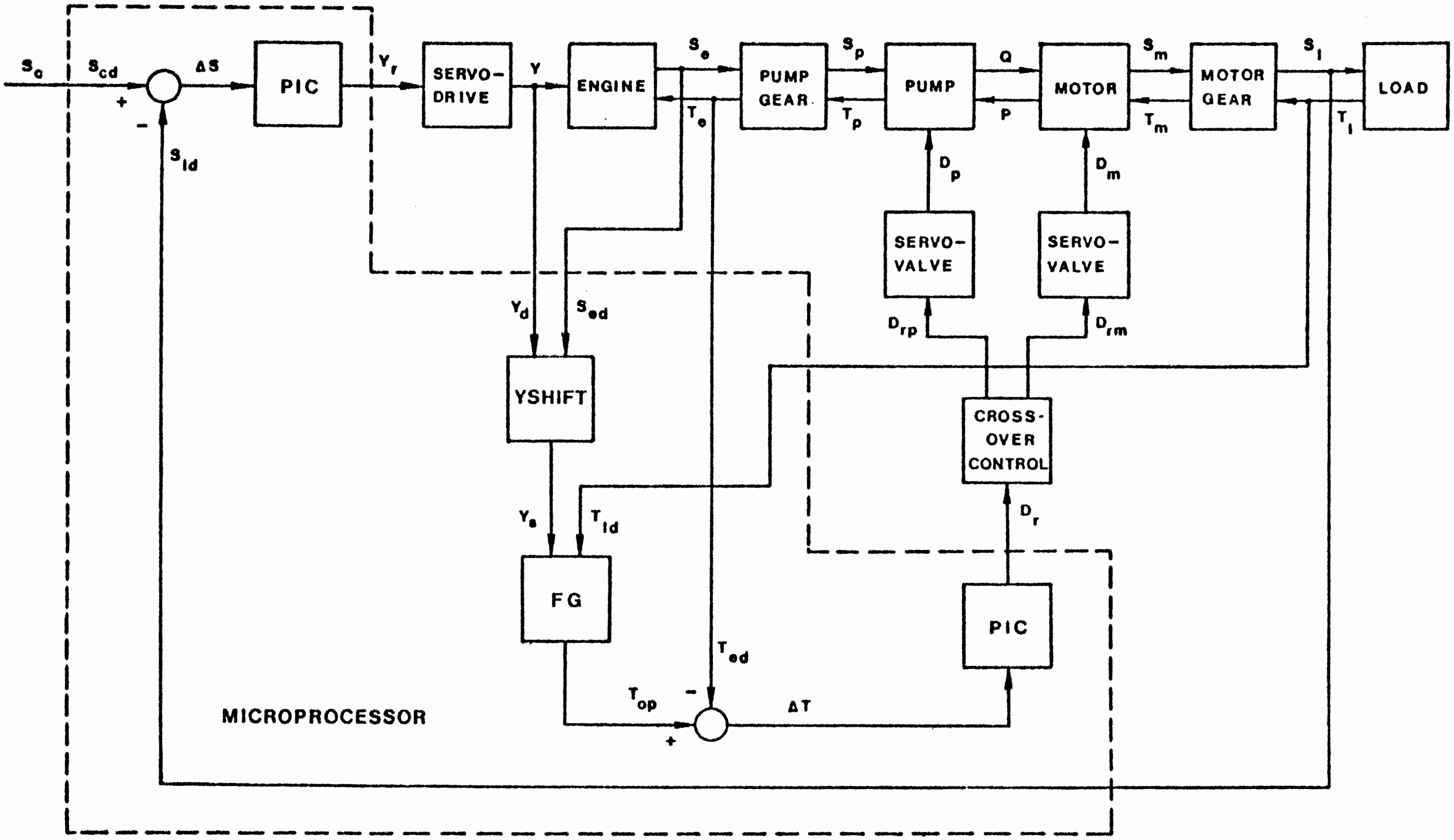


Figure 6. Control System Concept

engine loading torque T_{ed} is compared with the optimum engine loading torque, T_{op}, which is generated in the function generator (FG) as a function of the measured load torque $T_{\ell d}$ and the delayed throttle setting Y_s. The torque error, ΔT, is fed into a discrete PI controller, whose output D_r is scheduled by a crossover controller. Output signals from the crossover controller act through electrohydraulic servovalve controllers [21] on the pump and motor swashplates in a direction tending to eliminate the torque error. The selected engine loading torque then results in a near minimum fuel consumption.

A function YSHIFT is employed to eliminate the error signal results from the engine transport delay and to improve system stability (see paragraph 9.2.2). The optimum operation for arbitrary loading is scheduled through use of a two-dimensional function generator, FG, defined in section 2.2.

To expand the useful speed range of the HST, both pump and motor selected are variable-displacement type. This requires proper phasing of the pump and motor swashplates. The crossover controller mentioned before is used to fulfill this function. Figure 7 shows the circuit for the crossover control, together with the forward-backward direction control.

To illustrate the system operation, assume that the vehicle system is in the steady state with the command speed set at half its full value with the accelerator in the half stroke position. Further, assume that the driver causes a step input in the accelerator to its full value; this results a positive speed error ΔS. Consequently, the PI controller opens the engine throttle, the engine speeds up, and more oil is pumped into the power line until the speed error vanishes. At the same time,

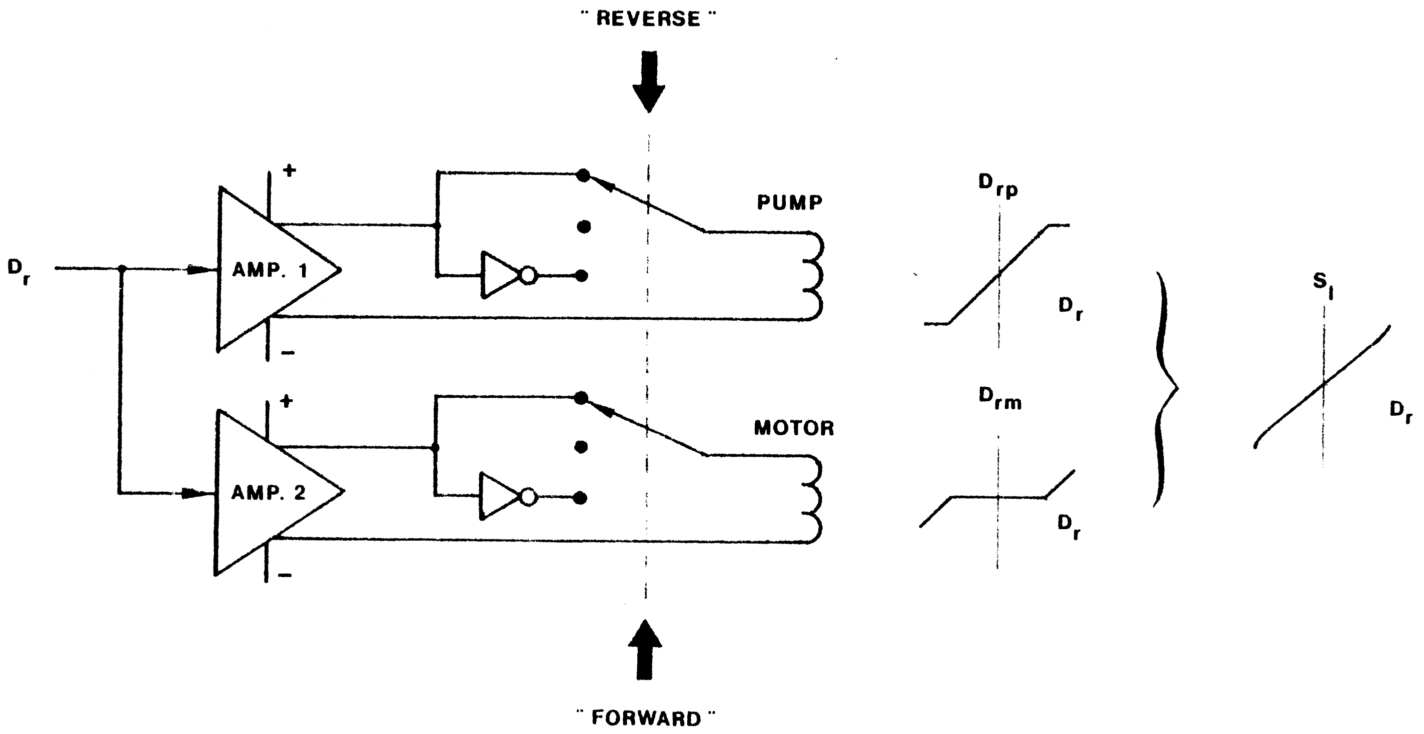


Figure 7. Pump/Motor Crossover Control Circuit

however, due to the change in the throttle setting and the load torque, the optimum engine loading torque signal T_{op} changes its value, which in turn perturbs the torque error ΔT. Consequently, the output of the displacement PI controller adjusts the pump or the motor displacement to a new value via the crossover controller, resulting in a zero torque error. The system then assumes a new steady state.

Besides the characteristics indicated in Table I, the proposed controller has two additional advantages: (1) Different control algorithms can be tied together. For example, a second function generator based on the maximum acceleration performance criterion can be added. The driver can select or change the control modes from one to another as he wishes. (2) Scheduled gains and time constants of the controller is allowable, which results in a more desirable system performance and drive economy. Both advantages would be difficult to implement with other types of controller.

CHAPTER IV

SYSTEM MODELING

In this chapter the mathematical models for various system elements are derived for the purpose of system sizing, parameter adjustment, and performance evaluation. Figure 6 shows the whole drive system including both the power circuit and system control, and lists all important system variables. The following sections describing the development of individual component models should be read with reference to Figure 6.

4.1 Engine

The engine is viewed as a dynamic system responding to the throttle position Y and the engine loading torque T_e, with the engine output speed S_e. A model suggested by Monk and Comfort [17] is shown in the block diagram in Figure 8. The throttle position is the input, the engine speed is defined as the output, and the engine loading torque is considered as a disturbance. The engine responds to the net accelerating torque, T_a, as a first order system with a moment of inertia J_e. The accelerating torque is the engine input torque, T_y, minus the damping torque, T_d, and the engine loading torque. The input torque is assumed to be proportional to the throttle position with a transport delay, t_1, which is inversely proportional to the engine speed. The delay can be explained as a time necessary for the new fuel mixture to reach the combustion chamber after a change of the throttle position. The engine speed relates to the throttle position and the engine loading torque as:

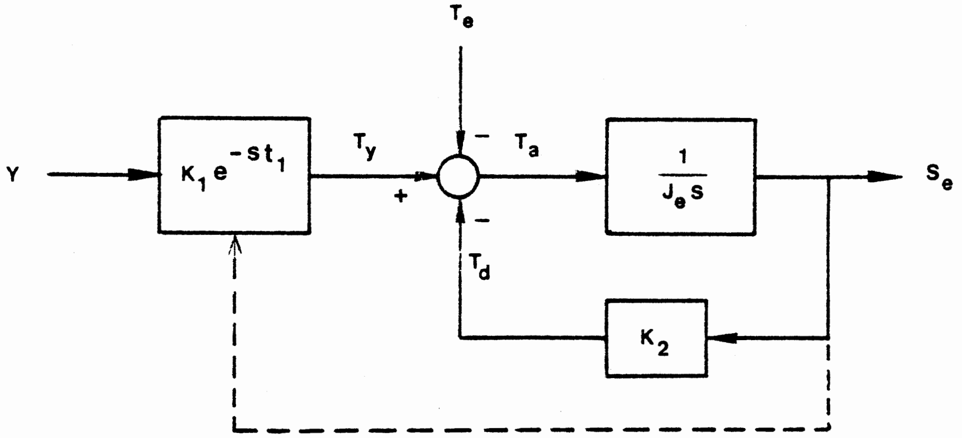


Figure 8. Block Diagram of the Engine Model

$$J_e \dot{S}_e = T_y - T_d - T_e$$

$$= K_1 Y(t - t_1) - K_2 S_e - T_e \tag{4.1}$$

where the engine transport delay t_1 is

$$t_1 = K_3/S_e(t) \tag{4.2}$$

and where

K_1 = throttle gain;

K_2 = engine damping coefficient; and

K_3 = engine transport delay constant.

The throttle position Y is physically limited as:

$$Y_{idle} \leq Y \leq Y_{max} \tag{4.3}$$

In the actual system, the engine moment of inertia is replaced by the moment of inertia of the engine-gear-pump unit.

$$J_c = J_e + J_{pg} + J_p/G_p^2 \tag{4.4}$$

The engine damping characteristic is present implicitly in the brake horsepower versus throttle position and engine speed relationship. Thus when the brake horsepower is used to calculate the engine output torque, Equation (4.1) can be rewritten as:

$$J_c \dot{S}_e = T_{out} - T_e \tag{4.5}$$

where T_{out} is the delayed engine output torque calculated from the brake horsepower.

In this study, all the design procedures and the feasibility of the proposed μP-based control strategy are demonstrated by means of an example system. In this example system, the military A042 IC four-cycle gasoline engine has been chosen as a prime mover. The performance data for this engine were obtained experimentally on a test bench [16] and are available in Table III. Based on these data, the various engine constants, i.e., K_1, K_2, and K_3, and the idling throttle position Y_{idle} are:

K_1 = 458.4 in.-lbf/rad
K_2 = 0.94 in.-lbf-sec/rad
K_3 = 10.9 rad

and

Y_{idle} = 0.17 deg.

For idling speed, S_{idle} = 70 rad/sec. The calculation procedures are given in Appendix C.

4.2 Gears

The pump gear and the motor gear are considered to be lossless. The pump gear ratio, G_p, relates the speeds and torques of the engine and the

TABLE III

PERFORMANCE DATA OF A042 MILITARY ENGINE (EXPERIMENTAL)

Engine Efficiency

TE	SE	0.	35.	70.	105.	140.	175.	210.	245.	280.	315.
0.	I	7.0	8.8	9.2	10.0	10.2	10.2	9.5	8.8	8.0	7.5
30.	I	7.0	9.0	10.2	11.2	11.5	11.4	10.9	10.2	9.5	8.8
60.	I	7.0	9.2	11.0	12.3	12.9	13.0	12.7	12.1	11.3	10.1
90.	I	7.0	9.3	11.8	13.5	14.4	14.8	14.0	14.2	13.3	12.3
120.	I	7.0	9.6	12.3	14.5	15.7	16.5	16.9	16.5	15.7	14.3
150.	I	7.0	9.8	12.8	15.5	17.1	16.4	19.0	18.7	17.6	16.3
180.	I	7.0	10.0	13.3	16.3	18.4	20.5	22.0	22.0	20.0	17.3
210.	I	7.0	10.2	13.8	17.0	20.0	23.4	26.0	24.8	21.1	17.3
240.	I	7.0	10.4	14.1	17.5	21.3	26.3	31.3	24.5	20.0	14.5
270.	I	7.0	10.6	14.4	18.0	22.0	27.0	25.8	21.5	16.5	13.5
300.	I	7.0	10.5	14.2	17.5	21.0	24.0	21.0	18.0	14.0	11.0

Throttle Position (deg)

TE	SE	0.	35.	70.	105.	140.	175.	210.	245.	280.	315.
0.	I	70.0	0.0	0.0	0.7	2.1	4.9	9.1	11.9	15.4	19.6
30.	I	70.0	5.6	2.1	2.1	4.2	5.6	9.8	13.3	17.5	22.4
60.	I	70.0	10.5	3.5	4.2	4.9	7.0	11.2	15.4	19.6	24.5
90.	I	70.0	14.0	4.9	5.6	5.6	8.4	12.6	17.5	22.4	26.6
120.	I	70.0	52.5	7.7	6.4	7.7	10.5	15.4	20.3	25.2	30.8
150.	I	70.0	70.0	10.5	9.8	9.8	13.3	17.5	23.1	26.0	37.1
180.	I	70.0	70.0	14.0	10.5	11.9	16.1	21.0	26.6	34.3	52.5
210.	I	70.0	70.0	16.8	12.6	14.0	19.6	24.5	35.0	46.2	70.0
240.	I	70.0	70.0	21.0	15.4	18.2	23.1	30.8	43.4	70.0	70.0
270.	I	70.0	70.0	70.0	34.3	34.3	36.4	46.9	70.0	70.0	70.0
300.	I	70.0	70.0	70.0	70.0	69.3	69.3	70.0	70.0	70.0	70.0

pump as follows:

$$G_p = \frac{S_e}{S_p} = \frac{T_p}{T_e} \tag{4.6}$$

The motor gear ratio, G_m, relates the speeds and torques of the motor and the vehicle load as follows:

$$G_m = \frac{S_m}{S_\ell} = \frac{T_\ell}{T_m} \tag{4.7}$$

The dynamics of the pump gear and the motor gear are expressed by the moments of inertia J_{pg} and J_{mg}, respectively. J_{pg} can be included in the engine moment of inertia and J_{mg} can be added to the vehicle inertial mass.

From section 5.2, for the example system

$G_p = 3.7$

$G_m = 1.5$.

4.3 Pump and Motor

The models of the axial-piston variable-displacement pump and motor are obtained based on the constant loss coefficient models developed by Wilson [18], with modifications for compressibility and moments of inertia of the rotors as follows:

Pump flow rate:

$$Q_p = D_p S_p - \frac{C_{sp} D_{pm}}{\mu} P - \frac{V}{2B} \dot{P} \tag{4.8}$$

Pump torque:

$$T_p = (D_p + C_{fp} D_{pm}) P + C_{dp} \mu D_{pm} S_p + J_p \dot{S}_p \tag{4.9}$$

Motor flow rate:

$$Q_m = D_m S_m + \frac{C_{sm} D_{mm}}{\mu} P + \frac{v}{2B} \dot{P} \tag{4.10}$$

Motor torque:

$$T_m = (D_m - C_{fm} D_{mm}) P - C_{dm} \mu D_{mm} S_m - J_m \dot{S}_m \tag{4.11}$$

where

D_p, D_m = displacements for pump and motor, respectively;

D_{pm}, D_{mm} = maximum displacements for pump and motor;

C_{sp}, C_{sm} = slip coefficients for pump and motor;

C_{dp}, C_{dm} = viscous drag coefficients for pump and motor;

C_{fp}, C_{fm} = dry friction coefficients for pump and motor;

v = total volume under compression;

B = bulk modulus of hydraulic oil; and

μ = oil viscosity.

The pump displacement and the motor displacement are physically limited as:

$$-D_{pm} \leq D_p \leq D_{pm} \tag{4.12}$$

$$-D_{mm} \leq D_m \leq D_{mm} \tag{4.13}$$

Assume there is no leakage from connecting pipes, equating Equations (4.8) and (4.10) yields

$$\dot{P} = \frac{B}{v} \left[D_p S_p - D_m S_m - \left(\frac{C_{sp} D_{pm} + C_{sm} D_{mm}}{\mu} \right) P \right] \tag{4.14}$$

This equation is used to calculate the hydraulic pressure.

Similarly, as for gears, the dynamics of the pump and motor are expressed by the moments of inertia J_p and J_m and can be lumped with the inertia of the engine and the vehicle, respectively.

4.4 Load

The load model, representing a vehicle of an inertia mass M, takes into account the propulsive force F_p, the rolling resistance F_r, the air resistance F_a, and the grade resistance F_g. The vehicle velocity, V, as a result of the net accelerating force is

$$M\dot{V} = F_p - F_r - F_a - F_g$$

$$= \frac{T_\ell}{R} - Wa\left(1 + \frac{V}{b}\right) - C_a\rho\,\frac{(V + V_w)^2}{2}\,A - W\sin\phi \tag{4.15}$$

where

R = wheel radius;

W = vehicle weight;

a = rolling resistance coefficient;

b = velocity correction coefficient;

C_a = air resistance coefficient;

ρ = air density;

V_w = head wind velocity;

A = front area of vehicle; and

ϕ = slope of terrain.

The values of the constants are given in section 5.1.

For tracked vehicles, the vehicle is driven by the sprockets attached to the output of the HST through final drive gearing. For this kind of vehicle, the load model discussed above should be modified by taking into account the track-vehicle damping resistance [2].

4.5 Engine Throttle Control

The digital throttle control signal, Y_{rd}, is the output of the throttle PI-controller responding to the speed error ΔS described as:

$$Y_{rd} = C_1 \; \Delta S + \frac{1}{\tau_1} \int_o^t \Delta S \; dt + Y_{rdo} \tag{4.16}$$

where the speed error:

$$\Delta S = S_{cd} - S_{\ell d} \tag{4.17}$$

and C_1 is the proportional gain and τ_1 is the integral time constant.

The equivalent discrete PI controller can be derived using rectangular numerical integration [19]. This gives:

$$(Y_{rd})_n = C_1 (\Delta S)_n + \frac{T_s}{\tau_1} \sum_{k=0}^{n} (\Delta S)_k \tag{4.18}$$

where the summation is the difference equivalent of integration, and $(Y_{rd})_n$ and $(\Delta S)_n$ are sampled values of the control signal and the error signal at time $t = nT_s$. T_s is the sampling time interval.

The integrator output is limited as follows:

$$YI_{min} \le \frac{T_s}{\tau_1} \sum_{k=0}^{n} (\Delta S)_k \le YI_{max} \tag{4.19}$$

which prevents a saturation of the throttle servoactuator and subsequently dangerous time delays in the throttle operation. As an example, assume a long uphill drive, which is associated with a positive steady-state speed error. With no limits, the controller integrator would continue to integrate the speed error saturating the servoactuator input. Further assume that for some reason the speed error would change sign (e.g., de-stroke the accelerator). It would take a certain time for the integrator to decrease the controller output signal Y_r under the throttle limit Y_{max} to desaturate the servo and to slow the engine.

The upper and lower limits of the integrator output are determined in Appendix C. They are

$$YI_{max} = 66.$$

$$YI_{min} = 0.16$$

The gain C_1 and the integral time constant τ_1 are adjusted based on some optimization technique, which is the topic of Chapter VIII.

4.6 Displacements Control

The digital displacement control signal, D_{rd}, is an output of the displacement PI controller and depends on the torque error ΔT. Similarly, the discrete form of the displacement PI controller is described as follows:

$$(D_{rd})_n = C_2 (\Delta T)_n + \frac{T_s}{\tau_2} \sum_{k=0}^{n} (\Delta T)_k \tag{4.20}$$

where the torque error

$$\Delta T = T_{op} - T_{ed} \tag{4.21}$$

The optimum engine loading torque, T_{op}, is generated from the function generator (FG) as

$$T_{op} = f(Y_s, T_{\ell d}) \tag{4.22}$$

where Y_s, the delayed throttle position, is the output of the subroutine YSHIFT (refer to section 6.5.2).

The integrator output is limited as follows:

$$DI_{min} \leq \frac{T_s}{\tau_2} \sum_{k=0}^{n} (\Delta T)_k \leq DI_{max} \qquad (4.23)$$

which again prevents a saturation of the pump and the motor swashplate servoactuators for reasons similar to those discussed in the last section.

From Appendix C,

$DI_{max} = 300.$

$DI_{min} = 0.$

4.7 Crossover Controller

A variable displacement pump driving a variable displacement motor can be used to give an extremely wide range speed ratio. Generally, it is desirable to interconnect the controls for the pump and the motor to give a preferred phasing or crossover point between speed control from the pump and that from the motor. The usual practice is to first stroke the pump while the motor is held at full displacement. When the pump has reached full displacement, additional speed can be obtained by stroking the motor. This phasing relationship has been proven to be the optimum phasing scheme. By using the computer program for optimum operation search listed in Appendix G.2, two runs were performed. One run was made with the phasing constraint discussed above; the other was made without it. A comparison of the results showed that nearly optimum operations can be achieved with or without the constraint. The maximum relative error is only 0.2 percent, which occurs at low vehicle speed (S_ℓ = 2 rad/

sec). In order to simplify the control algorithm, a crossover controller has been used in the control system (see section 3.2). From Figure 6, it can be seen that only one control signal D_r is needed to adjust the pump and motor swashplates through the use of the crossover controller.

Referring to Figure 9, the model for the crossover control circuitry can be simulated by using a limit function together with a dead space function as follows:

$$D_{rp} = \ell_1 \cdot \mathrm{LIMIT}\ (D_r, D_c) \tag{4.24}$$

where

$$D_{rp} = D_r \qquad \text{for } -D_c \le D_r \le D_c$$

$$D_{rp} = D_c \qquad \text{for } D_r > D_c$$

$$D_{rp} = -D_c \qquad \text{for } D_r < -D_c$$

$$D_{rm} = \ell_2 \cdot \mathrm{DEADSP}\ (D_r, D_c) \tag{4.25}$$

where

$$D_{rm} = 0 \qquad \text{for } -D_c \le D_r \le D_c$$

$$D_{rm} = D_r - D_c \qquad \text{for } D_r > D_c$$

$$D_{rm} = D_r + D_c \qquad \text{for } D_r < -D_c$$

In Equations (4.24) and (4.25), ℓ_1 and ℓ_2 are slopes for LIMIT and DEADSP, respectively. D_c is the crossover point. Usually, ℓ_1 and ℓ_2 are set equal, and D_c is set to one-half of the full input D_{rmax} (see Figure 9 a). But this strategy is only valid when the pump and motor are of equal size. For different sizes of pump and motor, ℓ_1, ℓ_2, and D_c can be determined based on the following criterion: the ratios of the displacement change to the current change (input to the crossover circuitry) for both pump

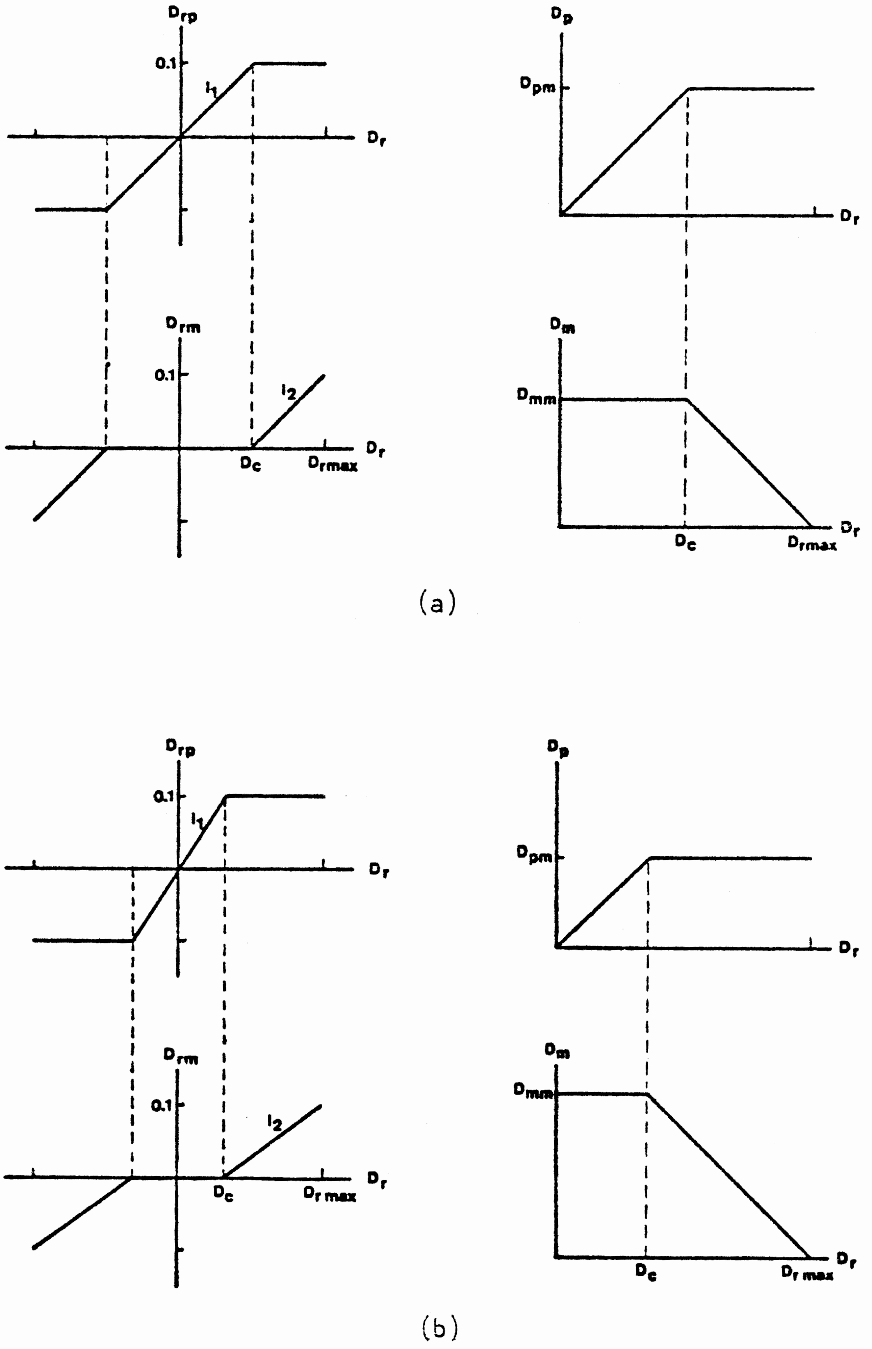


Figure 9. Comparison of Different Crossover Controller Settings

and motor are set equal for steady-state operation. The determining procedure is illustrated via the example system as follows: referring to Figure 9 b, suppose that the full input current D_{rmax} to the crossover controller is 0.2 amp. When the input current increases from 0 to 0.2 amp, the pump displacement increases from 0 to maximum and the motor displacement decreases from maximum to zero. So the total change of displacements is

$$\begin{aligned} \Delta D &= \Delta D_p + \Delta D_m \\ &= 0.323 + 0.501 \\ &= 0.824 \text{ in.}^3/\text{rad.} \end{aligned}$$

Then, the crossover point D_c can be determined as

$$\begin{aligned} D_c &= \frac{\Delta D_p}{\Delta D} (D_{rmax}) \\ &= \frac{0.323}{0.324} (0.2) \\ &= 0.078 \text{ amp} \end{aligned}$$

and slopes ℓ_1 and ℓ_2 are calculated from

$$\ell_1 = \frac{0.1}{D_c} = 1.28$$

$$\ell_2 = \frac{0.1}{D_{rmax} - D_c} = 0.82$$

where 0.1 amp in both equations is the maximum output current from the crossover controller. This value was chosen from the specifications for electrohydraulic servoactuators [21].

From the determined values of D_c, ℓ_1, and ℓ_2, the ratios of displacement change to input current change for the pump and the motor are the same; both are 4.12.

Computer runs on the example system have shown that the drive system with the crossover controller (Figure 9b) gives better fuel economy and dynamic response than that with the crossover controller (Figure 9a).

4.8 Servoactuators

The servoactuators for throttle, pump displacement, and motor displacement operations are modeled as first order systems with time constants based on manufacturers' data.

For the engine throttle operation, an electric DC servoactuator was selected. The throttle position is

$$Y = \frac{1}{\tau_y} \int_o^t (Y_r - Y)\, dt + Y_o \tag{4.26}$$

where τ_y is the throttle servo time constant. According to Reference [20], τ_y was chosen as

$$\tau_y = 8 \times 10^{-3} \text{ sec}$$

For the operation of the swashplates of the pump and the motor, two identical electrohydraulic servo units [21] are applied. The pump displacement is given by

$$D_p = \frac{1}{\tau_d} \int_o^t (D_{rp} - D_p) dt + D_{po} \tag{4.27}$$

and the motor displacement is given by

$$\tilde{D}_m = \frac{1}{\tau_d} \int_o^t (D_{rm} - \tilde{D}_m) dt + D_{po} \tag{4.28}$$

where τ_d is the displacement servo time constant. According to Reference [21], τ_d is

$$\tau_d = 79.6 \times 10^{-3} \text{ sec}$$

$\tilde{D}_m$ in Equation (4.28) is a "dummy" motor displacement. Since the motor is held at full displacement D_{mm} at the beginning, and then destroked by the control of the crossover controller. Therefore, the actual motor displacement is

$$D_m = D_{mm} - \tilde{D}_m \tag{4.29}$$

4.9 Fuel Consumption

The instantaneous fuel consumption rate of the drive can be calculated from Equation (2.2) as follows:

$$\dot{f} = \frac{S_e T_e}{\eta_e} \tag{4.30}$$

where S_e is the engine speed, T_e is the engine loading torque, and η_e is the engine efficiency. For the engine used in the example system, the functional dependence of η_e on S_e and T_e is given in Table IIIa. The engine efficiency for every engine speed and torque combination can be obtained from Table IIIa by interpolation.

From Equation (4.30), the total fuel consumption for the drive to operate continuously for time t is given by

$$f = \int_o^t \dot{f}\, dt + f_o \tag{4.31}$$

The distance travelled for time t is

$$L = \int_o^t V\, dt + L_o \tag{4.32}$$

where V is the vehicle velocity. The fuel consumption per unit of distance is:

$$\tilde{f} = f/L . \tag{4.33}$$

CHAPTER V

SYSTEM SIZING

The next step in the design is the sizing of system components for specified steady-state performance.

5.1 Engine

The engine must supply the steady-state road power demand. Hence, the engine sizing is based on the maximum vehicle velocity V_{max}. Equation (4.15) may be rearranged to give an expression for load power as follows:

$$P_{\ell} = V[M\dot{V} + Wa\ (1 + \frac{V}{b}) + C_a \rho\ \frac{(V + V_w)^2}{2}\ A + W\sin\phi] \qquad (5.1)$$

where the variables and constants were defined previously.

Taking into account the overall transmission efficiency, η_t, the preliminary maximum engine power based on the road power required for steady-state operation at maximum velocity on a flat road without wind is:

$$P_{emax} = (V_{max}/\eta_t) \left[Wa \left(1 + \frac{V_{max}}{b} \right) + C_a\, \rho\, A\, \frac{V_{max}^2}{2} \right] \qquad (5.2)$$

The result establishes a nominal size for the engine. For the example system, the vehicle specification was assumed to be:

W = 1700 lbf

M = 1750 lbm

$A = 18\ \text{ft}^2 = 2592\ \text{in.}^2$

$R = 12\ \text{in.}$

$C_a = 0.35$

$V_{max} = 45\ \text{mph} = 792\ \text{in/sec}$ (on level road)

and from Reference [22]:

$a = 0.01$

$b = 1760\ \text{in./sec}$

$\rho = 0.07485\ \text{lbm/ft}^3 = 1.12 \times 10^{-7}\ \text{lbf-sec}^2/\text{in.}^4$

Using Equation (5.2), the preliminary maximum engine power is:

$P_{emax} = 9.7\ \text{hp}$ (for $\eta_t = 0.7$)

The most suitable engine for this power range appears to be the military A042 four-cycle gasoline IC engine. This engine was selected for availability of its performance data [16] given in Table III. The technical data for this engine are:

Number of cylinders:	2
Bore and stroke:	3.00 in. x 3.00 in.
Displacement:	42.4 cu in.
Maximum net hp:	12.5 hp at 3000 rpm
Maximum engine speed:	315 rad/sec
Maximum engine torque:	300 in.-lbf at 2300 rpm.

5.2 System Components

The axial-piston pump and motor, and the gear ratios are sized based on the requirement that the units must transmit the maximum engine power. The sizing procedures are described below:

1. Define two operational conditions.
   - a. The maximum vehicle speed on maximum grade road (operational condition 1);
   - b. The maximum vehicle speed on level road (operational condition 2).

Based on the maximum values of vehicle speed and road grade, the load speed and torque at both operational conditions can be calculated from

$$S_\ell = V/R \tag{5.3}$$

and

$$T_\ell = R\left[Wa \left(1 + \frac{V}{b}\right) + \frac{1}{2} C_a \rho A V^2 + W\sin\phi\right] \tag{5.4}$$

2. Specify the speed range of the engine selected in section 5.1, and note its full throttle torque, T_{full}, at maximum engine speed S_{emax}.

3. Choose the appropriate coefficients for the transmission and a value for hydraulic oil viscosity.

4. Choose a maximum working pressure.

5. Calculate the maximum motor displacement based on the maximum load torque and load speed at operational condition 1. Assume that at maximum load torque, $T_{\ell max}$, the motor displacement is at a maximum. Use the value of pressure from step 4. The equation is:

$$D_{mm} = \frac{T_m}{(1 - C_{fm})P_{max} - C_{dm}\,\mu\,S_m} \tag{5.5}$$

Since the load speed is small, it is more economical to use a smaller motor with a mechanical gear reducer. Assume the gear ratio is G_m. Then, in Equation (5.5) T_m and S_m are obtained from

$$T_m = \frac{T_{\ell max}}{G_m} \tag{5.6}$$

and

$$S_m = G_m S_\ell \tag{5.7}$$

6. Choose a maximum pump displacement based on the maximum load speed and load torque at operational condition 2. For a variable-pump and variable-motor transmission, the pump displacement should always be at a maximum when the motor displacement is being decreased. Choose a minimum motor displacement for the maximum speed operation. Then calculate an approximate pump displacement from the ideal equation

$$D_p = D_m S_m/S_p \tag{5.8}$$

where

$$S_p = S_{emax}/G_p \tag{5.9}$$

Calculate the pressure from the equation

$$P = \frac{T_m + C_{dm} \mu D_{mm} S_m}{D_m - C_{fm} D_{mm}} \tag{5.10}$$

Then calculate the total leakage flow, Q_{st}, from the equation

$$Q_{st} = \frac{C_{sp} D_{pm} + C_{sm} D_{mm}}{\mu} P \tag{5.11}$$

Use approximate pump displacement for D_{pm} in this calculation.

Finally, the maximum pump displacement can be calculated from the equation[1]

$$D_{pm} = (D_m S_m + Q_{st})/S_p \tag{5.12}$$

7. The maximum torque requirement of the pump must be calculated. This must be checked at both high speed, low torque, and low speed, high torque operational conditions. At the high speed end, pressure is obtained from the point of maximum speed as in step 6: then, using maximum S_p obtained from Equation (5.9), pump torque is calculated by

$$T_p = (1 + C_{fp})\ D_{pm}\ P + C_{dp}\ \mu\ D_{pm}\ S_p \tag{5.13}$$

The pump displacement at low speed, high torque operation must be calculated. Maximum allowable pressure selected in step 4 is used. Total leakage flow is calculated from Equation (5.11). Then

$$D_p = (D_{mm}\ S_m + Q_{st})/S_p \tag{5.14}$$

Using this value for D_p, T_p can be calculated from

$$T_p = (D_p + C_{fp}\ D_{pm})P + C_{dp}\ \mu\ D_{pm}\ S_p \tag{5.15}$$

again using the maximum S_p. The higher of the two torques calculated in this step should be used to compare with $(G_p \cdot T_{full})$ to see if

$$T_p \leq G_p\ T_{full} \qquad \text{(if so, acceptable)} \tag{5.16}$$

8. From Equations (5.7) and (5.11), the maximum flow rate can be calculated based on the operational condition 2.

$$Q = D_m\ S_m + Q_{st} \tag{5.17}$$

using minimum motor displacement as in step 6 for D_m. With this maximum value for flow rate, proper pipe size can be determined.

The sizing procedures illustrated above have been programmed for solution on an IBM 370 computer (see Appendix G.1). Table IV shows a part of the computer printouts obtained based on the following input data:

TABLE IV

ACCEPTABLE SIZES OF SYSTEM COMPONENTS

GP	GM	DPM	DMM	QMAX	HPE
3.4	1.0	0.246	0.710	22.8	10.0
3.4	1.0	0.270	0.710	25.0	9.9
3.4	1.0	0.294	0.710	27.2	10.0
3.8	1.0	0.275	0.710	22.9	10.0
3.8	1.0	0.302	0.710	25.1	9.9
3.8	1.0	0.329	0.710	27.3	10.0
4.2	1.0	0.305	0.710	22.9	9.9
4.2	1.0	0.334	0.710	25.1	9.9
4.2	1.0	0.364	0.710	27.3	10.0
3.4	1.2	0.268	0.592	24.9	9.9
3.4	1.2	0.292	0.592	27.1	9.8
3.4	1.2	0.317	0.592	29.4	10.0
3.8	1.2	0.300	0.592	24.9	9.9
3.8	1.2	0.327	0.592	27.2	9.8
3.8	1.2	0.355	0.592	29.4	10.0
4.2	1.2	0.333	0.592	25.0	9.8
4.2	1.2	0.362	0.592	27.2	9.8
4.2	1.2	0.393	0.592	29.5	10.0
3.4	1.4	0.267	0.508	24.8	10.0
3.4	1.4	0.292	0.508	27.0	9.9
3.4	1.4	0.316	0.508	29.3	9.8
3.4	1.4	0.341	0.508	31.6	10.0
3.8	1.4	0.299	0.508	24.8	10.0
* 3.8	1.4	0.326	0.508	27.1	9.8
3.8	1.4	0.354	0.508	29.4	9.8
3.8	1.4	0.381	0.508	31.6	10.0
4.2	1.4	0.331	0.508	24.9	10.0
4.2	1.4	0.361	0.508	27.1	9.8
4.2	1.4	0.392	0.508	29.4	9.8
4.2	1.4	0.422	0.508	31.7	10.0
3.4	1.6	0.291	0.445	27.0	10.0
3.4	1.6	0.316	0.445	29.3	9.9
3.4	1.6	0.340	0.445	31.6	9.9
3.8	1.6	0.326	0.445	27.0	10.0
3.8	1.6	0.353	0.445	29.3	9.9
3.8	1.6	0.381	0.445	31.6	9.9
4.2	1.6	0.361	0.445	27.1	10.0
4.2	1.6	0.391	0.445	29.4	9.9
4.2	1.6	0.422	0.445	31.7	9.9
3.4	1.8	0.340	0.396	31.5	10.0
3.4	1.8	0.365	0.396	33.9	10.0
3.8	1.8	0.381	0.396	31.6	10.0
3.8	1.8	0.409	0.396	33.9	10.0
4.2	1.8	0.391	0.396	29.4	10.0
4.2	1.8	0.422	0.396	31.7	9.9
4.2	1.8	0.453	0.396	34.0	10.0

Vehicle specifications and constants: as defined in section 5.1.

Operational condition 1:

Road grade G (%) = 12 (or $\phi = 6.84°$)

Maximum vehicle speed $V_{max} = 11$ mph

Operational condition 2:

Road grade G (%) = 0

Maximum vehicle speed $V_{max} = 45$ mph

Engine maximum speed and corresponding full throttle torque:

$S_{emax} = 315$ rad/sec

$T_{full} = 210$ in.-lbf

Transmission coefficients; chosen as reasonable values at about the limits of the state-of-the-art:

$C_{sp} = C_{sm} = 4.0 \times 10^{-9}$

$C_{dp} = C_{dm} = 2.5 \times 10^{5}$

$C_{fp} = C_{fm} = 0.05$

Oil viscosity:

$\mu = 5.75 \times 10^{-6}$ lbf-sec/in.^{2}

Maximum working pressure:

$P_{max} = 4000$ psi.

From Table IV, the proper set can be selected according to the transmission efficiency and commercial availability. The set marked * was chosen as the most suitable. This choice yields the lowest required engine power (i.e., the transmission efficiency is high) and pump and motor displacements which are matched to those of the available commercial units--the axial-piston variable-displacement Sundstrand [23] pump (Series 20) and motor (Series 21). The maximum displacements for the Sunstrand units are:

$D_{pm} = 2.03 \text{ in.}^3/\text{rev} = 0.323 \text{ in.}^3/\text{rad}$

$D_{mm} = 3.15 \text{ in.}^3/\text{rev} = 0.501 \text{ in.}^3/\text{rad}$

These units also allow for attachment of electrohydraulic servos for displacement control.

The gear ratios G_p and G_m were finally modified by using the new displacements D_{pm} and D_{mm}. The refined values are:

$G_p = 3.7$

$G_m = 1.5$

The choice of the accompanying boost pump is best based on suggestions given by the manufacturers of the main pump.

ENDNOTE

[1] For steady state, Equation (4.14) yields

$$D_p\ S_p = D_m\ S_m + \frac{C_{sp}\ D_{pm} + C_{sm}\ D_{mm}}{\mu}\ p$$

define

$$Q_{st} = \frac{C_{sp}\ D_{pm} + C_{sm}\ D_{mm}}{\mu}\ p$$

then

$$D_p = (D_m\ S_m + Q_{st})/S_p\ .$$

CHAPTER VI

MICROPROCESSOR-BASED CONTROLLER ORGANIZATION

6.1 System Description

The functions represented within the dashed lines in Figure 6 are to be performed by the µP. The µP-based control system is built around the central processing unit (CPU) (see Figure 10). This is supported by a random-access memory (RAM), a programmable read-only memory (PROM), a MICROM, a time-base, and an analog input-output board.

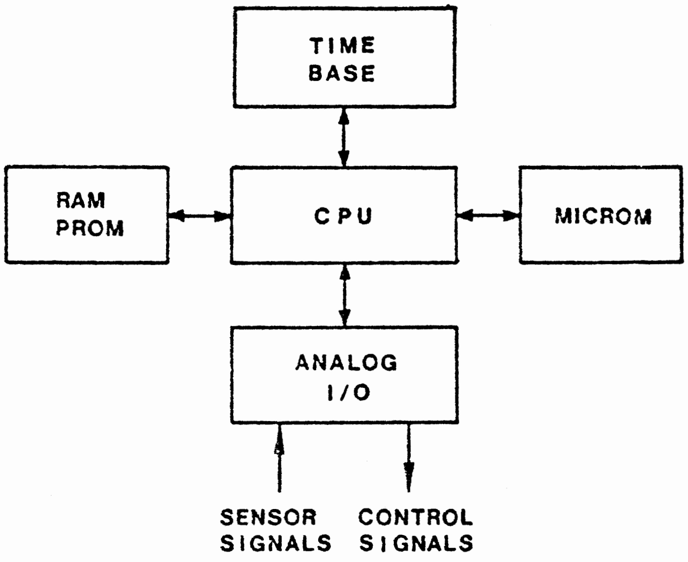


Figure 10. µP-Based Control System Configuration

The CPU executes all computation and control functions. It determines how the engine and transmission combination will be set up to meet the demanded vehicle speed at the operating point. The PROM contains the control program and the optimal operating points for engine operation. A RAM is needed for temporary storage of data used in computations. The MICROM is a microinstruction ROM Chip, which contains microcode to implement the fixed and floating point arithmetic instructions [24]. The time-base is used to insure a constant sampling rate. The analog input-output board consists of a data acquisition unit (see section 6.2) and a data distribution unit (see section 6.3). Both units execute the CPU's manipulations of the engine and transmission.

There are six input signals to the control system. They are:

1. S_c : command vehicle speed signal, which is controlled by a conventional accelerator pedal.
2. S_ℓ : load speed
3. Y : engine throttle position
4. S_e : engine speed
5. T_ℓ : load torque
6. T_e : engine loading torque

All signals are sensed and digitized through the data acquisition unit for use by the CPU. Computation results are converted back to analog signals via the data distribution unit, and then communicated to the servoactuators.

The control system works as follows (forward motion mode):

1. The direction selector is moved to the "forward" position (see Figure 7).

2. The command vehicle speed (accelerator pedal position) is set at a given value.

3. Under the control of the CPU, the data acquisition unit converts all sensor inputs into digital numbers and transfers them into the μP.

4. The μP determines the state of the system from these inputs and computes optimum actuator values for all controlled functions.

5. Output all digital values and convert them into suitable physical control commands for the servoactuators.

6. Repeat steps 3 through 5 at a fixed time interval (of about 4 ms for the example system, see sections 6.6 and 9.2) to ensure good vehicle stability and driveability under all conditions.

6.2 Data Acquisition

The data acquisition unit is a subsystem of the controller mechanism. It has an 8-channel multiplexer followed by a sample-hold and a 12-bit A/D converter (see Figure 11).

The actions of the data acquisition unit are under the control of the CPU. This unit provides the initial signal processing of the various engine and load parameters. The CPU requests the processing of a particular physical parameter by sending an appropriate input address. The multiplexer selects a channel on the command of the address decoding logic. For each channel, the sample-hold acquires the input signal and switches into the hold mode. After allowing for the hold-mode settling time, a start-convert pulse initiates the A/D converter and the CPU enters the wait state. When the conversion of this channel is finished, the CPU leaves the wait state and loads the converted signal. Then the multi-

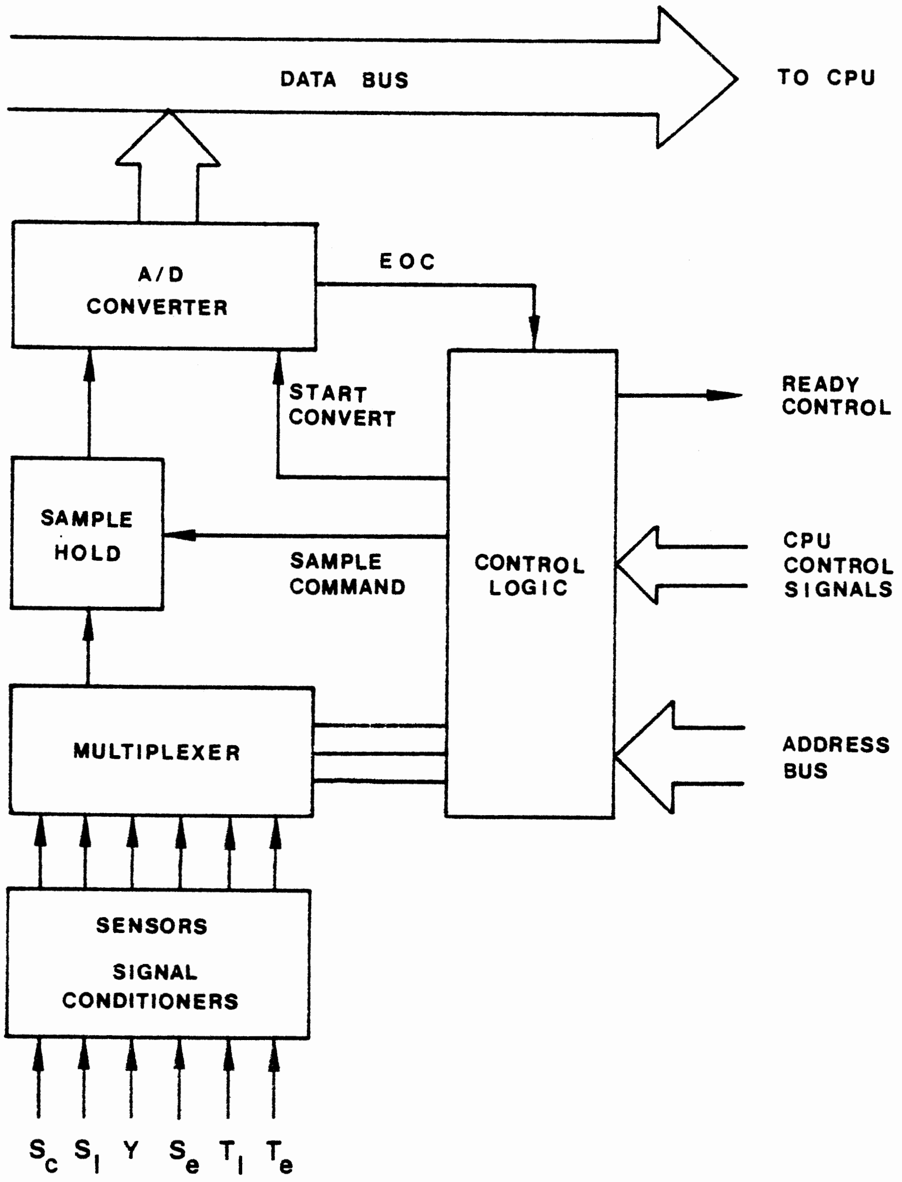


Figure 11. Data Acquisition Unit

plexer switches to the next channel and the sampling and conversion process is repeated.

The signal levels appearing at the multiplexer input must be compatible with A/D conversion requirements. This compatibility is achieved through signal conditioning with appropriate interface devices i.e. transducers and high impedance amplifiers.

In developing the control signals, the settling times of various components must be considered. This information is necessary for determining the sampling rate in section 6.6. The times to be considered are the multiplexer settling time, the sample and hold settling and acquisition times, and the A/D conversion time. The total delay between the decoding of the input address and the completion of conversion would be the sum of these component settling times. Using the data for ADV11-A [25], the time required to process the analog data to digital form would be 9 µs for each input. For the proposed control system, six analog signals are provided to the acquisition unit, so the total multiplexed A/D conversion time is approximately 54 µs.

6.3 Data Distribution

The data distribution unit (Figure 12) uses a 12-bit D/A convertor and a storage register together with two sample-holds to distibute data to two analog channels Y_r and D_r for controlling the engine throttle position and the pump/motor displacements. As digital data are transferred into the D/A converter and its output changes, the appropriate sample-hold samples the new output voltage and then, once the converter's output has settled, switches into the hold mode. Each sample-hold circuit is updated in sequence as new data arrive, and holds its voltage until

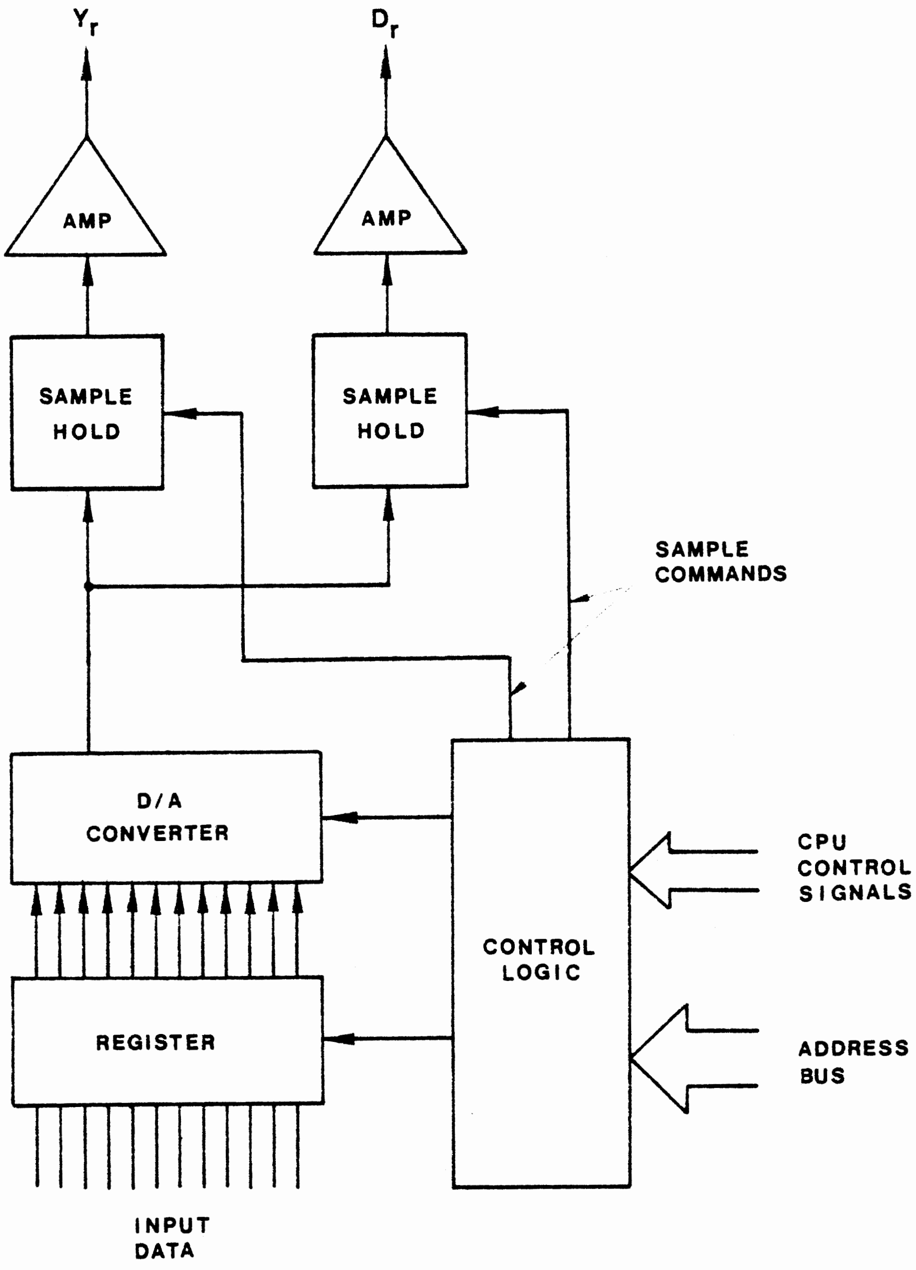


Figure 12. Data Distribution Unit

the next turn. From Reference [25], the rise and settling times for the AAV11-A D/A converter are 4 μS.

Since the μS has only limited drive capabilities, each sample-hold must be followed by a current amplifier.

6.4 Selection of Microprocessor

In selecting the most suitable μP, various μP capabilities must be considered: (1) instruction execution speed, (2) suitable instruction set, (3) convenient I/O operation scheme, e.g., DMA, and (4) provision of floating-point arithmetic versus fixed-point arithmetic. Of the attributes listed above, the provision for floating-point arithmetic is considered to be among the most crucial. It is easy to see that, for the floating-point arithmetic, scaling would be much more flexible than that for the fixed-point arithmetic.

For the engine-HST control proposed in this study, some simple μPs may be applied. The LSI-11 μP is used because: (1) it has available floating-point arithmetic as a firmware option; (2) it can utilize the extensive software developed for the PDP-11 series of mini-computers; and (3) it has the ability for expansion to handle additional control functions effectively.

6.4.1 Features

The important features of the LSI-11 are listed below:

1. 16-bit word (two 8-bit bytes). Direct addressing of 32K 16-bit words.

2. 400 plus instruction set. The instruction set of more than 400 instruction permits the user to take advantage of standard PDP-11 soft-

ware. Inclusion of the optional floating instruction set (FIS).

3. The processor module is built around a set of four N-channel MOS chips, which include control and data elements as well as two microcoded ready-only memories (MICROMS).

4. Word or byte processing: very efficient handling of 8-bit characters.

5. Asynchronous operation: system components run at their highest possible speed.

6. Stack processing: hardware sequential memory manipulation makes it easy to handle structure data, subroutines, and interrupts.

7. Direct memory access (DMA).

8. Eight general-purpose registers.

9. Priority-structured I/O system.

10. Vectored interrupt: fast interrupt response without device polling.

11. Power-fail/Auto restart: Whenever DC power-sequencing signals indicate an impending AC power loss, a microcoded power-fail sequence is initiated. When power is restored, the processor can automatically return to the run state.

6.4.2 System Organization

A complete and powerful μC system can be configured by utilizing the μP, appropriate memory, I/O devices, and interconnection hardware. The LSI-11 bus is the interface which enables a complete system to be configured. All LSI-11 modules connected to this common bus structure receive the same interface signals. The LSI-11 bus control and data lines are bidirectional, open-controller lines which are asserted when low. All transactions on the bus are asynchronous. The bus is composed of 16 multiplexed data/address lines, 6 data transfer control lines, 6 system control lines, and 5 interrupt and direct memory access (DMA) control lines. The μP connected to the LSI-11 bus controls the time allocation of the LSI-11 bus for peripherals and performs arithmetic and logic operations and instruction decoding. The μP is implemented with four LSI 40-pin chips. They are the control chip, the data chip, and two microm chips. The functions of each chip are briefly explained below:

1. Control chip: The chip provides the micro-instruction address sequence for the microm and control for the data access part. It contains the features of programmable translation array, location counter, return register, data transfer control logic, and interrupt logic.

2. Data chip: This chip incorporates the paths, registers, and logic to execute microinstructions. It offers the features of register file, arithmetic and logic unit (ALU), condition flags logic, and data/address port.

3. Microm chips: There are two chips which provide storage of the microcode for emulation of teh basic PDP-11/35, 40 instruction set, resident octal debugging technique (ODT) firmware, and resident ASCII/console routine.

4. Optional third microm chip: An optional third microm can be added to the LSI-11 processor, via a socket available on the μP module, to extend the instruction set to include fixed and floating point arithmetic instructions.

6.4.3 Instruction Timing

Table V shows the execution times of representative LSI instruc-

TABLE V

LSI-11 INSTRUCTION TIMING

Instruction	Execution Time (μs)
MOV	2.45 ∿ 3.50
ADD	3.50 ∿ 4.20
SUB	3.50 ∿ 4.20
CMP	3.15 ∿ 3.50
XOR	3.50 ∿ 4.20
CLR	3.85 ∿ 4.20
INC	4.20 ∿ 4.90
DEC	4.20 ∿ 4.90
ROL	4.55
JMP	5.25
JSR	8.40
RTS	5.25
RTI	8.75 ∿ 9.10
ALL BRANCHES	3.50
FADD	42.10
FSUB	42.40
FMUL	74.20 ∿ 121.10
FDIV	151.00 ∿ 232.00

tions, including the floating-point instructions. Special attention should be given to the execution times of the following five instructions: (1) MOV, (2) FADD, (3) FSUB, (4) FMUL, and (5) FDIV. The instruction MOV will be necessary in obtaining data from and storing data in memory, while the other four instructions will constitute all the computations in floating-point arithmetic performed in the μP.

6.5 Software Development

6.5.1 Formating and Scaling

The sensor input must be formated and scaled before the control algorithm can begin its calculation (Figure 13). First, the analog voltage signal for a particular input is converted to a 12-bit fixed-point binary number, which is then converted to a 32-bit floating-point representation. Next, the control algorithm must be calculated with the input scaled to the proper units. A scaling factor must be used to convert units of voltage to the proper units of input before actual calculation of the control algorithm. The output from the control algorithm is converted from its units to volts, converted to fixed-point notation, then converted to an analog voltage, and sent to actuators.

In order to save execution time, the scaling factors for the input and output should be incorporated in some physical constants (loke gains, time constants, etc.) if possible. For example, the scaling factor of the input signal S_e can be incorporated in the engine transport delay constant K_3 (see description of subroutine YSHIFT in section 6.5.2).

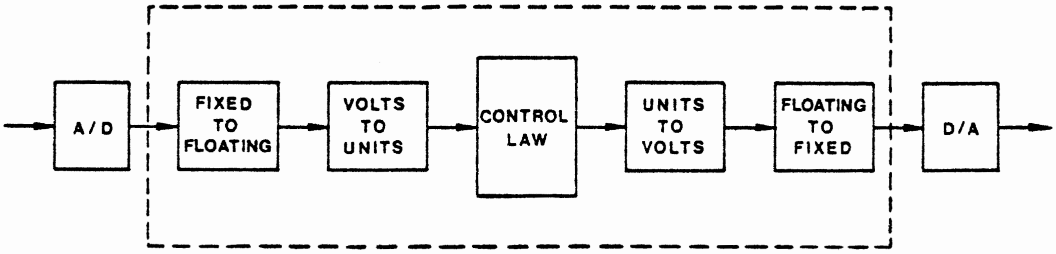


Figure 13. Formating and Scaling

6.5.2 Program Structure

The calculations for the control algorithms are performed by a set of software programs that execute every sampling interval. The simplified flowchart of the main program of the control system is shown in Figure 14. The operating sequence is as follows:

1. When the power is applied, the system is initialized; registers are cleared or set up to be used as counters and flags; storage areas in RAM are cleared or set to initial values. For the example system, the variables YI, YRD, DI, and DRD are set to the following values (see Appendix C),which would be used by subroutine PIC.

YI = 0.16

YRD = 0.16

DI = 0

DRD = 0.

2. The sampling interval is based on the time-base input to insure that sampling is done at regular intervals.

3. Six analog signals (S_c, S_ℓ, Y, S_e, T_ℓ, T_e) are input via the data acquisition unit, and then stored in proper memory locations (S_{cd}, $S_{\ell d}$,

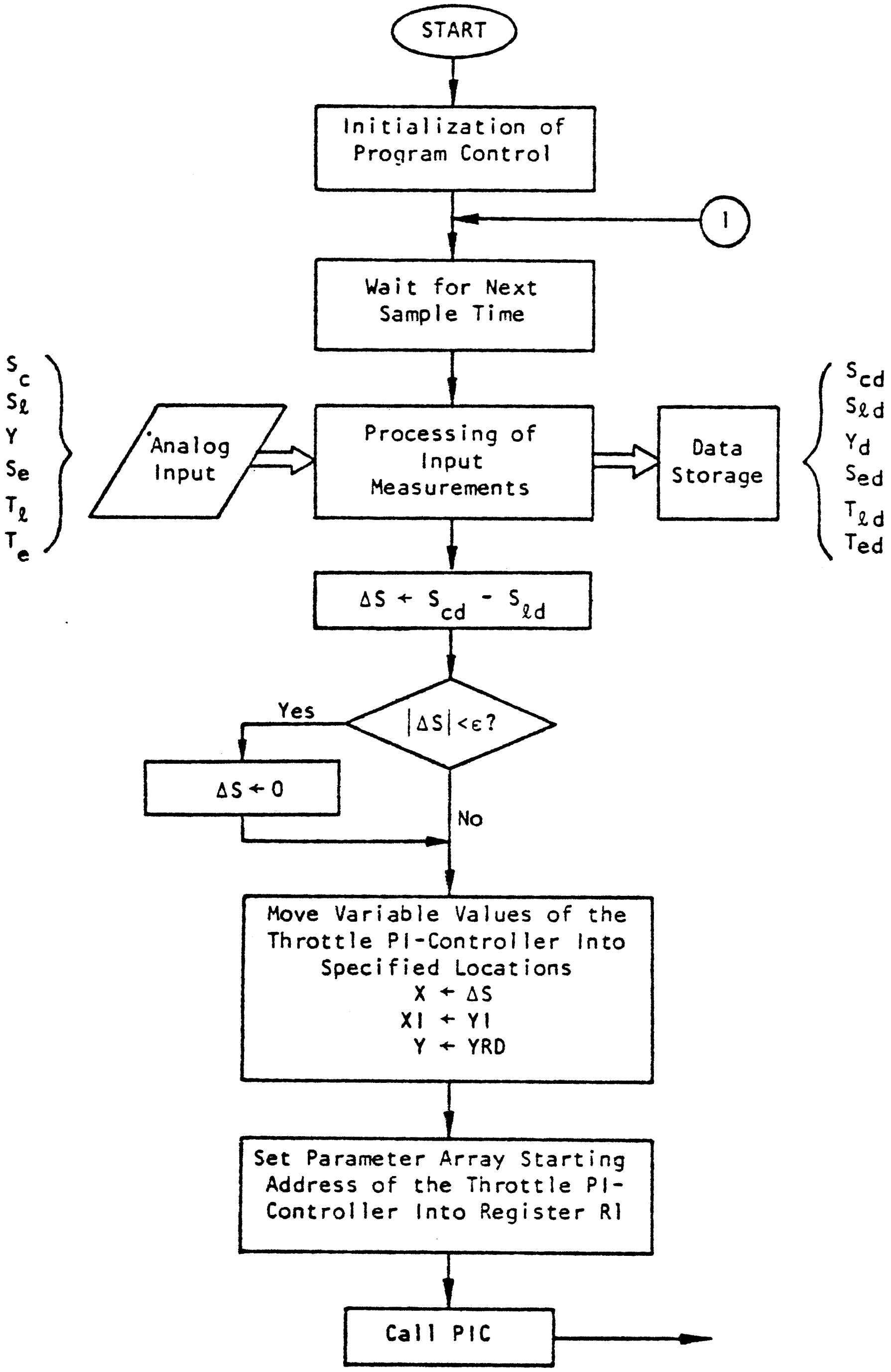


Figure 14. Simplified Flow Chart of the Main Program for the Digital Control Algorithm

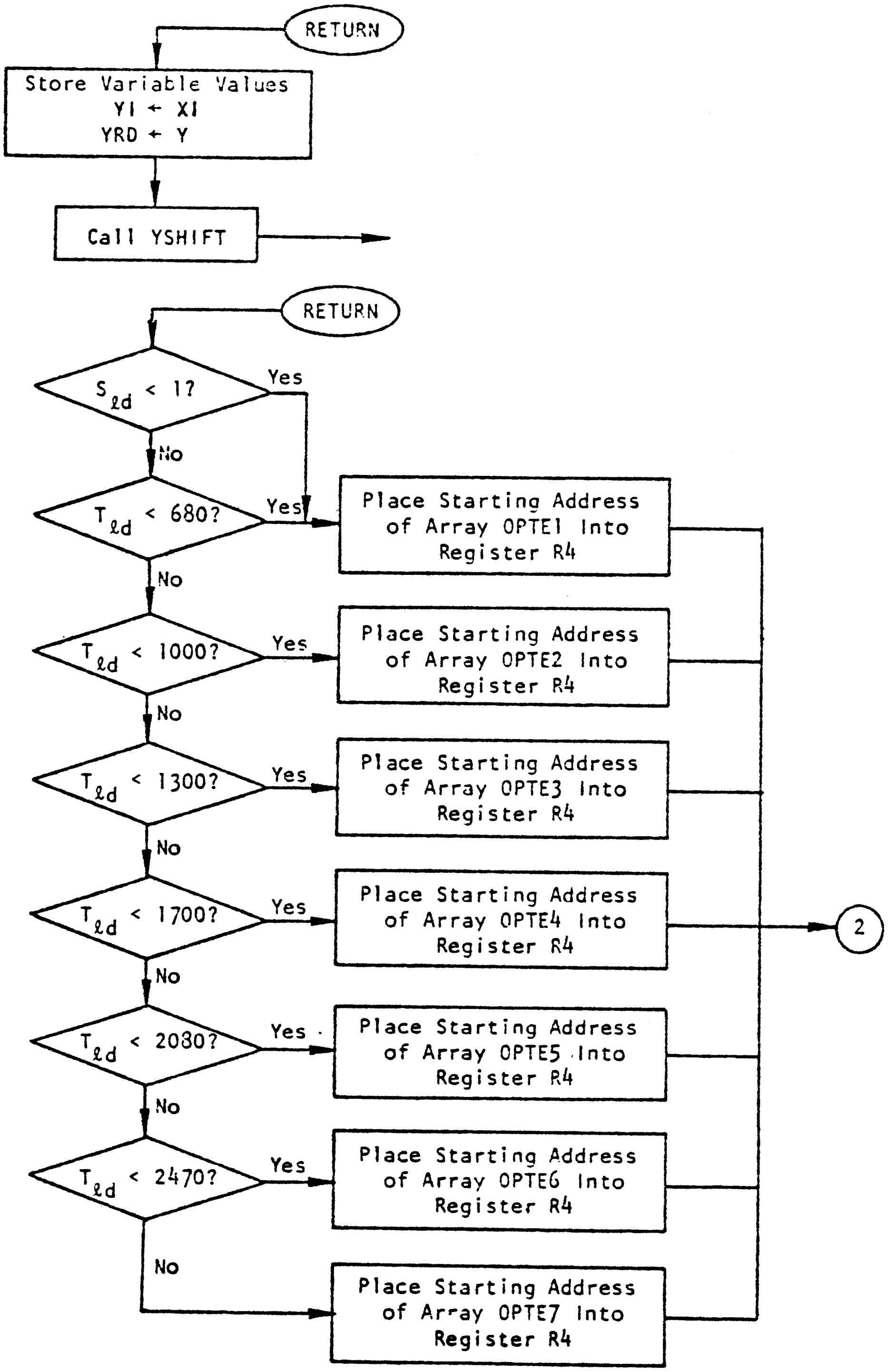


Figure 14. (Continued)

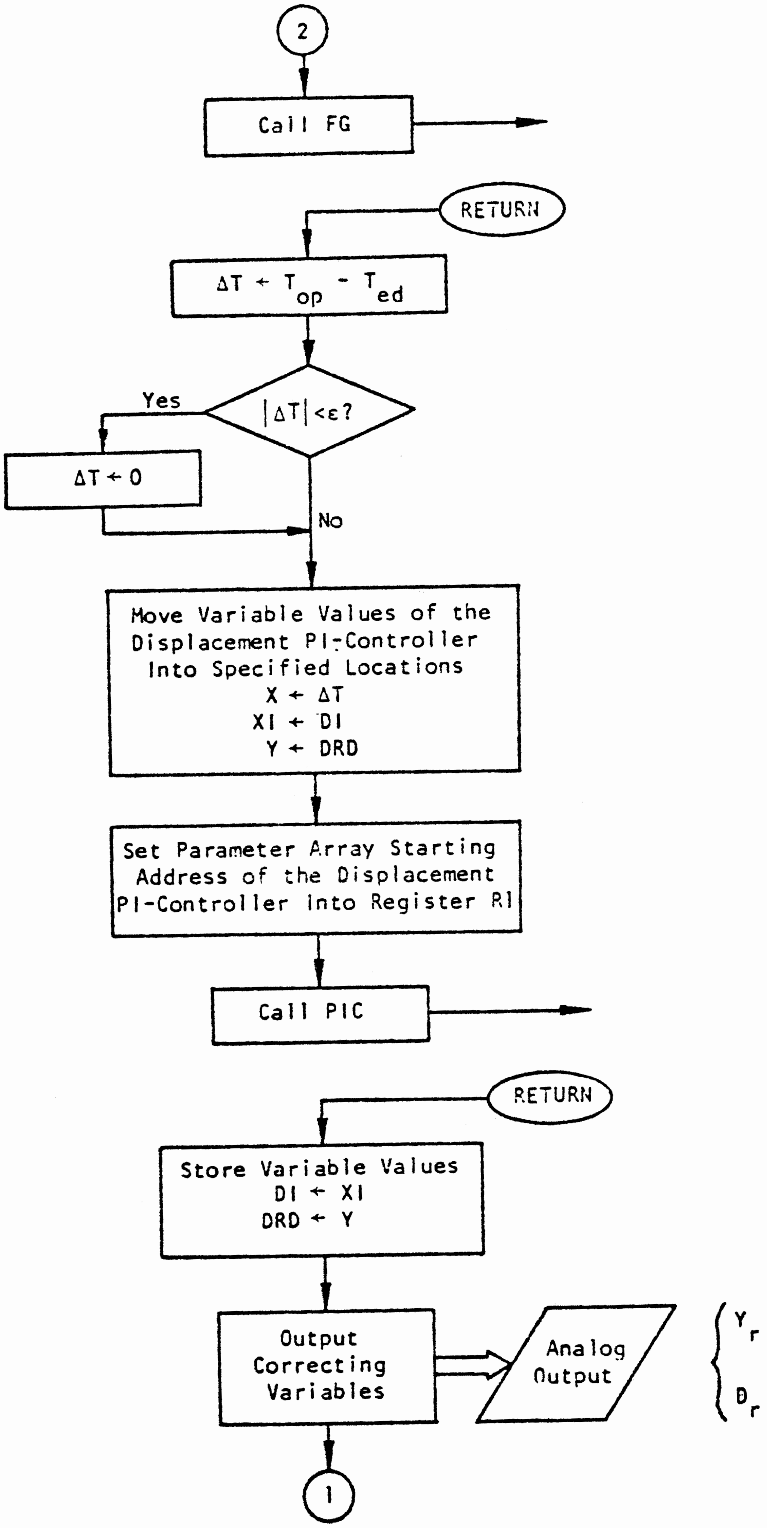


Figure 14. (Continued)

Y_d, S_{ed}, $T_{\ell d}$, T_{ed}). The detailed software control process is shown in Figure 15. The processor selects the multiplexer channel address, triggers the A/D conversion for that channel and transfers the digitized data from the A/D converter into memory after the conversion process is complete.

4. When all signals have been converted, the control algorithm is executed. Then the two computed control signals, Y_r and D_r, are transmitted to the plant via the data distribution unit.

5. The program pointer returns to the starting point after completing one cycle and does this continuously according to the time-base input.

6. The system will be reset through an interrupt service routine when the decelerator (brake) is depressed to its full stroke in case of emergency.

Three subroutines are called during control algorithm execution; they are PIC, YSHIFT, and FG. The PIC routine is used to calculate the PI controller's output based on the discrete algorithm, Equation (4.18) or (4.20). The flowchart shown in Figure 16 shows that the routine checks the integrator output constraints first (see Equation (4.19) or (4.23)), and then calculates the controller output. There are seven arguments in this routine, i.e.,

Variables
- X: error signal input
- XI: integrator output
- Y: controller output

Parameters
- YMAX: upper limit of integrator output
- YMIN: lower limit of integrator output
- TCONST: (sampling interval)/(integral time constant)
- GAIN: proportional gain .

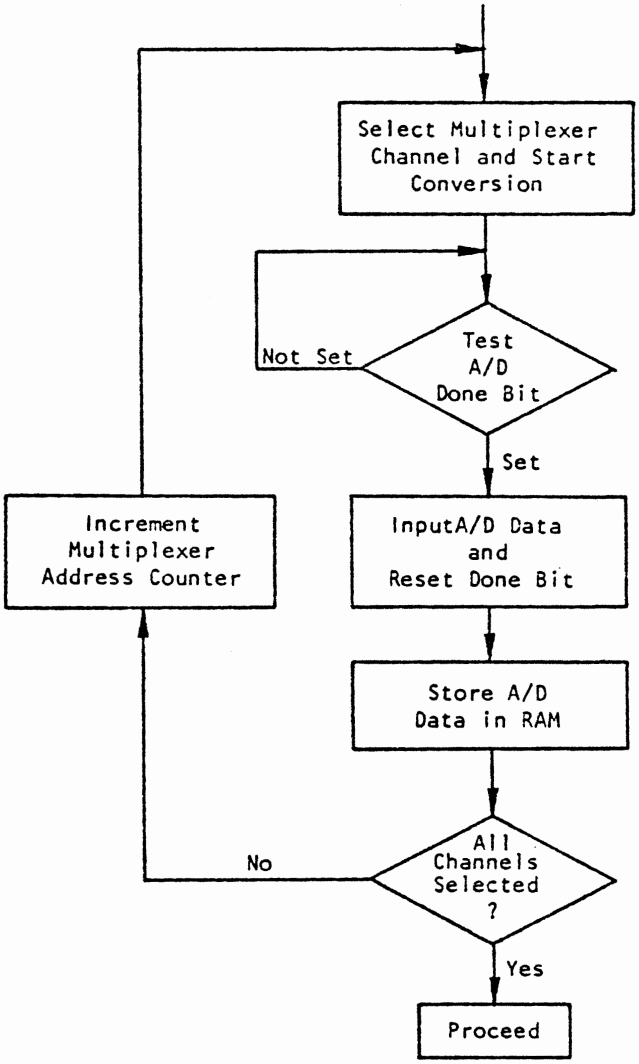


Figure 15. Flow Chart for Data Acquisition

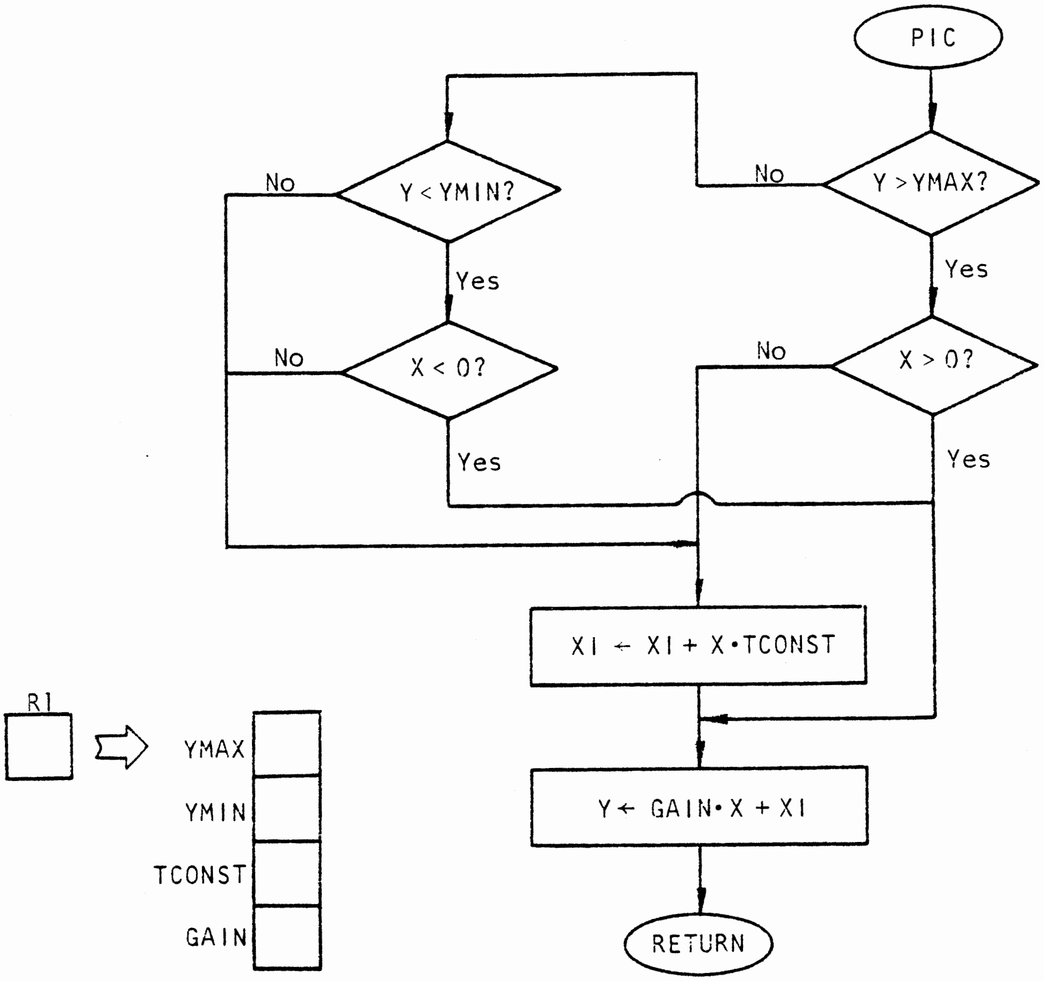


Figure 16. Flow Chart for Subroutine PIC

For each PI controller, the initial values of integrator output and controller output are initialized in the MAIN program; the values for the four parameters are stored in memory into an array in the sequence of YMAX, YMIN, TCONST, GAIN. Before each calling, the MAIN program moves the values of the three variables into memory locations X, XI, Y, and places the parameter array starting address for YMAX into the register R1; then the data can access the subroutine through direct and indirect (indexed) addressing. The register R1 functions as an address indicator. The addresses YMIN, TCONST, and GAIN can be indicated by means of the increment instruction.

The subroutine YSHIFT was designed to simulate the engine transport delay. It was employed in the feed-forward path to reduce the error signal between engine throttle input changes and output torque changes. The program logic of this routine is as follows: An array YS of length NYS is used to store the delayed throttle position values. At each sampling time, the µP determines where the delayed value is based on the engine transport delay, then it removes that value from the array and uses that value instead of the undelayed value.

The array length NYS can be determined from the following equation:

$$\text{NYS} \geq \frac{\text{Max. transport delay}}{\text{Sampling interval}} + 1.5 \qquad (6.1)$$

From Equation (4.2), it can be seen that the engine maximum transport delay occurs at idling condition. For the example system, $K_3 = 10.9$ and $S_{idle} = 70$ rad/sec (see Appendix C). So, the maximum transport delay is 0.156 sec ($= K_3/S_{idle}$). The selected sampling interval is 4 ms (see section 6.6). Then, the array length is calculated as:

$$NYS \geq \frac{0.156}{0.004} + 1.5 = 40.5; \quad \text{select } 40$$

If the maximum trnasport delay in Equation (6.1) is replaced by the instant transport delay, the location of the value being removed is indicated as follows:

$$\text{Location} = \frac{\text{Transport delay}}{\text{Sampling interval}} + 1.5$$

$$= \left(\frac{K_3}{T_s}\right) \frac{1}{S_{ed}} + 1.5; \text{ (select the integer part)} \qquad (6.2)$$

Figure 17 shows the flowchart of YSHIFT. It should be noted that in order to speed up the computation, the scaling factor for engine speed should be incorporated into (K_3/T_s) before storing the constant. So, the value of C used in the flowchart was precalculated as:

$$C = \left(\frac{K_3}{T_s}\right) / (\text{Scaling factor of } S_e)$$

$$= \frac{10.9}{0.004} / (\frac{315}{2047})$$

$$= 17708.2$$

The undelayed value (i.e., the current throttle position value Y_d) is directly stored in the memory location YS(1). After the delayed value has been removed to Y_s, all values in the array are renewed by serial shift.

The subroutine FG calculates the optimum engine loading torque T_{op} corresponding to the delayed throttle position Y_s. This routine was developed based on the table look-up and linear interpolation technique given in Appendix B. In order to simplify the control algorithm, the two-dimensional function generator (optimum engine operation schedule determined in section 2.2) was replaced by seven one-dimensional function

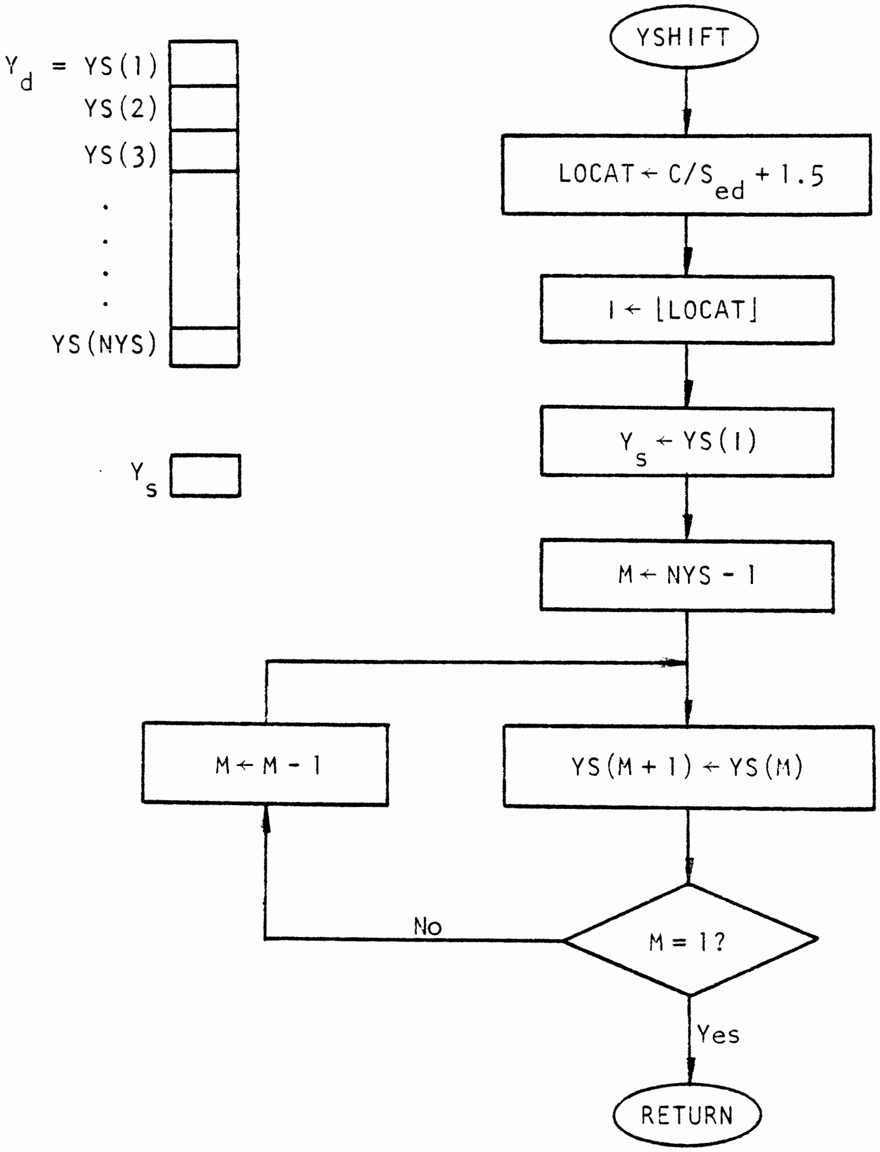


Figure 17. Flow Chart for Subroutine YSHIFT

generators (arrays OPTE1 through OPTE7) as shown in Table II. Before calling the subroutine, the μP determines the proper function generator based on the load torque $T_{\ell d}$ (see MAIN program flowchart in Figure 14), and then places the array starting address of the selected function generator into register R4. Figure 18 shows that the μP first calculates OUT according to Equation (B.1) or (B.2), and then separates the integer part and the fractional part of OUT by shifting operation. Two constants are read from memory: Y0 and RYDEL. Y0 is the minimum entry (i.e., the idling throttle position value); RYDEL is the inverse of the interval of table entries. N is the length of the function generator array.

In order to compensate the digitized error, the value of Y0 and the values in the function generators (i.e., in Table II) were digitized based on the 12-bit A/D conversion level before being stored.

Another software requirement is the inclusion of error signal checking (see MAIN program flowchart in Figure 14).

6.6 Sampling Rate

The sampling rate affects simulation accuracy and system stability. If the sampling rate is too slow, the system is essentially operating open-loop between sampling times. In addition to the stability requirements, the digitization approach must meet the signal reconstruction requirements imposed by Shannon's sampling theorem [26]. This theorem basically states that in order to reconstruct a continuous signal, the sampling rate must be at least twice as fast as the highest frequency contained in the signal. In practice, sampling rates ten times the theoretical limit are common [27]. The higher limit on sampling rate is determined by the required computation time for the control algorithm.

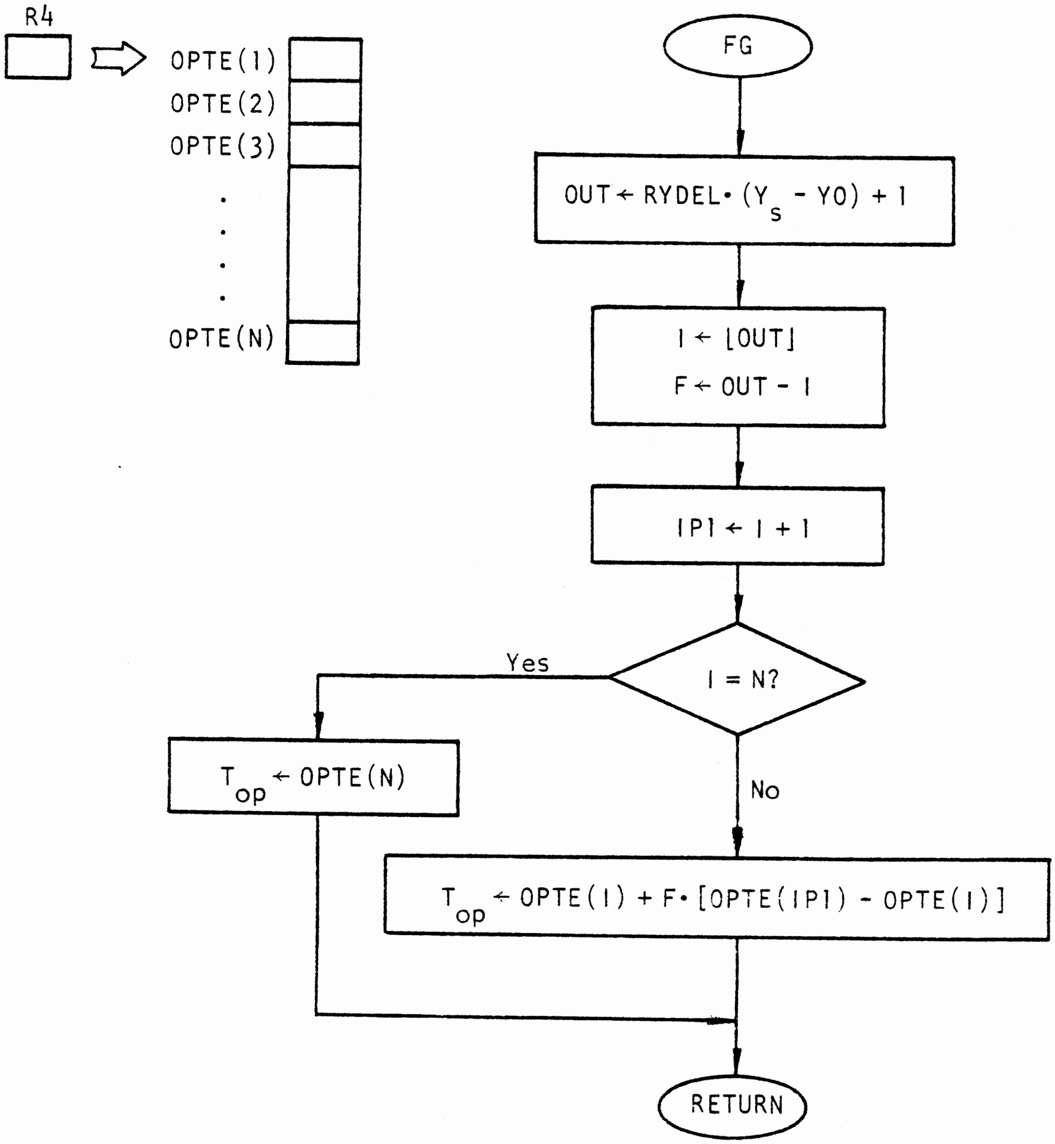


Figure 18. Flow Chart for Subroutine FG

So, the sampling rate must be selected appropriately based on the required computational time and the sampling requirement.

A computational summary of the control algorithm operations is shown in Table VI. In this table, the number of necessary arithmetic operations for each routine was counted approximately based on the flowcharts (Figures 14 through 18); the computational time was determined on the basis of the execution times for fixed-point and floating-point arithmetic operations on the LSI-11 μP (given in Table V). The time for other instructions execution was estimated based on the execution times for instructions CLR, MOV, CMP, INC, JSR, RTS, and Branches etc. Since multiplication and division take varying amounts of time for execution, the longest execution time is taken to make sure that the necessary computation is finished. The time required to convert the analog data to digital form is about 54 μs, and for data distribution the time is 8 μs. Therefore, the total estimated computational time for executing the entire control algorithm is 2.82 ms.

From Chapter VII, the highest frequency of the open-loop engine-HST system model in the example system is about 20 Hz. In the computer simulation of the entire system, a sampling rate of 250 Hz (12.5 times the highest system frequency) was used. With this sampling rate, there is no problem in completing all the required control operations and no information is lost during signal reconstruction.

The effects of the sampling rate on the system performance and fuel economy will be discussed in section 9.2.

6.7 Memory Requirements

The memory requirements for the control algorithms of the engine-HST

TABLE VI

TOTAL COMPUTATIONAL SUMMARY (ESTIMATED)

	ADD	FADD	FSUB	FMUL	FDIV	Computation Time (μS)	Other Instruction Execution Time (μS)
Data Process							62.00
MAIN			2			84.80	184.00
PIC$_1$		2		2		326.40	54.95
PIC$_2$		2		2		326.40	54.95
YSHIFT	1	1			1	278.30	919.10
FG	3	1	2	2		381.70	144.90
Totals	4	6	4	6	1	1397.60	1419.90

Total estimated computational time required = 2.82 ms control system are shown in Table VII. The memory requirement for the arithmetic instructions was estimated based on the flowcharts (Figures 14 through 18).

TABLE VII

MEMORY REQUIREMENTS FOR CONTROL ALGORITHMS

Memory Requirements	Memory Storage
Arithmetic Instructions	128
Table	294
Constants	24
Total (Estimated)	446 words

6.8 Environmental Effects

Many environmental factors must be considered in the design of a μP-based controller. The primary considerations are noise, extremes of temperature, shock and vibration, and moisture. There are several sources of electrical noise in the vehicle system. The ignition system with its spark generation is a primary source. Static electricity is a problem in moving vehicles. Also, CB radios may contribute a possible source of noise. Actually the consideration of these factors is very complex and could be the subject of additional research. Usually, analog filters are required to filter the noise. A screen box can be used to package the entire μC and to get rid of some electrical noise.

The ranges of ambient temperature could vary depending on the environment. Components should be selected to function over the required range; those that cannot operate over the required temperature range would require protection. In some cases, the μC components and memory would require supplementary heating elements prior to initial operation.

Mobile equipment often will be subjected to shock and vibration caused by the terrain. In addition, the engine and other components are often sources of vibration on the vehicle. In order to protect against shock and moisture, the μC should be packaged in an environmentally isolated container. This container should be mounted so that damping effects would minimize shock and vibration hazards. The entire package should be located in the driver's cab, where there is maximum protection from these hazards.

CHAPTER VII

SAMPLING REQUIREMENT

As stated previously, in addition to the stability requirement, a digitization approach must meet the signal reconstruction requirements imposed by Shannon's sampling theorem. In this chapter, the highest frequency of the open-loop engine-HST system model is calculated to check if the sampling requirement is met.

Before calculating the highest system frequency, the mathematical model of the engine-HST system must be linearized and formed into a transfer function (see Appendix D).

There are four inputs in the linearized system; each is treated independently of the others. From Appendix D, the output to each input is described as:

$$\frac{\Delta V}{\Delta Y_r} = \frac{NA(1)}{DA(6)s^5 + DA(5)s^4 + DA(4)s^3 + DA(3)s^2 + DA(s)s + DA(1)} \tag{7.1}$$

$$\frac{\Delta V}{\Delta D_{rp}} = \frac{NB(2)s + NB(1)}{DB(5)s^4 + DB(4)s^3 + DB(3)s^2 + DB(2)s + DB(1)} \tag{7.2}$$

$$\frac{\Delta V}{\Delta D_{rm}} = \frac{NC(3)s^2 + NC(2)s + NC(1)}{DB(5)s^4 + DB(4)s^3 + DB(3)s^2 + DB(2)s + DB(1)} \tag{7.3}$$

$$\frac{\Delta V}{\Delta \phi} = \frac{ND(3)s^2 + ND(2)s + ND(1)}{DD(4)s^3 + DD(3)s^2 + DD(2)s + DD(1)} \tag{7.4}$$

where

ΔV = change of vehicle velocity;

ΔY_r = change of engine throttle control signal;

ΔD_{rp} = change of pump displacement control signal;

ΔD_{rm} = change of motor displacement control signal; and

$\Delta \phi$ = change of the slope of terrain.

The coefficients in the numerators and the denominators were defined in Table XIII.

The highest system frequency can be found as follows: Determine the maximum root of each denominator of Equations (7.1), (7.2), and (7.4) independently for a particular operating point. The maximum value of the three maximum roots is the maximum frequency of the open-loop engine-HST system for this particular operating point. Repeat this process for the other operating points, and determine the highest frequency of the engine-HST system model.

A computer program was developed for the maximum natural frequency determination (see Appendix G.3). In this program, a subroutine POLRT (from the IBM scientific subroutine package) is called to calculate the real and complex roots of the denominator polynomials. Table VIII shows the maximum frequencies of the example engine-HST system model at various operating points. From this table, it can be seen that the highest frequency of the example system is about 20 Hz.* Based on Shannon's theorem, if the sampling rate is taken at least two times this value, that is, 40 Hz, there is no loss of information. Because the highest frequency for a closed loop system is greater than that for an open loop system, and

---

*The reason for 20 Hz for all cases in Table VIII is: There is a negative real root of -125 (in unit of rad/sec) in the denominator of Equation (7.1), which is independent of the operating points and is the maximum root of the system.

TABLE VIII

HIGHEST FREQUENCY FOR ENGINE-HST SYSTEM MODEL

ALPHAI	SEI	DPI	DMI	PI	VI	FMAX
0.0	70.1	0.048	0.501	290.1	12.0	19.9
0.0	106.4	0.323	0.401	477.1	180.0	19.9
0.0	142.5	0.323	0.263	1045.9	360.0	19.9
0.0	169.8	0.323	0.188	2255.2	576.0	19.9
0.0	268.6	0.323	0.225	2563.6	780.0	19.9
1.14	71.2	0.065	0.501	658.8	12.0	19.9
1.14	109.4	0.323	0.501	922.8	144.0	19.9
1.14	150.7	0.323	0.326	1641.6	300.0	19.9
1.14	196.2	0.299	0.238	2726.9	480.0	19.9
1.14	274.1	0.323	0.288	2544.7	624.0	19.9
2.28	71.9	0.081	0.501	1427.4	12.0	19.9
2.28	106.4	0.291	0.501	1477.5	120.0	19.9
2.28	150.7	0.323	0.401	1971.6	240.0	19.9
2.28	194.0	0.299	0.313	2742.9	360.0	19.9
2.28	258.2	0.323	0.351	2613.9	480.0	19.9
3.42	72.4	0.097	0.501	1995.4	12.0	19.9
3.42	113.7	0.283	0.501	2045.5	120.0	19.9
3.42	170.5	0.323	0.451	2374.6	240.0	19.9
3.42	236.9	0.323	0.426	2646.1	360.0	19.9
4.56	72.7	0.113	0.501	2562.8	12.0	19.9
4.56	129.1	0.258	0.501	2612.9	120.0	19.9
4.56	181.6	0.307	0.501	2674.2	216.0	19.9
4.56	241.9	0.323	0.501	2751.3	312.0	19.9
5.70	97.2	0.097	0.501	3129.3	12.0	19.9
5.70	132.8	0.218	0.501	3166.6	96.0	19.9
5.70	205.0	0.250	0.501	3223.9	192.0	19.9
5.70	241.0	0.283	0.501	3277.3	264.0	19.9
6.84	101.1	0.105	0.501	3654.7	12.0	19.9
6.84	122.6	0.178	0.501	3714.5	60.0	19.9
6.84	196.9	0.210	0.501	3758.7	144.0	19.9
6.84	239.9	0.242	0.501	3806.1	216.0	19.9

there is neither an infinite string of pulses nor an ideal reconstruction filter, sampling rates greater than this theoretical limit are typically used in practice. In the example system, a sampling rate of 250 Hz (about 12.5 times the highest system frequency) was used, which is fast enough to meet the signal reconstruction requirement.

CHAPTER VIII

CONTROLLER PARAMETERS ADJUSTMENT

The drive dynamic performance is affected by the adjustment of the PI controller parameters. In addition, from Reference [28] it can be seen that the drive economy also depends on the controller adjustment. Hence, it is possible to apply an optimization technique to find optimum values for the controller gains C_1, C_2 and integral time constants τ_1, τ_2.

8.1 Optimum Synthesis

The optimum design of the vehicle drive system requires the identification of the values of the controller parameters C_1^*, C_2^*, τ_1^*, and τ_2^* at which the fuel consumption is minimum. The optimum gains and time constants thus found should also provide satisfactory drive dynamic performance. The fuel consumption per unit of distance traveled, $\tilde{f}$, was defined in section 4.9. The dynamic performance of the drive system is measured by the performance index, which is defined as the integral of time multiplied by the absolute value of the vehicle velocity error over a given time interval, T_m, i.e.,

$$\text{ITAE} = \int_o^{t_m} t|\Delta V|\,dt$$

The optimum procedure is outlined below. First, the controller parameters are adjusted to minimize the performance index to some satisfactory value λ. Then, the parameters are adjusted to minimize the fuel consumption with the requirement on drive dynamic performance as an implicit constraint. The criterion for the optimum synthesis of the vehicle drive system can be expressed mathematically as follows:

Objective function: minimize [f]

C_1^*, C_2^*

τ_1^*, τ_2^*

Subject to:

$$\left.\begin{array}{l} C_1 > 0 \\ C_2 > 0 \\ \tau_1 > 0 \\ \tau_2 > 0 \end{array}\right\} \text{(explicit constraints)}$$

and

$$\text{ITAE} \leq \lambda \quad \text{(implicit constraint)}$$

In this study, a direct search optimization known as the simplex method [29, 30] was used. This method is simple and does not require the function derivatives. The optimization procedure is outlined in Appendix E. The coded program is given in Appendix G.4. In the program, the penalty function technique [31] was used to handle the implicit constraint.

8.2 Optimum Parameters Search

Using the optimization algorithm, the optimum parameters C_1^*, C_2^*, τ_1^*, and τ_2^* can be found for a given driving schedule. A full-stroke accelerator step input (V_c = 45 mph) applied on the example system was taken to demonstrate the search for the optimum system adjustment. The computer output is contained in Appendix G.4. The selected values of the parameters C_1, C_2, τ_1, and τ_2, and the fuel consumption $\tilde{f}$, performance index ITAE, etc. for each optimization run also are presented in Appendix G.4. The values for C_1, C_2, τ_1, and τ_2 are automatically selected by the optimization algorithm. After 18 iteration runs, the improved adjustment of the controller settings improve the vehicle fuel economy by approximately 2.2 percent (see Table IX). This is achieved by slowing down the throttle controller (gain C_1 is decreased and time constant τ_1 is increased) and speeding up the displacement controller (gain C_2 is increased and time constant τ_2 is decreased). In other words, the drive is trying to smooth the engine throttle changes and to adhere more closely to the prescribed engine loading torque versus throttle position schedule.

TABLE IX

EFFECTS OF CONTROLLER PARAMETERS ON FUEL ECONOMY AND SYSTEM DYNAMIC PERFORMANCE

	Preliminary Adjustment	Improved Adjustment*
C_1	0.33	0.28
C_2	18.20	20.27
τ_1	1.00	1.69
τ_2	5.00	4.23
$\tilde{f}$	4.75	4.64
ITAE	2.88×10^4	3.20×10^4

*For 18 iterations.

The improvement in fuel consumption is not too impressive, because the iteration was limited to 18 steps. The reason for this limitation is that for a given driving schedule, the complete set of equations representing the drive dynamics has to be solved to calculate the fuel consumption $\tilde{f}$ and the system performance index ITAE. It is necessary to solve the entire system of dynamic equations repeatedly for every set of C_1, C_2, τ_1 and τ_2. Therefore, the optimization process is computer time consuming. One way to overcome this drawback is to employ the hybrid computer technique [32]. In this approach, the vehicle system is modeled on a high computing speed analog computer, whereas the control algorithm calculation, parameter optimization, implicit constraint checking, and the analog computer control are performed in the digital section. With this technique, more improvement in fuel consumption may be obtained by increasing the iteration steps. It would be worthwhile to investigate the feasibility of this idea in further detail. However, the results should be considered with caution. Some dynamic performance will be sacrificed as a result of this optimization process. Thus, there is a compromise between fuel saving and system dynamic performance.

Since the hybrid computing technique results in a substantial reduction in simulation time, the optimization process can be used to search the optimum parameter settings corresponding to different amplitude step input or different driving schedules. Then variable gains and time constants μP-based controller design is feasible (which is more difficult to implement with analog components).

CHAPTER IX

SYSTEM PERFORMANCE EVALUATION AND DISCUSSION

This chapter includes system performance evaluation and discussion. The first part consists of determining the velocity and acceleration response for different road conditions from the example vehicle response to the accelerator pedal step input. The second part discusses the effects of driver operation, engine transport delay, crossover controller settings, and sampling rate on fuel economy, and system dynamic performance.

9.1 Example System Performance

The vehicle response (e.g., velocity versus time) to an accelerator pedal step input was calculated using the simulation program given in Appendix G.5. The observation period was 150 sec, in which the system comes sufficiently close to the steady state.

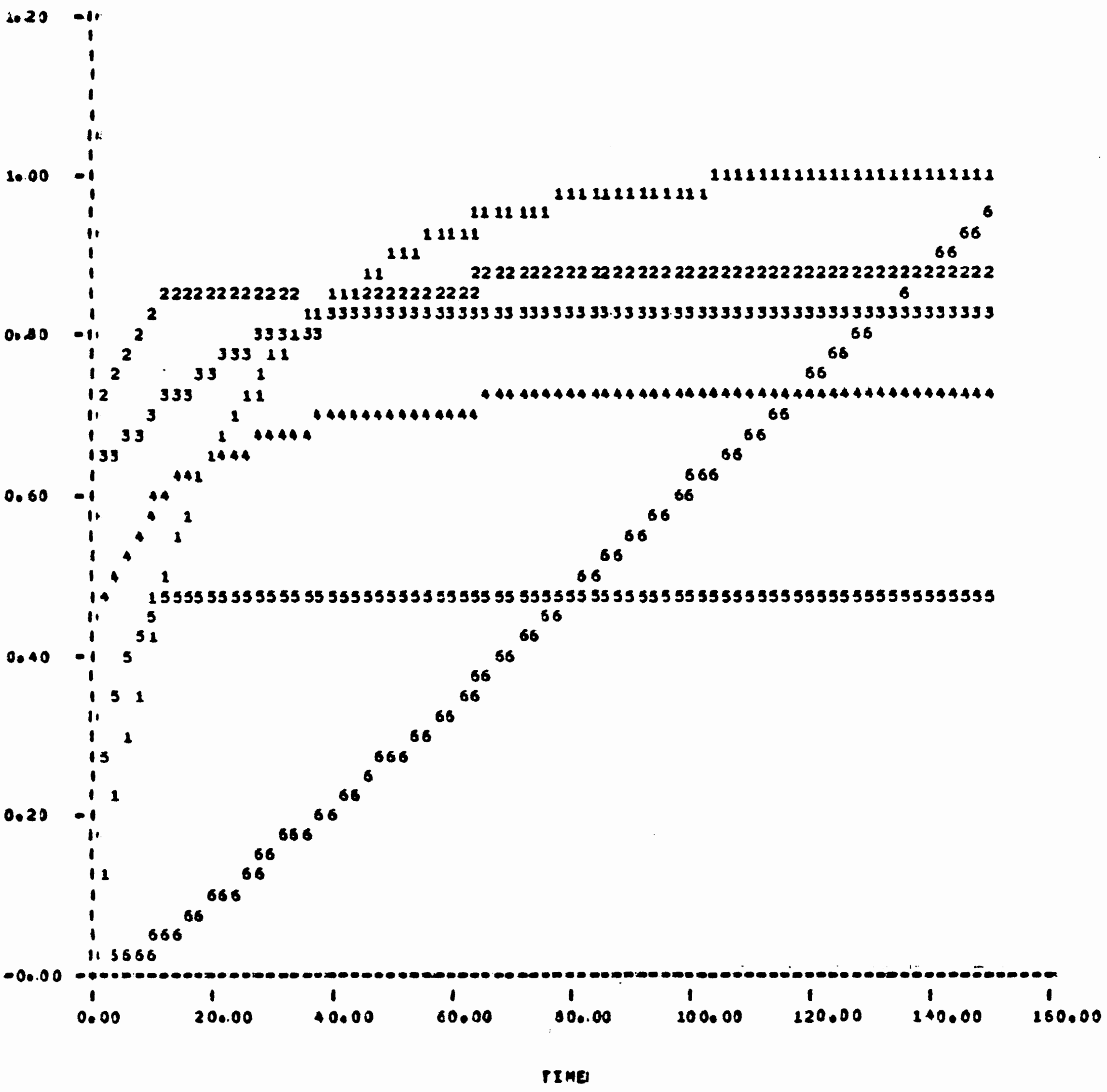
9.1.1 Level Road, No Wind Conditions

Figures 19a,b show the vehicle response to a full-stroke accelerator step input (V_c = 45 mph) on a level road without wind with 4 ms sampling interval. All important system variables are plotted. The following performance values were obtained from these results:

The velocity after 150 seconds is:

$$V_{150} = 790.3 \text{ in./sec } (44.9 \text{ mph})$$

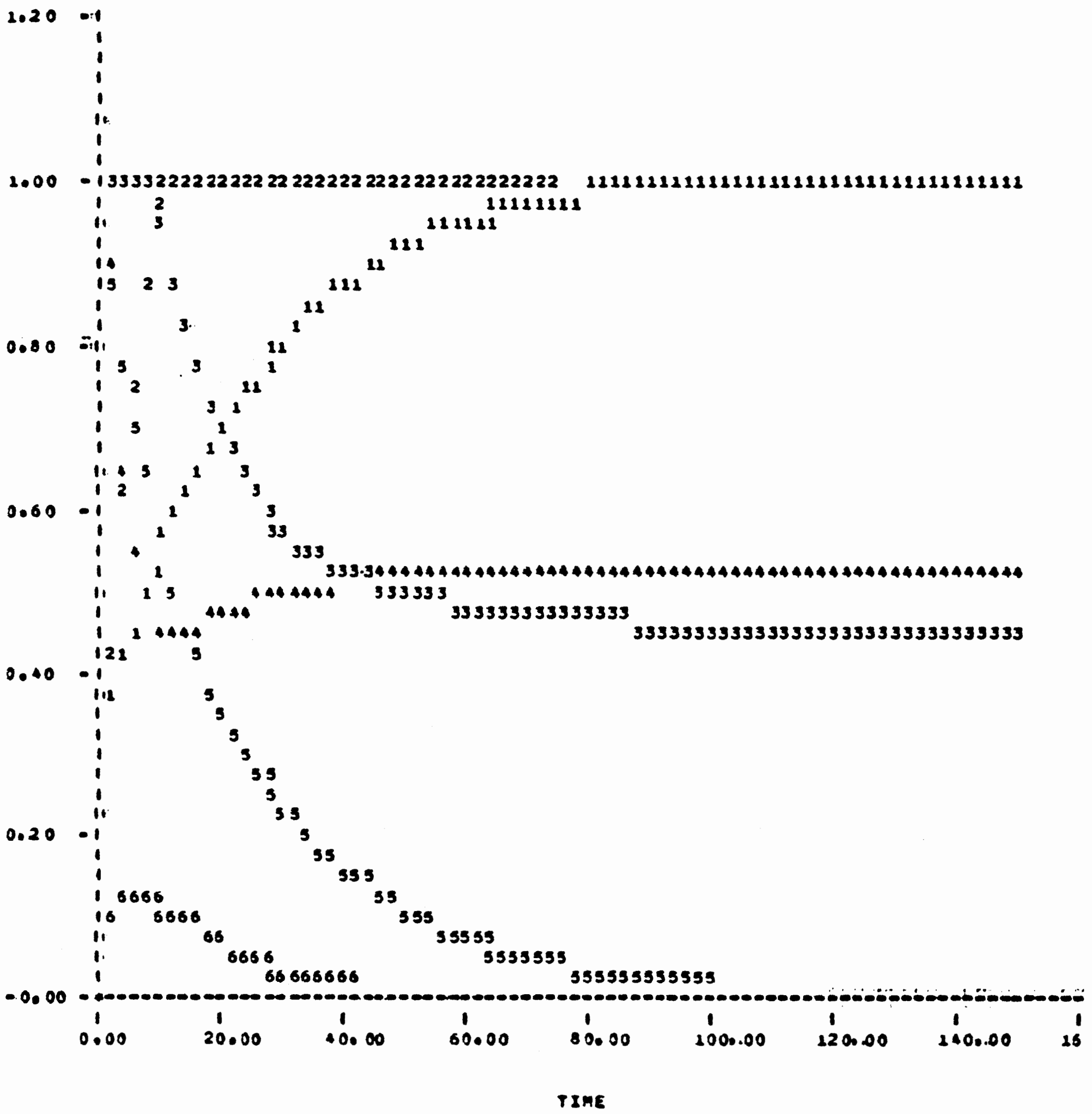
SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	V	7.92 E 2	in/sec
2	Se	3.15 E 2	rad/sec
3	Te	3.00 E 2	in-lbf
4	HPE	1.43 E 1	hp
5	HPL	1.43 E 1	hp
6	f	5.00 E 5	lbm



(a)

Figure 19. System Response to an Accelerator Full Stroke Step Input (V_c = 45 mph) on a Level Road With 4 ms Sampling Interval

SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	Y	7.00E 1	deg
2	Dp	3.23E-1	cu.in/rad
3	Dm	5.01E-1	cu.in/rad
4	P	5.00E 3	psi
5	ΔS	6.60E 1	rad/sec
6	ΔT	3.00E 2	in-lbf



(b)

Figure 19. (Continued)

The average acceleration from 79.2 to 712.8 in./sec in 50.1 sec (rise time) is:

$$\dot{V} = 12.65 \text{ in./sec}^2 \text{ (0.72 mph/sec)}$$

9.1.2 Uphill Road, No Wind Conditions

The vehicle response to a full-stroke accelerator pedal step input (V_c = 45 mph), when the vehicle was initially at rest on a 12 percent (6.84°) uphill road and no wind conditions, is shown in Figures 20a,b. The vehicle velocity after 150 seconds is:

$$V_{150} = 219.12 \text{ in./sec (12.45 mph)}$$

The response to a partial stroke accelerator pedal step input (V_c = 15 mph) for a 12 percent (6.84°) uphill road is shown in Figures 21a,b. The vehicle velocity after 150 seconds is:

$$V_{150} = 211.2 \text{ in./sec (12 mph)}$$

The differences between Figures 20 and 21 are discussed in the following section.

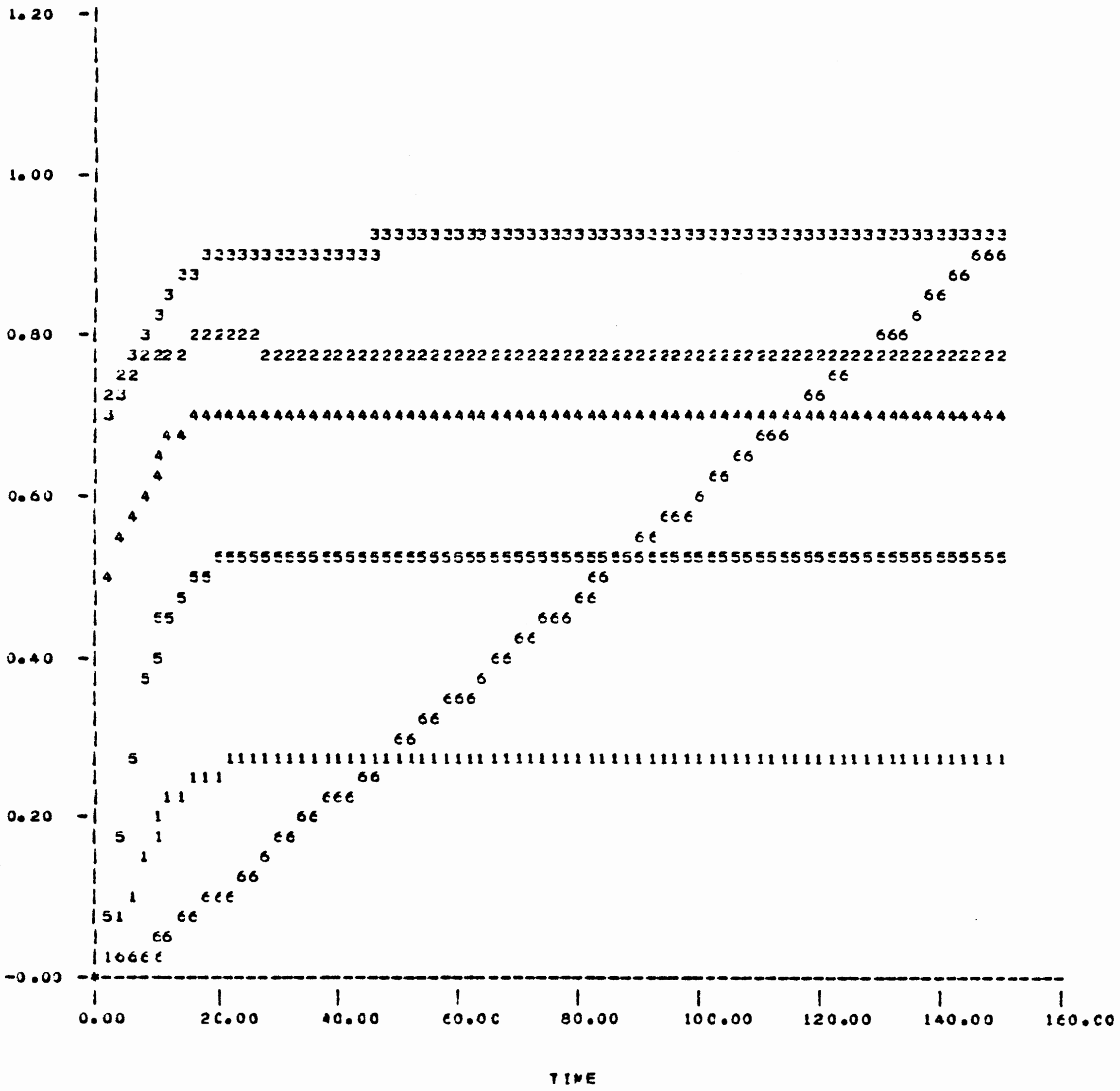
9.2 Discussion

This section presents the results of computer simulation investigations of the effects of driver operation, engine transport delay, crossover control circuit setting, controller parameter adjustment, and sampling time interval on the fuel consumption and system dynamic response.

9.2.1 Effects of Driver Operation

The computer output for the vehicle responses to the full-stroke (V_c = 45 mph) and the partial stroke (V_c = 15 mph) accelerator pedal step

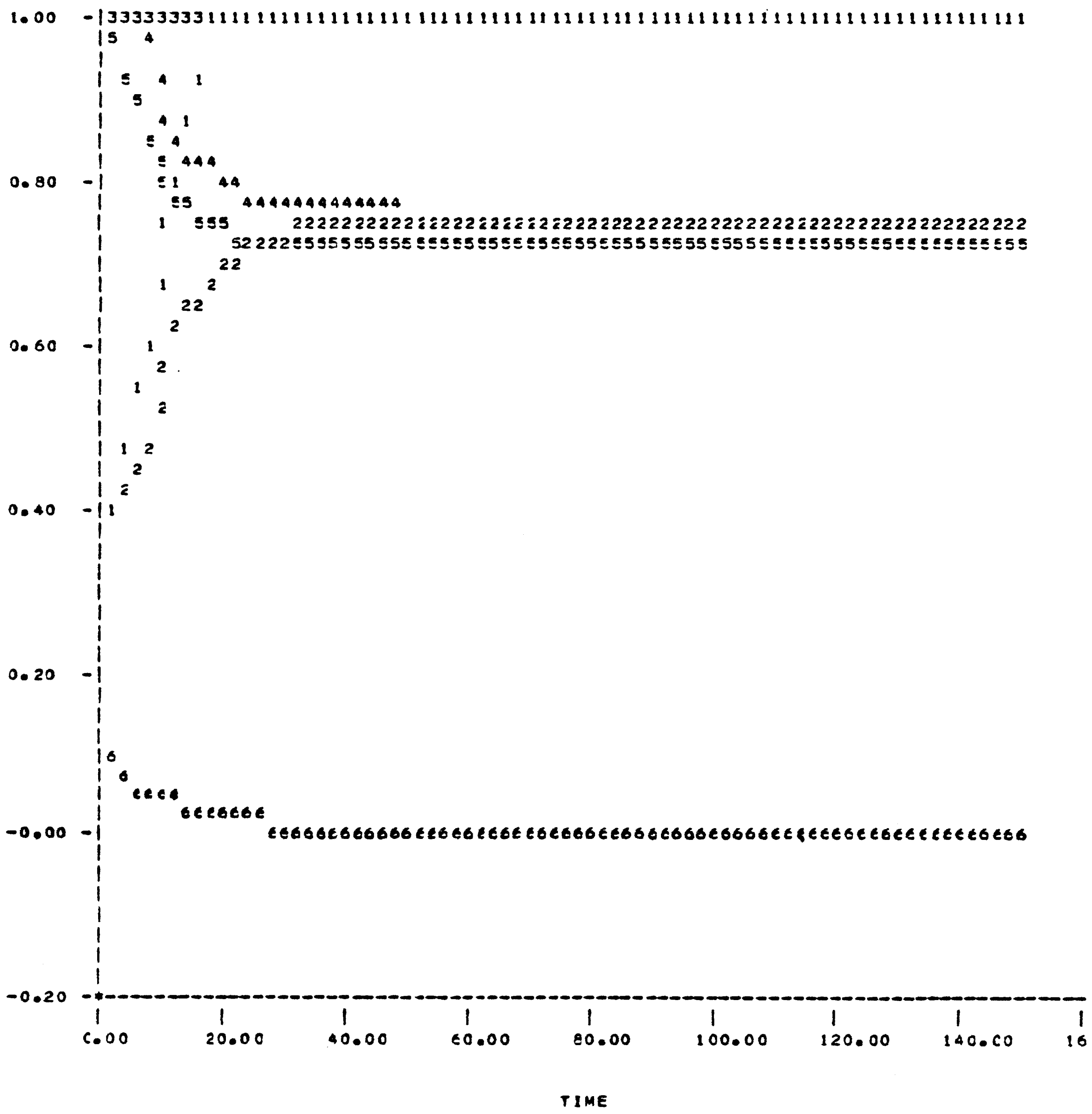
SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	V	7.92 E 2	in/sec
2	Se	3.15 E 2	rad/sec
3	Te	3.00 E 2	in-lbf
4	HPE	1.43 E 1	hp
5	HPL	1.43 E 1	hp
6	f	5.00 E 5	lbm



(a)

Figure 20. System Response to an Accelerator Full Stroke Step Input (V_c = 45 mph) on an Uphill Road (G(%) = 12) With 4 ms Sampling Interval

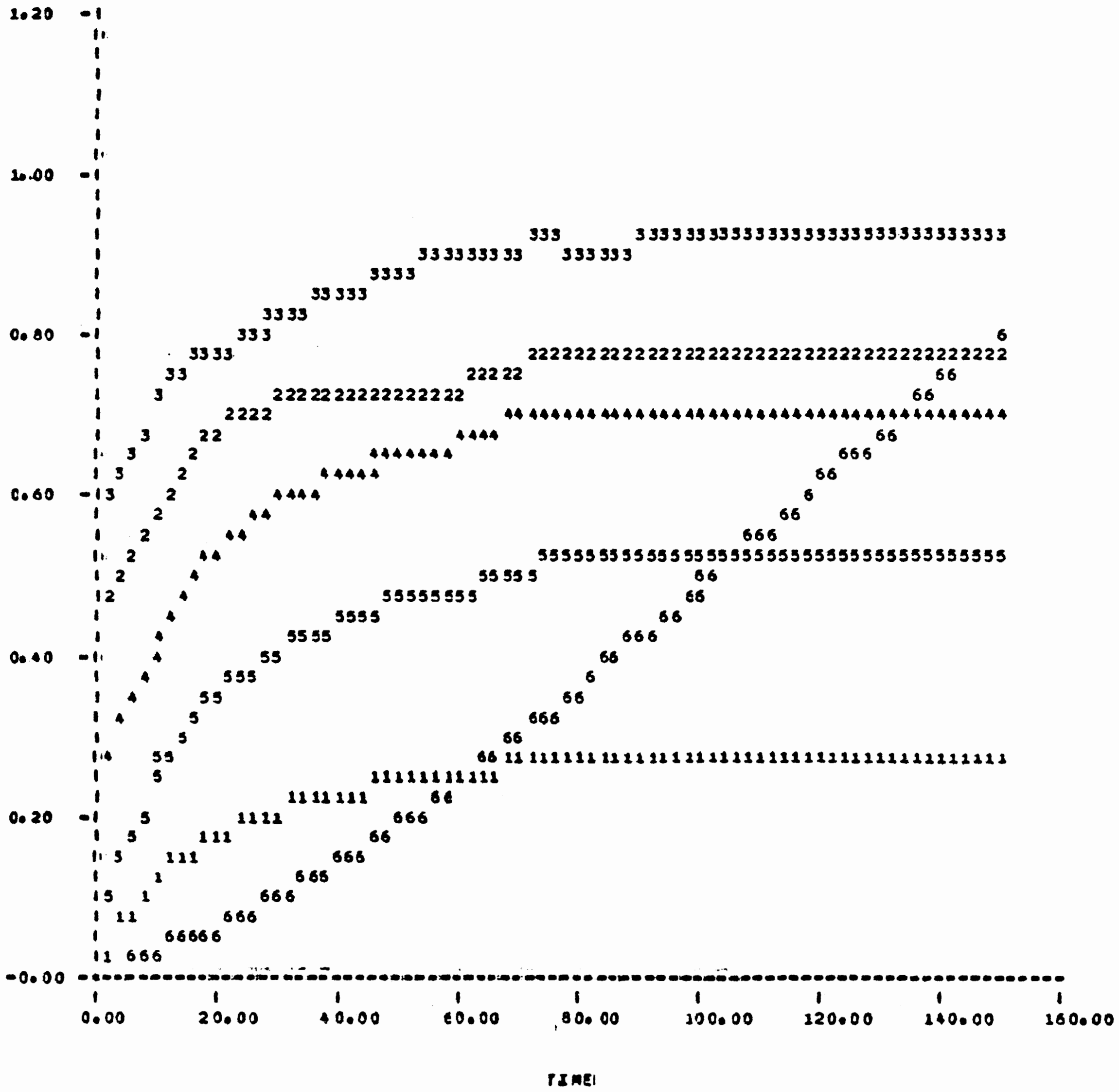
SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	Y	7.00E 1	deg
2	Dp	3.23E-1	cu.in/rad
3	Dm	5.01E-1	cu.in/rad
4	P	5.00E 3	psi
5	ΔS	6.60E 1	rad/sec
6	ΔT	3.00E 2	in-lbf



(b)

Figure 20. (Continued)

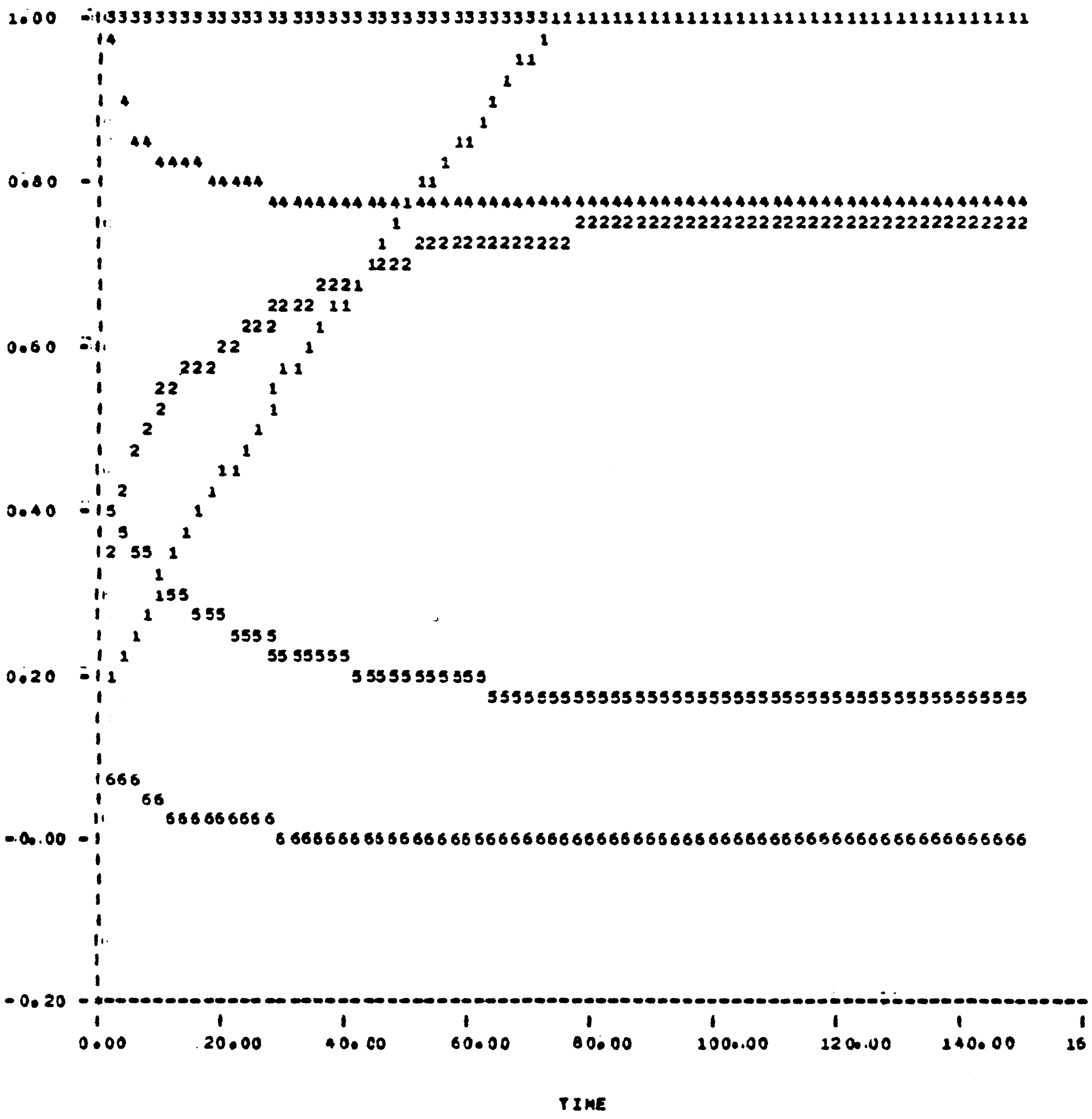
SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	V	7.92 E 2	in/sec
2	Se	3.15 E 2	rad/sec
3	Te	3.00 E 2	in-lbf
4	HPE	1.43 E 1	hp
5	HPL	1.43 E 1	hp
6	f	5.00 E 5	lbm



(a)

Figure 21. System Response to an Accelerator Partial Stroke Step Input (V_c = 15 mph) on an Uphill Road (G(%) = 12) With 4 ms Sampling Interval

SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	Y	7.00E 1	deg
2	Dp	3.23E-1	cu.in/rad
3	Dm	5.01E-1	cu.in/rad
4	P	5.00E 3	psi
5	ΔS	6.60E 1	rad/sec
6	ΔT	3.00E 2	in-lbf



(b)

Figure 21. (Continued)

input on a 12 percent uphill road without wind are compared in Table X. It reveals that the case with $V_c = 45$ mph results in a faster dynamic response and a poorer fuel economy than that in the case with $V_c = 15$ mph. Therefore, in order to achieve the lowest fuel consumption, the engine throttle changes should be slow. Of course, the dynamic response will suffer in this case.

TABLE X

EFFECTS OF STEP INPUT AMPLITUDE ON FUEL ECONOMY AND SYSTEM DYNAMIC PERFORMANCE

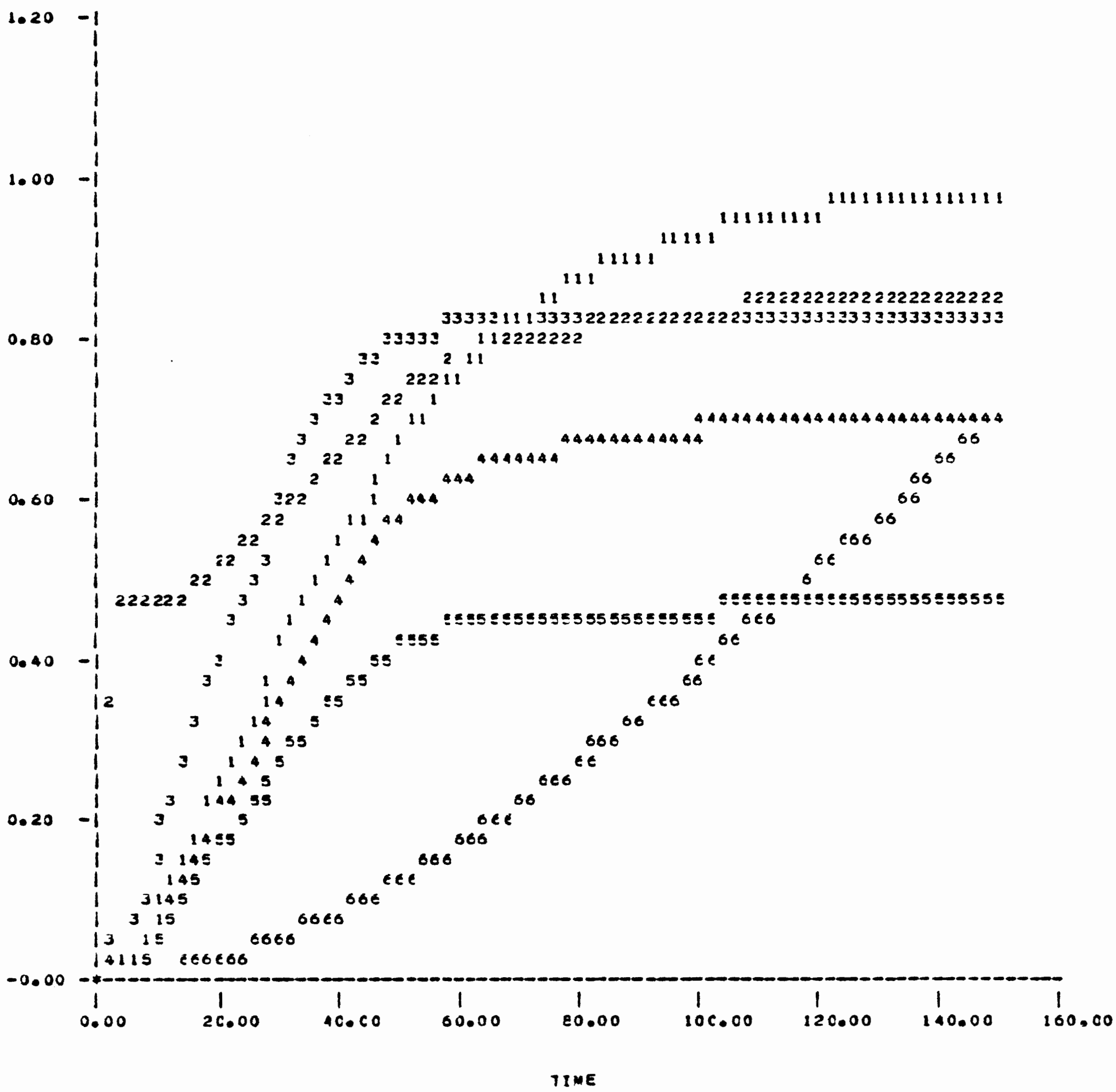
V_c	$\tilde{f}$	V_{150}	Rise Time*
15 mph	13.13	12.00 mph	105.3 sec
45 mph	14.77	12.45 mph	17.5 sec

*The rise times were calculated based on the steady-state maximum vehicle velocity of 12.45 mph.

For the purpose of getting rid of the unfavorable effect of sudden engine throttle changes on the fuel economy, for example, a function LIMIT can be incorporated in the control algorithm to change the accelerator pedal step input into a limited ramp input. Figures 22a,b show the resulting vehicle response to the full-stroke accelerator pedal step input ($V_c = 45$ mph) on a level road. The step input was replaced by a ramp input (saturated at 50 sec) according to the following relationships:

$$V_{c,ramp} = \frac{V_c}{50} \cdot \text{LIMIT } (T, 50)$$

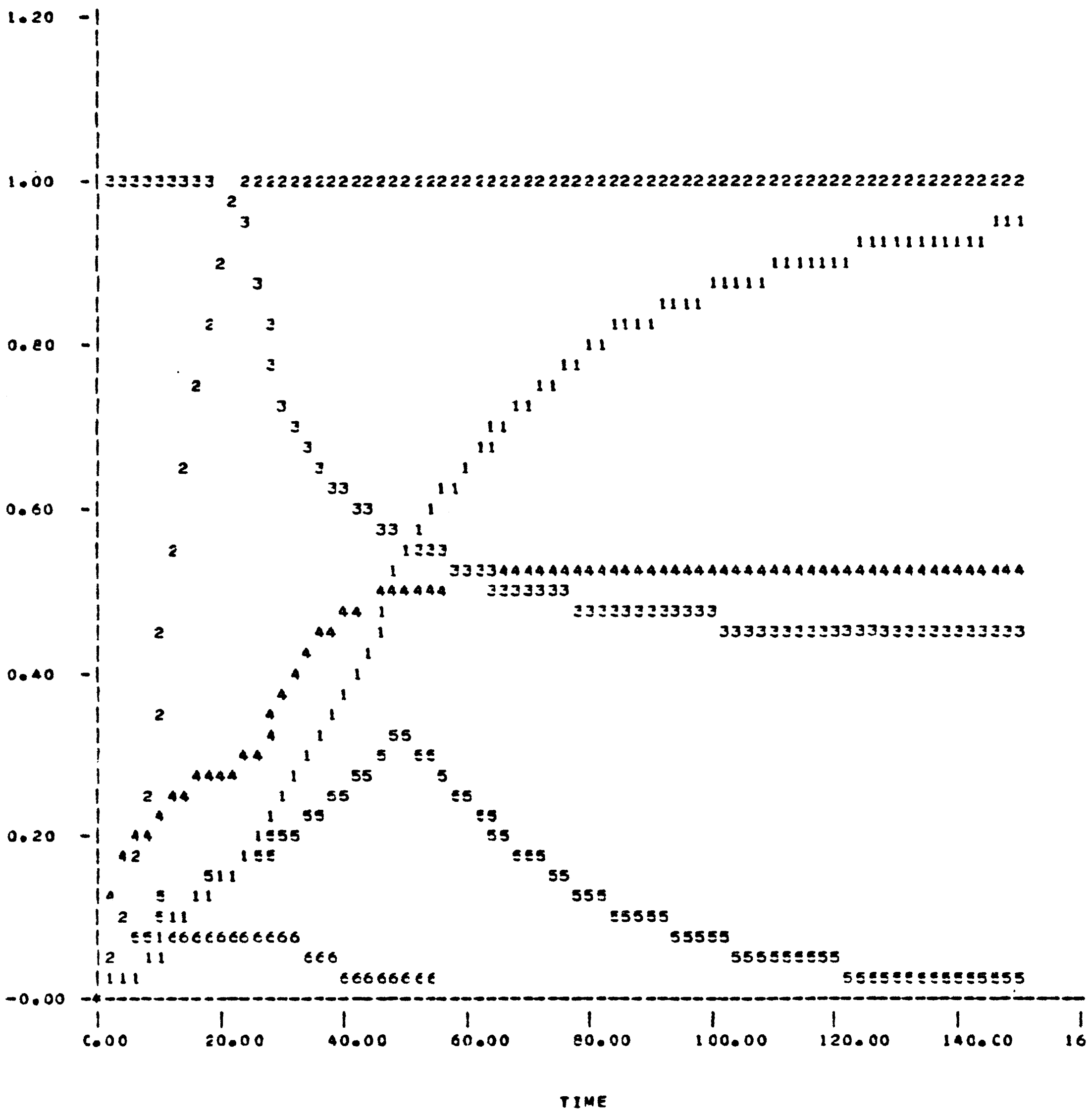
SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	V	7.92 E 2	in/sec
2	Se	3.15 E 2	rad/sec
3	Te	3.00 E 2	in-lbf
4	HPE	1.43 E 1	hp
5	HPL	1.43 E 1	hp
6	f	5.00 E 5	lbm



(a)

Figure 22. System Response to an Accelerator Limited Ramp Input (V_c = 45 mph Ramped in 50 sec) on a Level Road With 4 ms Sampling Interval

SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	Y	7.00E 1	deg
2	Dp	3.23E-1	cu.in/rad
3	Dm	5.01E-1	cu.in/rad
4	P	5.00E 3	psi
5	ΔS	6.60E 1	rad/sec
6	ΔT	3.00E 2	in-lbf



(b)

Figure 22. (Continued)

$$= 0.9 \ \text{LIMIT} \ (T, 50)$$

where the function LIMIT is the same as that defined in section 4.7. T is the time, and 50 sec was selected as the limit of the ramp input. In this example, the fuel economy is improved about 10 percent compared with the case shown in Figure 19.

9.2.2 Effects of Engine Transport Delay and Function of YSHIFT

Due to engine transport delay, the first reaction of the control system to an input change is to move the transmission ratio in the wrong direction, which could lead to an engine stall problem. This problem can be best explained with reference to the control system diagram in Figure 6. Suppose there is no function YSHIFT in the feed forward path. When the throttle position is changed, the function generator (FG) will generate an optimum engine loading torque, T_{op}, corresponding to the current throttle position value. This T_{op} is compared with the actual engine loading torque, T_e; then a positive torque error ($\Delta T > 0$) is generated, which tends to stroke the pump displacement and increase the engine loading torque. However, due to engine transport delay, no evidence of the change of the throttle position is observed in the engine output torque. Therefore, engine stall may occur.

To prevent this potential stall problem, a software function YSHIFT was employed in the control system. The function YSHIFT acts like a delay element. It is used to delay the sensed throttle position signal (and the optimum engine loading torque) by a period approximately equal to the engine transport delay. Then the error signal resulted from the engine transport delay may be eliminated and system stability will be improved.

9.2.3 Effects of Crossover Control Circuit Settings

In order to simplify the control algorithm, a crossover controller was used to phase the pump and motor displacements. The conventional crossover controller settings used for identical pump and motor sizes may not be suitable when the pump and motor are of different sizes. In the example system, the size of the pump is smaller than that of the motor. If D_c is set to 1/2 D_{rmax} (say 0.1 amp; see Figure 9), and the input signal D_r is increased from 0 to 0.1 amp, the pump displacement will increase from 0 to maximum (0.323 in.^{3}/rad). As D_r is further increased from 0.1 to 0.2 amp, then the motor displacement will decrease from maximum (0.501 in.^{3}/rad) to 0. Since the ratios (pump and motor) of the displacement changes to the input current changes are different, it can be seen that for small input signal range, the pump displacement increases very slowly. The result may be an unacceptable following of the optimum engine loading torque versus throttle position schedule.

The responses of two systems were compared by using computer simulation. System No. 1 contains a crossover controller with $D_c = 1/2\ D_{rmax}$ and $\ell_1/\ell_2 = 1$. System No. 2 contains a crossover control circuit with $D_c = D_{pm}\ D_{rmax}/(D_{pm} + D_{mm})$ and $\ell_1/\ell_2 = D_{rmax}/D_c - 1$. The results (see Table XI) reveal that system No. 2 has better fuel economy and dynamic performance than system No. 1. Thus, it can be concluded that the crossover controller settings determined by the scheme described in section 4.7 appear the most suitable.

TABLE XI

EFFECTS ON CROSSOVER CONTROLLER SETTINGS ON FUEL ECONOMY AND SYSTEM DYNAMIC PERFORMANCE

System	$\tilde{f}$	ITAE
No. 1	4.66	3.20×10^4
No. 2	4.64	3.19×10^4

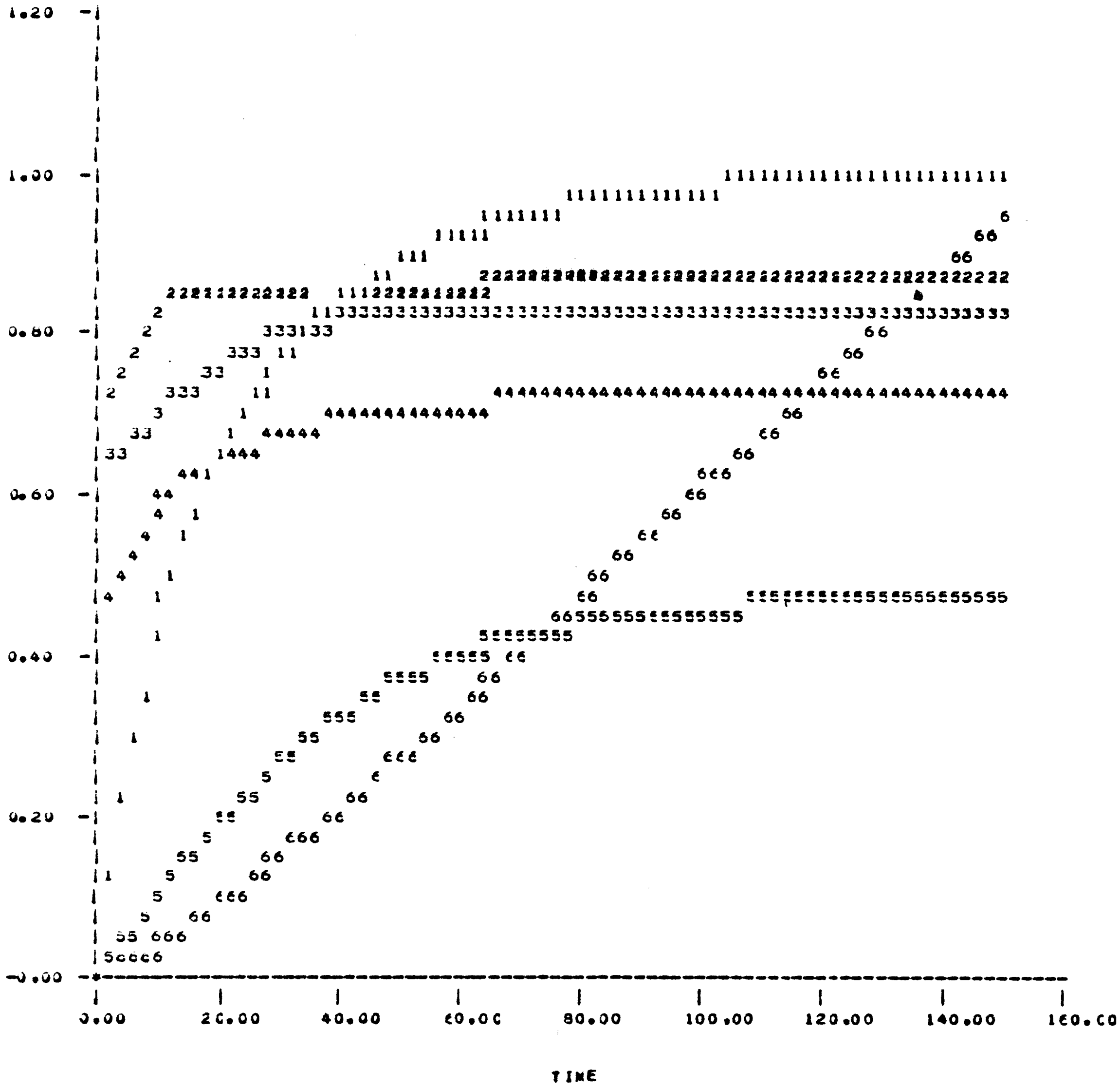
9.2.4 Effects of Controller Parameters Adjustment

From section 8.2, it was found that the drive system with improved controller adjustment achieves better fuel economy than the system before optimization. But the system dynamic performance will suffer.

9.2.5 Effects of Sampling Rate

Figures 23 and 24 show the vehicle responses to a full-stroke accelerator step input with sampling time intervals of 6 ms and 8 ms, respectively. The 6 ms (166 Hz) sampling interval gave an asymptotic steady response, but the 8 ms (125 Hz) sampling interval caused the system to approach a limit cycle. When the sampling interval is increased, the torque error signal ΔT as well as other system variables become oscillatory. The reason for the oscialIation is that the amplitude of the "step" control signal D_r is increased as the sampling interval is increased. For an 8 ms sampling interval, the amplitude of D_r increases so far that the pump/motor displacements are overstroked; this in turn overloads the engine and results in a sign change in torque error signal ($\Delta T < 0$). The

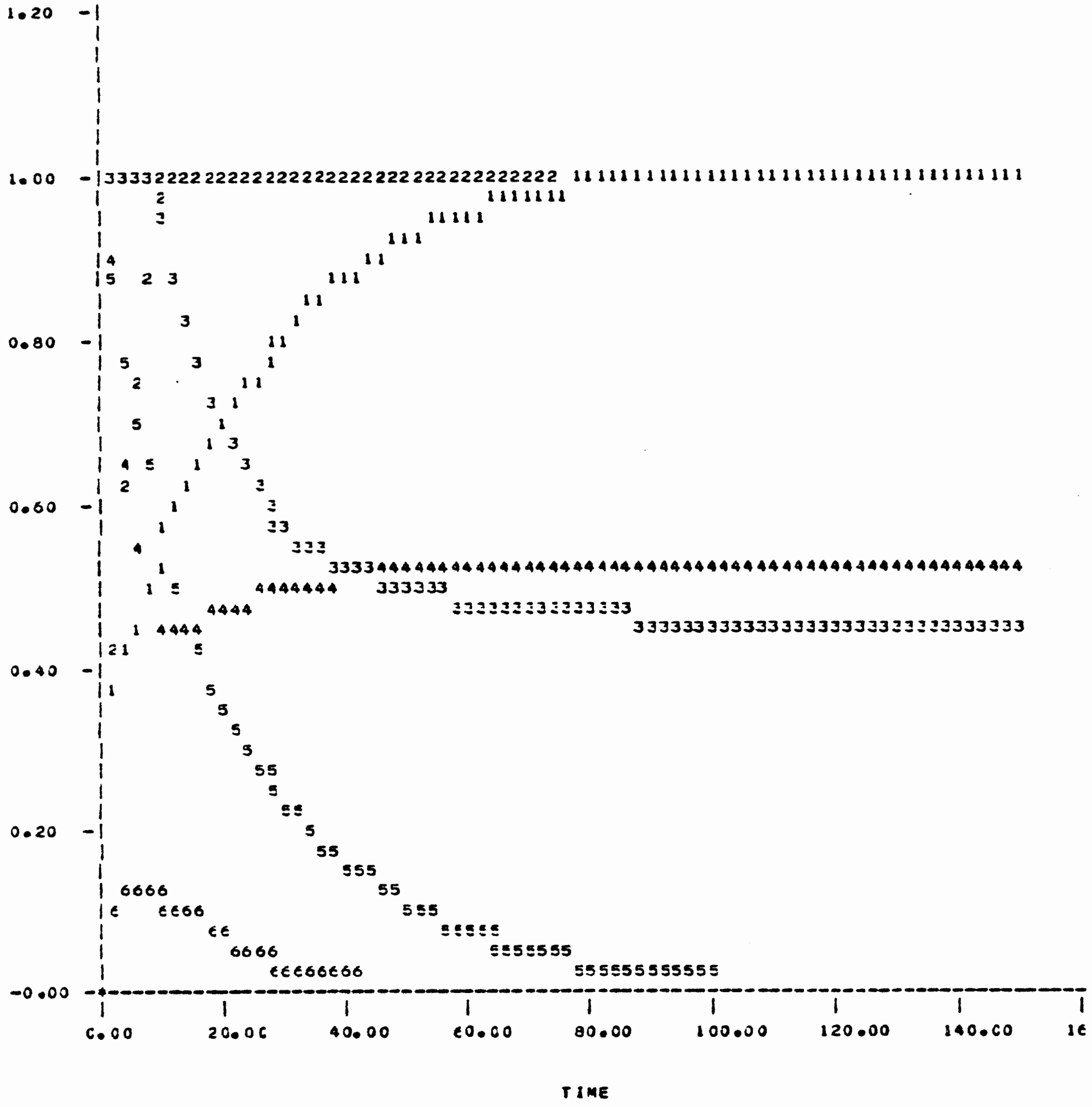
SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	V	7.92 E 2	in/sec
2	Se	3.15 E 2	rad/sec
3	Te	3.00 E 2	in-lbf
4	HPE	1.43 E 1	hp
5	HPL	1.43 E 1	hp
6	f	5.00 E 5	lbm



(a)

Figure 23. System Response to an Accelerator Full Stroke Step Input (V_c = 45 mph) on a Level Road With 6 ms Sampling Interval

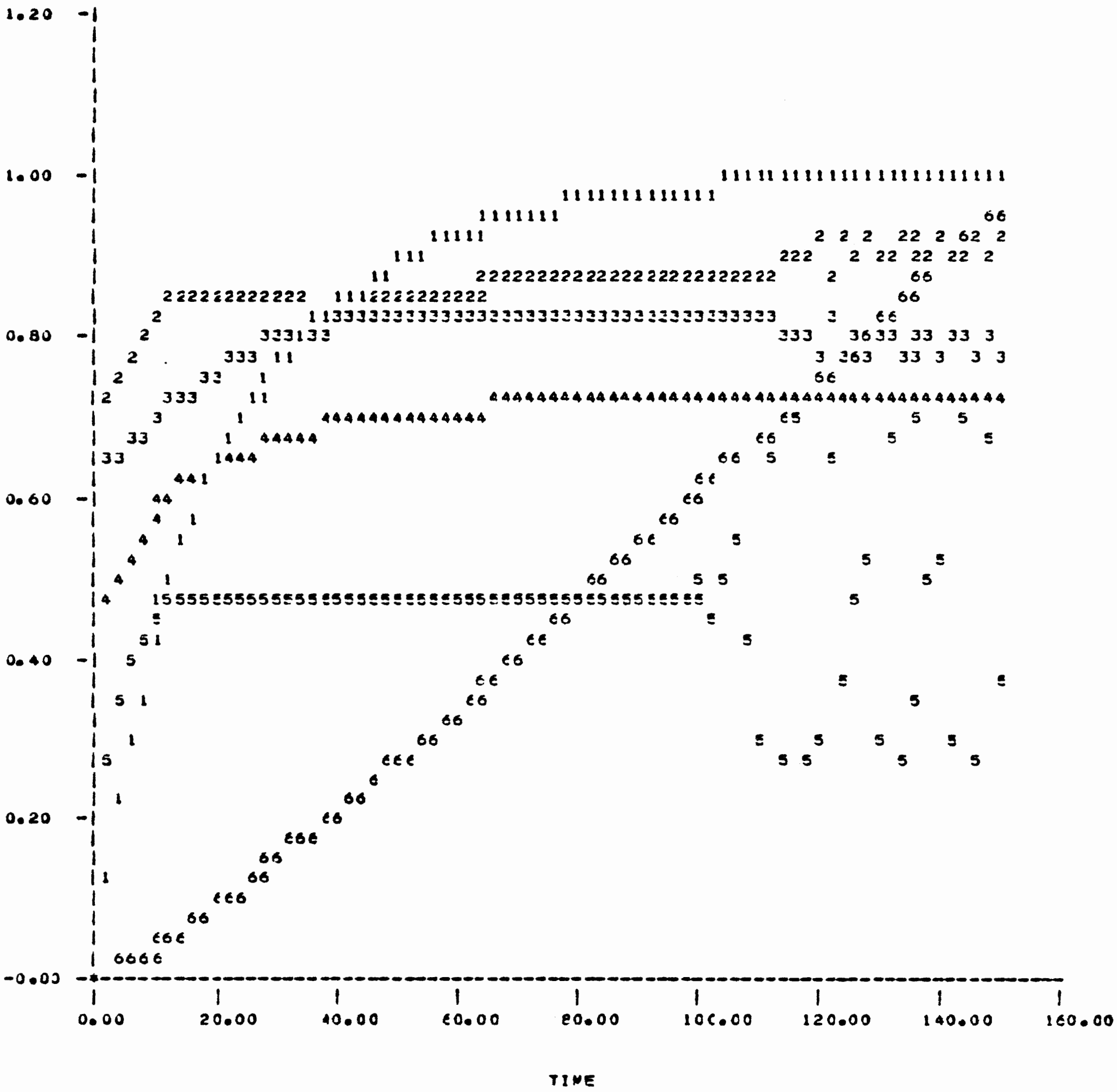
SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	Y	7.00E 1	deg
2	Dp	3.23E-1	cu.in/rad
3	Dm	5.01E-1	cu.in/rad
4	P	5.00E 3	psi
5	ΔS	6.60E 1	rad/sec
6	ΔT	3.00E 2	in-lbf



(b)

Figure 23. (Continued)

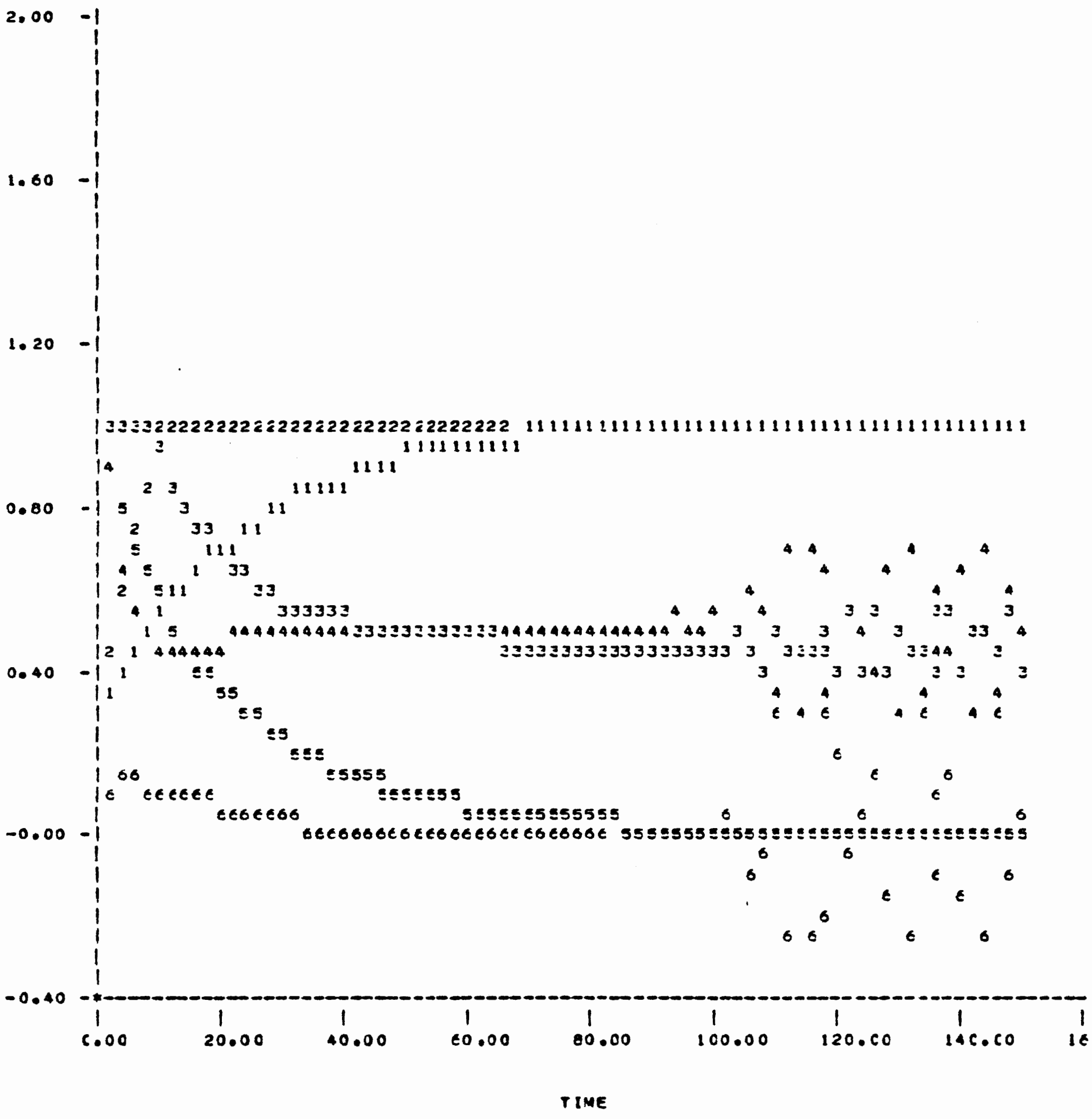
SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	V	7.92 E 2	in/sec
2	Se	3.15 E 2	rad/sec
3	Te	3.00 E 2	in-lbf
4	HPE	1.43 E 1	hp
5	HPL	1.43 E 1	hp
6	f	5.00 E 5	lbm



(a)

Figure 24. System Response to an Accelerator Full Stroke Step Input (V_c = 45 mph) on a Level Road With 8 ms Sampling Interval

SYMBOL	VARIABLE	SCALE FACTOR	UNIT
1	Y	7.00E 1	deg
2	Dp	3.23E-1	cu.in/rad
3	Dm	5.01E-1	cu.in/rad
4	P	5.00E 3	psi
5	ΔS	6.60E 1	rad/sec
6	ΔT	3.00E 2	in-lbf



(b)

Figure 24. (Continued)

negative ΔT then overreduces the amplitude of D_r and causes reverse effects on pump/motor displacements, engine loading torque, and torque error itself. The interaction proceeds continuously.

The variation of the fuel consumption and the dynamic performance index with the sampling interval for the example vehicle model is shown in Table XII. Although the effects are not very large, the larger sampling interval (e.g., 8 ms) does result in the lowest fuel economy and forces the system to oscillate. So, in order to obtain good drive economy and system stability, the sampling rate should be the maximum possible based on the μP selected and the time required to execute the control algorithm.

TABLE XII

EFFECTS OF SAMPLING TIME INTERVAL ON FUEL ECONOMY AND SYSTEM DYNAMIC PERFORMANCE*

T_s	$\tilde{f}$	ITAE
4 ms	4.645	3.193×10^4
6 ms	4.646	3.190×10^4
8 ms†	4.699	3.183×10^4

*Results were obtained based on 2 ms integration step size.

†The sampling interval of 8 ms causes the system to approach a limit cycle.

It should be noted that in the discrete system computer simulation, the integration step size should be chosen to be a submultiple of the sampling interval to insure that an integration is performed when the sampling switch closes. The results listed in Table XII were obtained based on a step size of 2 ms.

CHAPTER X

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The purpose of this thesis was to develop a design procedure for microprocessor-based control of an engine-hydrostatic transmission system and to examine the feasibility of the concept on the basis of the system efficiency and dynamic performance through use of a practical example.

The design portion of the thesis entails the development of power and control circuits, sizing of the system components for a given specification, derivation of the digital control algorithms, μP selection, and sampling interval estimation. The preliminary system design is followed by optimum adjustment of the system controller parameters to produce maximum fuel economy. The design process was aided by the IBM 370 digital computer. Five computer programs were developed. They are:

Program 1: for system sizing
Program 2: for optimum operation search
Program 3: for the highest system frequency calculation
Program 4: for controller parameters adjustment
Program 5: for simulation.

The preliminary design procedure can be summarized as follows:

1. Calculate engine size from Equation (5.2) based on given system specification.

2. Provide engine data and vehicle specification as input to

computer program 1. Select a combination of pump, motor, and gear ratios from the computer output based on the commercial availability of components and transmission efficiency.

3. Determine the optimum system operating conditions by using program 2, and then develop the function generator which schedules the optimum operation.

4. Select μP, interface elements, and electrohydraulic hardware (see sections 6.1 through 6.4).

5. Code the μC program based on the control algorithm structure given in section 6.5.2 and calculate the total computational time.

6. Calculate the highest frequency of the engine-HST system model using program 3. Check the sampling requirement.

7. Adjust controller parameters using program 4.

8. Evaluate the system static and dynamic performance using program 5.

An example system was used to demonstrate the design procedure. The performance of the example system was determined for a step input in the accelerator position. The example system is very stable. The effects of driver operation, engine transport delay, crossover control circuit settings, controller parameter adjustment, and sampling time interval on the fuel consumption and system dynamic performance were studied. The following conclusions can be made:

1. Drive economy can be improved by proper engine loading. Economy also can be achieved by smooth operation of the throttle, but at the expense of dynamic performance.

2. Engine transport delay imposes an unfavorable effect on the drive system. But this problem can be effectively overcome by using the stored function YSHIFT.

3. For phasing a nonidentical pump and motor, the crossover control circuit settings can be adjusted such that the rate of pump displacement change equals the rate of motor displacement change. This strategy will lead to a better fuel economy and system performance than that with the conventional crossover controller settings.

4. The drive economy can be improved by optimizing the controller parameters. However, some dynamic performance will be sacrificed.

5. The drive economy and system dynamic performance are related to the sampling time interval. From the example system, it can be seen that there were no significant effects on the fuel economy and dynamic performance when the sampling interval was increased from 4 ms to 6 ms; however, as the sampling interval was increased to 8 ms, the fuel economy became worse and the system response became unstable. Therefore, the sampling interval should be chosen as small as possible.

6. In addition to the fuel savings, the use of a μP-based controller for an engine-HST system offers the unique advantage of small size, light weight, low power consumption, high reliability, and programming flexibility. Flexibility and computation capability are the major advantages gained by the μP-based controller. The μC program can be extended to perform other tasks, such as display functions, safety warning functions, and some functions recommended in section 10.2, etc. Meanwhile, there is redundant time to perform those functions (e.g., for the example system, a sampling interval of 6 ms is still acceptable because it gave an

asymptotic steady response). All of these benefits would seem to make the development of this control system viable.

10.2 Recommendations for Future Study

The following areas are recommended for future study:

1. The hardware of the crossover control circuit could be replaced by software, and thereby make more effective use of the capability of the μP.

2. The possibility of replacing the throttle PI controller with a sophisticated function generator should be investigated. The function generator would generate an optimum throttle position signal as a function of the speed error signal.

3. In cases where maximum acceleration is the important performance criterion, then fuel economy would play a secondary role. A second function generator could be developed based on the maximum acceleration performance criterion. The driver could select or change the control mode from one to another depending on which performance criterion is valued.

4. The promising results of this study suggest implementing the proposed control system in hardware.

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APPENDIX A

STATIC SYSTEM MODEL

The static or steady-state model used for searching the optimal operating conditions can be derived from the dynamic system model (Chapter IV) as follows.

Forcing the derivative terms in Equations (4.6), (4.7), (4.9) through (4.11), (4.14), and (4.15) yields

$$G_p = \frac{S_e}{S_p} = \frac{T_p}{T_e} \tag{A.1}$$

$$G_m = \frac{S_m}{S_\ell} = \frac{T_\ell}{T_m} \tag{A.2}$$

$$T_p = (D_p + C_{fp} D_{pm}) P + C_{dp} \mu D_{pm} S_p \tag{A.3}$$

$$T_m = (D_m - C_{fm} D_{mm}) P - C_{dm} \mu D_{mm} S_m \tag{A.4}$$

$$P = \mu \frac{D_p S_p - D_m S_m}{C_{sp} D_{pm} + C_{sm} D_{mm}} \tag{A.5}$$

$$Q = D_m S_m + \frac{C_{sm} D_{mm}}{\mu} P \tag{A.6}$$

$$S_\ell = \frac{V}{R} \tag{A.7}$$

$$T_\ell = R[Wa(1 + \frac{V}{b}) + C_a \rho A \frac{V^2}{2} + W\sin\phi] \tag{A.8}$$

All variables and constants were defined previously.

Rearrange Equation (A.5) to get

$$P = \mu \frac{d_p S_p - d_m D_r S_m}{C_1} \tag{A.9}$$

where

$$d_p = \frac{D_p}{D_{pm}} \tag{A.10}$$

$$d_m = \frac{D_m}{D_{mm}} \tag{A.11}$$

$$D_r = \frac{D_{mm}}{D_{pm}} \tag{A.12}$$

$$C_1 = C_{sp} + C_{sm} D_r \tag{A.13}$$

Substituting Equation (A.9) into Equations (A.3) and (A.4), respectively, yields

$$T_p = \frac{\mu D_{pm}}{C_1} [(d_{pc} d_p + C_1 C_{dp}) S_p - d_{pc} d_m D_r S_m] \tag{A.14}$$

and

$$T_m = \frac{\mu D_{mm}}{C_1} [d_{mc} d_p S_p - (d_{mc} d_m D_r + C_1 C_{dm}) S_m] \tag{A.15}$$

where

$$d_{pc} = d_p + C_{fp} \tag{A.16}$$

$$d_{mc} = d_m - C_{fm} \tag{A.17}$$

Rearrange Equation (A.15) to get

$$S_p = \frac{1}{d_{mc} d_p} [\frac{C_1}{\mu D_{mm}} T_m + (d_{mc} d_m D_r + C_1 C_{dm}) S_m] \tag{A.18}$$

With the defined variables, Equation (A.6) becomes

$$Q = D_{mm} \left(d_m S_m + \frac{C_{sm}}{\mu} P\right) \qquad (A.19)$$

Equations (A.1), (A.2), (A.7) through (A.14), (A.16) through (A.19) together with Equation (2.5) and engine performance data may be used to find the optimum operations for all interesting load conditions (given vehicle velocity V and road slope ϕ). The details of the searching program are given in Appendix G.2.

APPENDIX B

TABLE LOOK-UP AND BI-LINEAR INTERPOLATION

A table of numbers can be built from the optimum operating conditions (obtained in section 2.2) and directly store the table in a memory unit. Then the μP can determine the desired data by using the following table look-up and bi-linear interpolation technique which eliminates the need for table searching.

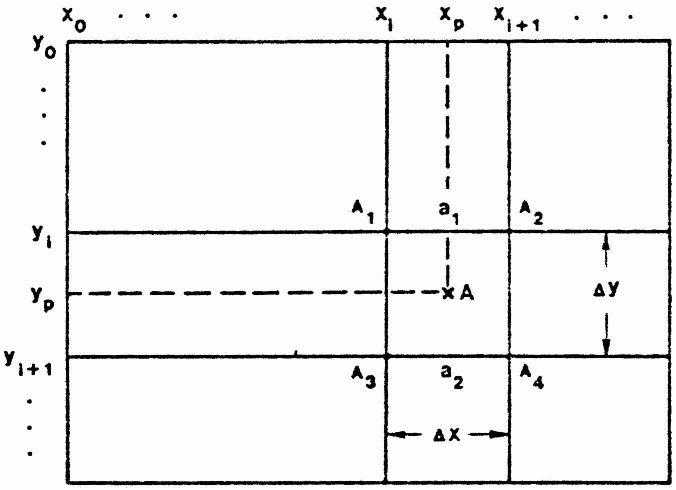

Figure 25. Typical FG Table

Suppose the value of A as a function of x and y is to be determined corresponding to the two values given x_p and y_p as shown in Figure 25. First, the μP computes the address of the table entries A_1, A_2, A_3 and A_4.

If the table entries are spaced at equal intervals (Δx, Δy), then

$$\frac{x_p - x_o}{\Delta x} = I_1 \text{ (integer part)} + f_1 \text{ (fractional part)} \tag{B.1}$$

$$\frac{y_p - y_o}{\Delta y} = I_2 \text{ (integer part)} + f_2 \text{ (fractional part)} \tag{B.2}$$

where I_1 is the address for x_i and I_2 is the address for y_i. The fractional parts f_1 and f_2 will be used for linear interpolation between table entries x_i and x_{i+1}, and between table entries y_i and y_{i+1}, respectively, as

$$a_1 = A_1 + f_1 \cdot (A_2 - A_1) \tag{B.3}$$

$$a_2 = A_3 + f_1 \cdot (A_4 - A_3) \tag{B.4}$$

then

$$A = a_1 + f_2 \cdot (a_2 - a_1) \tag{B.5}$$

The division by Δx, Δy in Equations (B.1) and (B.2) can be replaced with multiplication by $1/\Delta x$, $1/\Delta y$ in order to save computer time.

APPENDIX C

DETERMINATION OF ENGINE CONSTANTS AND THE LIMITS OF PI-CONTROLLERS' INTEGRATOR OUTPUT

C.1 Engine Damping Coefficient

Figure 26 shows the torque-speed characteristics of the A042 military engine. The approximate slope of the constant throttle position lines can be found from the tangent to the full throttle envelope in the vicinity of the maximum engine power, HPE_{max} [17]. The tangent is in fact the constant throttle position line for full throttle position Y_{max} of a linearized engine model. From Equation (4.1), the engine loading torque in the steady state is

$$T_e = T_y - K_2 S_e$$

The intersection of the tangent and the T_e-axis gives the maximum input torque $\tilde{T}_{ymax}$ = 560 in.-lbf, and that with the S_e-axis gives $\tilde{S}_{emax}$ = 595 rad/sec. It is seen that the damping coefficient K_2 can be determined as:

$$K_2 = \tilde{T}_{ymax}/\tilde{S}_{emax}$$

$$= 0.94 \text{ in.-lbf-sec/rad.}$$

C.2 Throttle Gain

Assuming a linear relationship between the throttle position and the input torque, the throttle gain is:

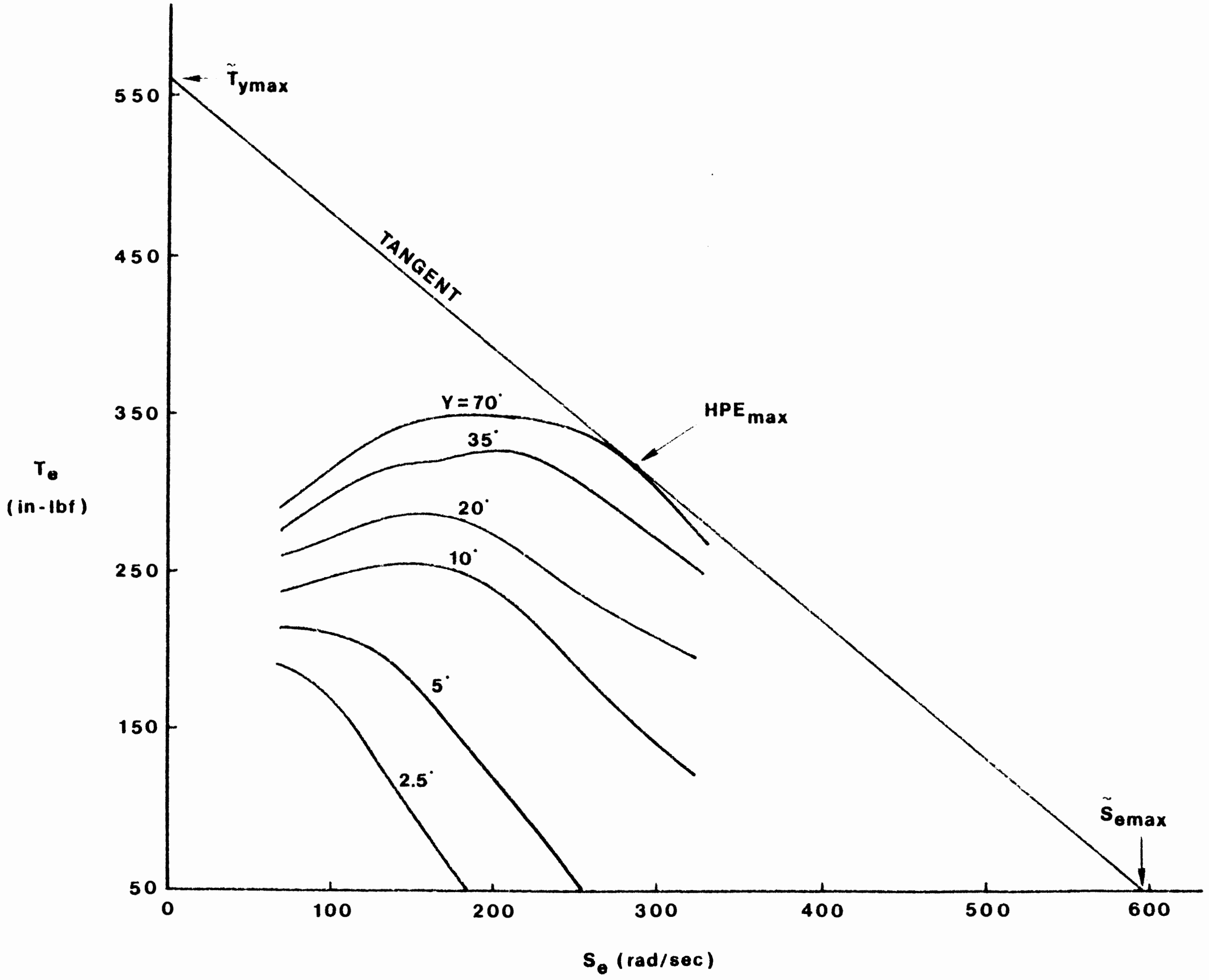

Figure 26. Torque-Speed Characteristics of an A042 Military Engine

$$K_1 = T_y/Y$$

For the maximum values $Y_{max} = 1.222$ rad (70°) and $\tilde{T}_{ymax} = 560$ in.-lbf, then

$$K_1 = 458.37 \text{ in.-lbf/rad.}$$

C.3 Transport Delay Constant

According to Reference [17], for a 1725 cc four-cylinder, four-stroke spark ignition engine, the transport delay constant is 10.9 rad. The selected A042 engine is a 695 cc, two-cylinder, four-stroke SI engine. It fires half as frequently as a four-cylinder, four-stroke SI engine. Since the engine size is only 695 cc, so the transport delay constant for the selected engine is estimated as:

$$K_3 = 10.9 \text{ rad.}$$

C.4 Idling Throttle Position

The idling engine loading torque results from the torque loss in the main pump. From Equations (4.6) and (4.9), the idling engine loading torque is:

$$\begin{aligned} T_{idle} &= C_{dp}\,\mu\,D_{pm}\,S_p/G_p \\ &= C_{dp}\,\mu\,D_{pm}\,S_{idle}/G_p^2 \\ &= 2.37 \text{ in -lbf} \end{aligned}$$

for idling speed $S_{idle} = 70$ rad/sec. The idling throttle position is then obtained from Table III by linear interpolation.

$$Y_{idle} = Y_{min} = 0.17 \text{ deg.}$$

C.5 Upper and Lower Limits of PI Controllers' Integrator Output

From Equation (4.26) the minimum input current to the electric servo-drive which is needed to maintain the idling throttle position under steady state is:

$$
\begin{aligned}
Y_r &= \frac{0.1}{Y_{max}} (Y_{idle}) \\
&= 2.43\text{x}10^{-4} \text{ amp}
\end{aligned}
$$

The equivalent voltage for 100Ω resistance is:

$$Y_{rh} = 2.43\text{x}10^{-2} \text{ volt}$$

This value is the output of the zero order hold and the 12-bit D/A converter. Based on the functions, ZHOLD and SIGOUT in Appendix G.5, the input to the D/A concerter can be computed as:

$$X1 = \frac{2047}{10} (2.43\text{x}10^{-2}) = 4.97$$

$$YRD = \frac{66}{2047} (X1) = 0.16$$

In practice, this value (voltage) comes from the throttle PI controller, so from Equation (4.18) or subroutine PIC (see Appendix G.5) it is easy to see that the lower limit of the integrator output of the throttle PI controller is:

$$YI_{min} = 0.16$$

Following the same procedure, the upper limit of the integrator output is:

$$YI_{max} = 66.$$

Similarly, the lower and upper limits of the integrator output of the displacement PI controller are:

$DI_{min} = 0.$

$DI_{max} = 300.$

APPENDIX D

LINEARIZED MODEL AND TRANSFER FUNCTION OF THE ENGINE-HST SYSTEM

D.1 Linearized Model

In order to linearize the equations for use in getting the transfer function for the engine-HST system, assume that all system variables undergo small changes from an initial steady-state operating condition. Let the subscript i denote the initial value of each variable before the change occurs. Then

$$S_e = S_{ei} + \Delta S_e$$

$$T_e = T_{ei} + \Delta T_e$$

$$Y = Y_i + \Delta Y$$

$$P = P_i + \Delta P$$

and so on. The linearization is accomplished by expanding the expressions in each equation with a first-order Taylor series about the steady-state operating condition, restricting the disturbances to small perturbations. Thus the product of perturbed variables will be small and can be neglected. Then the linearized forms of Equations (4.1), (4.6), (4.7), (4.9), (4.11), (4.14), (4.15), (4.26), (4.27), and (4.28) are:

$$(J_c s + K_2)\Delta S_e = K_1 e^{-t_{1i} s} \Delta Y - \Delta T_e \qquad (D.1)$$

$$\Delta S_e = G_p \, \Delta S_p \tag{D.2}$$

$$\Delta T_e = \Delta T_p / G_p \tag{D.3}$$

$$\Delta S_m = G_m \, \Delta S_\ell \tag{D.4}$$

$$\Delta T_m = \Delta T_\ell / G_m \tag{D.5}$$

$$\Delta T_p = E_1 \, \Delta P + P_i \, \Delta D_p + E_3 \, \Delta S_p \tag{D.6}$$

$$\Delta T_m = E_2 \, \Delta P + P_i \, \Delta D_m - E_4 \, \Delta S_m \tag{D.7}$$

$$(E_5 s + E_6)\Delta P = D_{pi} \, \Delta S_p + S_{pi} \, \Delta D_p - D_{mi} \, \Delta S_m - S_{mi} \, \Delta D_m \tag{D.8}$$

$$\Delta V = R \, \Delta S_\ell \tag{D.9}$$

$$\Delta T_\ell / R = (M_c s + E_7)\Delta V + E_8 \, \Delta\phi \tag{D.10}$$

$$(\tau_y s + 1)\Delta Y = K_y \, \Delta Y_r \tag{D.11}$$

$$(\tau_d s + 1)\Delta D_p = K_p \, \Delta D_{rp} \tag{D.12}$$

$$(\tau_d s + 1)\Delta D_m = -K_m \, \Delta D_{rm} \tag{D.13}$$

where s is the Laplace operator, and E_1, E_2, E_3, . . ., etc. are derived coefficients (see Table XIII). The perturbed variables ΔS_e, ΔY, ΔT_e, etc. indicate the Laplace transforms of variables. Other variables and constants were defined previously.

D.2 Transfer Function

During derivation of the transfer function, the derived coefficients should be read with reference to Table XIII. Combine Equations (D.1), (D.2), (D.3), and (D.6) to yield:

$$(J_c s + E_9) G_p^2 \, \Delta S_p = G_p K_1 e^{-t_{1i} s} \, \Delta Y - E_1 \, \Delta P - P_i \, \Delta D_p \tag{D.14}$$

Combining Equations (D.4), (D.5), (D.7), (D.9), and (D.10) yields

$$E_2 \;\Delta P = \frac{R}{G_m}\,(M_c s + E_{10})\Delta V + E_{11}\;\Delta\phi - P_i\;\Delta D_m \tag{D.15}$$

Combining Equations (D.4), (D.5), (D.8), and (D.9) yields

$$\Delta S_p = \frac{1}{D_{pi}}\,[(E_5 s + E_6)\Delta P - S_{pi}\;\Delta D_p + \frac{D_{mi}\;G_m}{R}\,\Delta V + S_{mi}\;\Delta D_m] \tag{D.16}$$

Substituting Equation (D.16) into Equation (D.14) to get

$$\begin{aligned} &\left[(J_c s + E_9)(E_5 s + E_6) + \frac{E_1\;D_{pi}}{G_p^2}\right]\Delta P \\ &\quad = \left[(J_c s + E_9)S_{pi} - \frac{P_i\;D_{pi}}{G_p^2}\right]\Delta D_p \\ &\quad - (J_c s + E_9)\left(\frac{D_{mi}\;G_m}{R}\,\Delta V + S_{mi}\;\Delta D_m\right) \\ &\quad + \frac{D_{pi}\;K_1}{G_p}\,e^{-t_{1i}s}\;\Delta Y \end{aligned} \tag{D.17}$$

Substituting Equation (D.15) into Equation (D.17) to get

$$\begin{aligned} &(J_c\;E_5\;s^2 + E_{12}\;s + E_{13})\left[\frac{R}{G_m}\,(M_c\;s + E_{10})\Delta V + E_{11}\;\Delta\phi - P_i\;\Delta D_m\right] \\ &\quad = E_2\left[(J_c\;s + E_9)S_{pi} - \frac{P_i\;D_{pi}}{G_p^2}\right]\Delta D_p \\ &\quad - E_2(J_r\;s + E_9)\left(\frac{D_{mi}\;G_m}{R}\,\Delta V + S_{mi}\;\Delta D_m\right) \\ &\quad + \frac{E_2\;D_{pi}\;K_1}{G_p}\,e^{-t_{1i}s}\;\Delta Y \end{aligned} \tag{D.18}$$

Rearranging Equation (D.18) to get

$$(E_{17}\ s^3 + E_{18}\ s^2 + E_{19}\ s + E_{20})\Delta V = E_{16}\ e^{-t_{1i}s}\ \Delta Y$$

$$+ (E_{21}\ s + E_{22})\Delta D_p + (E_{23}\ s^2 + E_{24}\ s + E_{25})\Delta D_m$$

$$- (E_{26}\ s^2 + E_{27}\ s + E_{28})\Delta\phi \qquad (D.19)$$

Substituting Equations (D.11), (D.12), (D.13) into Equation (D.19) yields

$$\Delta V = \frac{E_{29}\ e^{-t_{1i}s}}{(E_{30}\ s^4 + E_{31}\ s^3 + E_{32}\ s^2 + E_{33}\ s + E_{20})}\ \Delta Y_r$$

$$+ \frac{NB(2)s + NB(1)}{DB(5)s^4 + DB(4)s^3 + DB(3)s^2 + DB(2)s + DB(1)}\ \Delta D_{rp}$$

$$- \frac{NC(3)s^2 + NC(2)s + NC(1)}{DB(5)s^4 + DB(4)s^3 + DB(3)s^2 + DB(2)s + DB(1)}\ \Delta D_{rm}$$

$$- \frac{ND(3)s^2 + ND(2)s + ND(1)}{DD(4)s^3 + DD(3)s^2 + DD(2)s + DD(1)}\ \Delta\phi \qquad (D.20)$$

Taking

$$e^{-t_{1i}s} \cong \frac{1}{1 + t_{1i}s} \qquad (D.21)$$

Then

$$\frac{\Delta V}{\Delta Y_r} = E_{29}/[(E_{30}\ t_{1i})s^5 + (E_{31}\ t_{1i} + E_{30})s^4 + (E_{32}\ t_{1i} + E_{31})s^3$$

$$+ (E_{33}\ t_{1i} + E_{32})s^2 + (E_{20}\ t_{1i} + E_{33})s + E_{20}]$$

$$= \frac{NA(1)}{DA(6)s^5 + DA(5)s^4 + DA(4)s^3 + DA(3)s^2 + DA(2)s + DA(1)}$$

(D.22)

$$\frac{\Delta V}{\Delta D_{rp}} = \frac{NB(2)s + NB(1)}{DB(5)s^4 + DB(4)s^3 + DB(3)s^2 + DB(2)s + DB(1)} \qquad (D.23)$$

$$\frac{\Delta V}{\Delta D_{rm}} = - \frac{NC(3)s^2 + NC(2)s + NC(1)}{DB(5)s^4 + DB(4)s^3 + DB(3)s^2 + DB(2)s + DB(1)} \qquad (D.24)$$

$$\frac{\Delta V}{\Delta \phi} = - \frac{ND(3)s^2 + ND(2)s + ND(1)}{DD(4)s^3 + DD(3)s^2 + DD(2)s + DD(1)} \qquad (D.25)$$

TABLE XIII

DERIVED COEFFICIENTS

$K_y = Y_{max}/0.1$

$K_p = D_{pm}/0.1$

$K_m = D_{mm}/0.1$

$E_1 = D_{pi} + C_{fp}D_{pm}$

$E_2 = D_{mi} - C_{fm}Dmm$

$E_3 = C_{dp}\mu D_{pm}$

$E_4 = C_{dm}\mu Dmm$

$E_5 = v/B$

$E_6 = (C_{sp}D_{pm} + C_{sm}D_{mm})/\mu$

$E_7 = W_{a/b} + C_a P\ A\ V_i$

$E_8 = W\ \mathrm{COS}\ \phi_i$

$E_9 = K_2 + E_3/G_p^2$

$E_{10} = E_7 + E_4\ G_m^2/R^2$

$E_{11} = E_8 R/G_m$

$E_{12} = E_5 E_9 + E_6 J_c$

$E_{13} = E_6 E_9 + E_1 D_{pi}/G_p^2$

$E_{14} = E_9 S_{pi} - P_i D_{pi}/G_p^2$

$E_{15} = E_2 G_m D_{mi}/R$

$E_{16} = E_2 K_1 D_{pi}/G_p$

$E_{17} = E_5 J_c M_c R/G_m$

$E_{18} = (R/G_m)\ (E_{12} M_c + E_5 E_{10} J_c)$

$E_{19} = (R/G_m)\ (E_{13} M_c + E_{10} E_{12} + E_{15} J_c G_m/R)$

TABLE XIII (Continued)

$E_{20} = (R/G_m)(E_{10}E_{13} + E_9E_{15}G_m/R)$

$E_{21} = E_2J_cS_{pi}$

$E_{22} = E_2E_{14}$

$E_{23} = E_5J_cP_i$

$E_{24} = E_{12}P_i - E_2J_cS_{mi}$

$E_{25} = E_{13}P_i - E_2E_9S_{mi}$

$E_{26} = E_5E_{11}j_c$

$E_{27} = E_{11}E_{12}$

$E_{28} = E_{11}E_{13}$

$E_{29} = E_{16}K_y$

$E_{30} = E_{17}\tau_y$

$E_{31} = E_{18}\tau_y + E_{17}$

$E_{32} = E_{19}\tau_y + E_{18}$

$E_{33} = E_{20}\tau_y + E_{19}$

$DA(1) = E_{20}$

$DA(2) = E_{20}T_{1i} + E_{33}$

$DA(3) = E_{33}t_{1i} + E_{32}$

$DA(4) = E_{32}t_{1i} + E_{31}$

$DA(5) = E_{31}t_{1i} + E_{30}$

$DA(6) = E_{30}t_{1i}$

$DB(1) = E_{20}$

$DB(2) = E_{20}\tau_d + E_{19}$

$DB(3) = E_{19}\tau_d + E_{18}$

$DB(4) = E_{18}\tau_d + E_{17}$

$DB(5) - E_{17}\tau d$

$DD(1) = E_{20}$

$DD(2) = E_{19}$

$DD(3) = E_{18}$

$DD(4) = E_{17}$

$NA(1) = E_{29}$

$NB(1) = E_{22}K_p$

$NB(2) = E_{21}K_p$

$NC(1) = E_{25}K_m$

$NC(2) = E_{24}K_m$

$NC(3) = E_{23}K_m$

$ND(1) = E_{28}$

$ND(2) = E_{27}$

$ND(3) = E_{26}$

APPENDIX E

SIMPLEX METHOD FOR FUNCTION MINIMIZATION

The procedure of the simplex method is based on the work by Nelder and Mead [29]. This method adapts itself to the local landscape, using reflected, expanded, and contracted points to locate the minimum of a multivariable unconstrained nonlinear function. Derivatives are not required. The algorithm proceeds as follows:

1. A starting point, $X_{1,j}$, is selected.

2. A starting "simplex" is constructed consisting of the starting point and the following additional points:

$$X_{i,j} = X_{1,j} + \xi_{i,j} \cdot \Delta_j \qquad \text{(E.1)}$$

$$i = 2.\ 3, \ldots, N + 1$$

$$j = 1, 2, \ldots, N$$

where $\xi_{i,j}$ is determined from the following table:

$i \backslash j$	1	2	. . .	N-1	N
2	1	0	. . .	0	0
3	0	1	. . .	0	0
⋮	⋮	⋮	. . .	⋮	⋮
N	0	0	. . .	1	0
N+1	0	0	. . .	0	1

N is the total number of variables. The values used in Δ_j will depend on the required size of the simplex and the relative magnitudes of the units for each variable.

3. Once the simplex is formed, the objective function is evaluated at each point. The worst point (highest value of objective function) is replaced by a new point. Three operations are used--reflection, contraction, and expansion. A reflected point is located first as follows:

$$X_{i,j}(\text{reflected}) = X_{c,j} + \alpha[X_{c,j} - X_{i,j}(\text{worst})] \qquad (E.2)$$

$$j = 1, 2, \ldots, N$$

where α is a positive constant.

$X_{c,j}$ are the centroid coordinates of all points excluding the worst point and are calculated from the following:

$$X_{c,j} = \frac{1}{N}\left[\sum_{i=1}^{N+1} X_{i,j} - X_{i,j}(\text{worst})\right] \qquad (E.3)$$

$$j = 1, 2, \ldots, N$$

4. If the reflected point has the worst objective function value of the current points, a contracted point is located as follows:

$$X_{i,j}(\text{contracted}) = X_{c,j} - \beta[X_{c,j} - X_{i,j}(\text{worst})] \qquad (E.4)$$

$$j = 1, 2, \ldots, N$$

where β lies between 0 and 1.

If the reflected point is better than the worst point but is not the best point, a contracted point is calculated from the reflected point as follows:

$$X_{i,j}(\text{contracted}) = X_{c,j} - \beta[X_{c,j} - X_{i,j}(\text{reflected})] \qquad (E.5)$$

$$j = 1, 2, \ldots, N$$

The objective function is now evaluated at the contracted point. If an improvement over the current points is achieved, the process is restarted.

Otherwise, the points are moved one-half the distance toward the best point:

$$X_{i,j}(\text{new}) = \frac{1}{2}\,[X_{i,j}(\text{best}) + X_{i,j}(\text{old})] \tag{E.6}$$

$$j = 1, 2, \ldots, N$$

The process is then restarted.

5. If the reflected point calculated in step 3 is the best point, an expansion point is calculated as follows:

$$X_{i,j}(\text{expansion}) = X_{c,j} + \gamma[X_{i,j}(\text{reflected}) - X_{c,j}] \tag{E.7}$$

$$j = 1, 2, \ldots, N$$

where γ is a positive constant. If the expansion point is an improvement over the reflected point, the reflected point is replaced by the expansion point and the process is restarted. If the expansion point is not an improvement over the reflected point, the reflected point is retained and the process is restarted.

6. The procedure is terminated when the convergence criterion is satisfied or a specified number of iterations has been exceeded. The convergence criterion is: if $\varepsilon < \varepsilon_{min}$ the process will terminate, where

$$\varepsilon = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N+1} (Z_i - Z_c)^2 - (Z_{worst} - Z_c)^2\right]} \tag{E.8}$$

ε_{min} is the convergence parameter, and Z is the objective function value. A flow diagram illustrating the procedure is given in Figure 27.

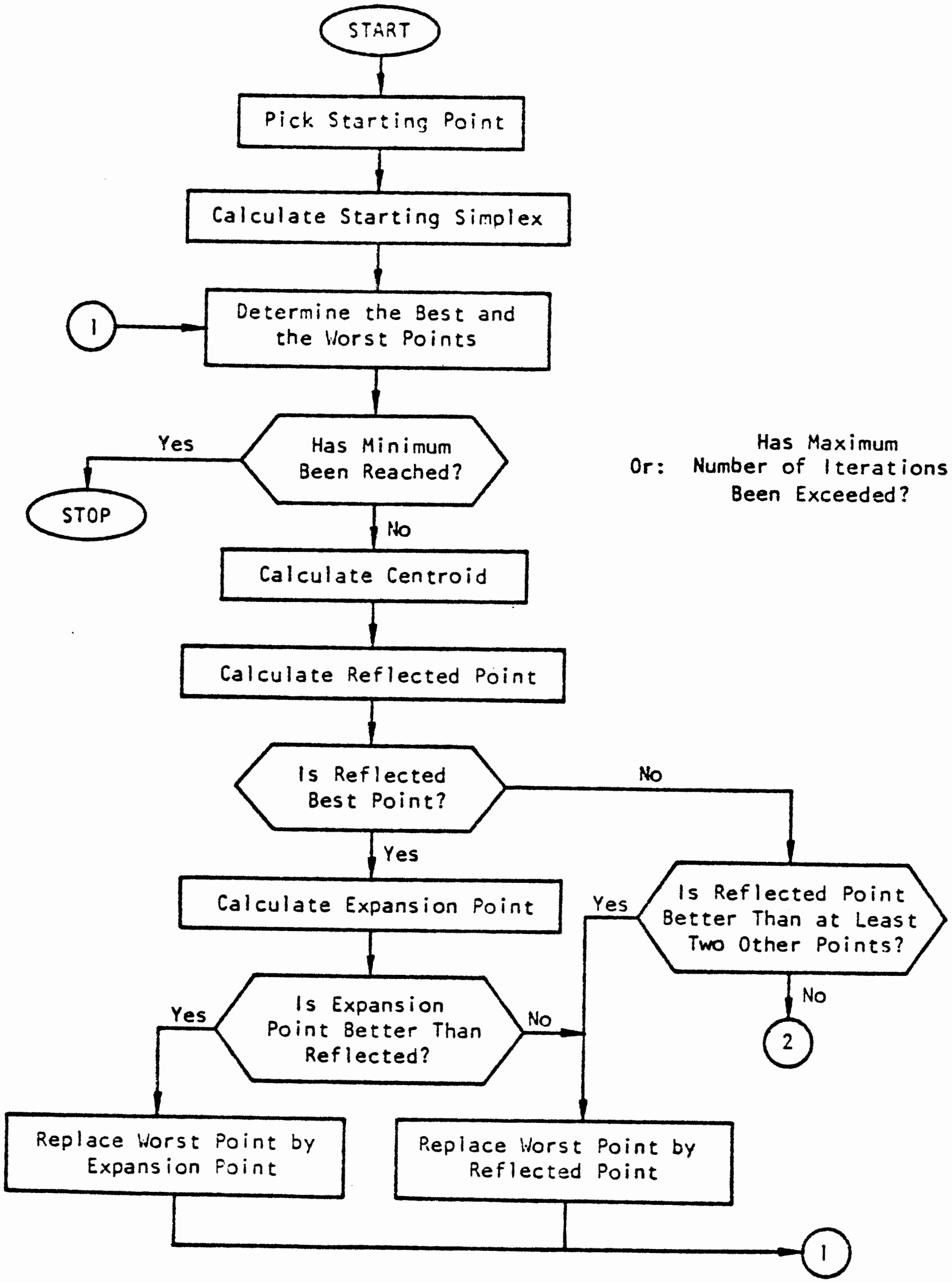

Figure 27. Flow Chart for Simplex Minimization Algorithm

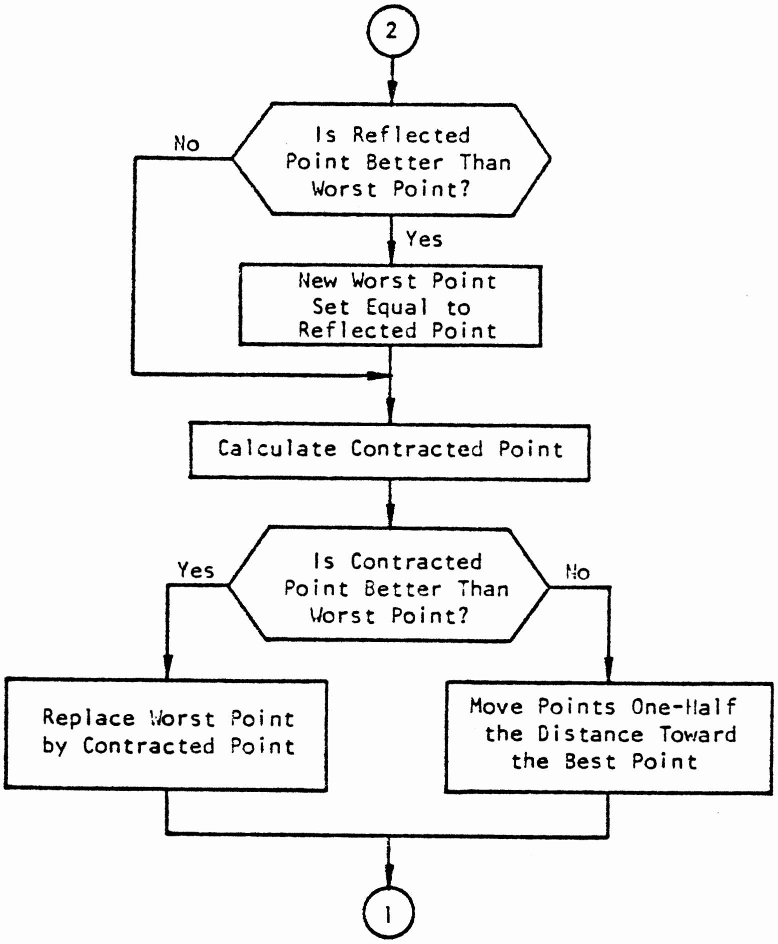

Figure 27. (Continued)

APPENDIX F

COMPUTATION PROCEDURE FOR DYNAMIC SYSTEM MODEL

In order to adjust parameters and evaluate the dynamic performance of the vehicle drive system, a discrete system computer simulation would be performed. In this appendix the computation procedure for the dynamic system models is described. It is helpful to understand the program logic in Appendix G.4 and G.5.

The dynamic models developed in Chapter IV can be separated into two categories; they are algebraic equations and first-order differential equations described as:

$$\bar{X} = f(\bar{X}, \bar{Y}, \bar{P}, t) \tag{F.1}$$

$$\overline{DY} = f(\bar{X}, \bar{Y}, \bar{P}, t) \tag{F.2}$$

where

X = algebraic variable;

Y = state variable;

P = parameter; and

t = time.

The solution would proceed in the following four major steps:

1. The value of the state variables are known from the initial conditions or as a result of previous numerical integration.

2. The algebraic equations (F.1) are solved since the values of the states and time are known and the only unknowns are the algebraic variables. After solution, all algebraic variables are now known.

3. The value of the state derivative is explicitly determined from the values of the state, algebraic, and time variables.

4. The values of the state and derivative of the state variables are known. Time is incremented and the values of the states of this new time are determined by numerical integration.

This procedure is repeated until the final time is reached.

APPENDIX G

COMPUTER PROGRAM LISTINGS

G.1 Program for System Sizing

This program is developed based on the sizing algorithms presented in section 5.2. The comment statements are self-explanatory.

```
C**************************************
C*                                    *
C*    PROGRAM FOR SYSTEM SIZING       *
C*                                    *
C**************************************
C
C
      DIMENSION SL(2),TL(2),SM(2),TM(2),P(2),Q(2),TP(2),V(2),
     *          ALPHA(2)
C-----
C     SPECIFY THE MAXIMUM VEHICLE SPEED ON MAXIMUM GRADE ROAD
C             AND THE MAXIMUM VEHICLE SPEED ON LEVEL ROAD
C-----
      DATA V/11., 45./, ALPHA/6.843, 0./
C-----
C     SPECIFY VEHICLE SPECIFICATION DATA
C             TRANSMISSION COEFFICIENTS
C             MAXIMUM WORKING PRESSURE
C             MAXIMUM ENGINE SPEED AND TORQUE
C-----
      A=2592.
      R=12.
      W=1700.
      CA=0.35
      AS=0.01
      BS=1760.
      RHO=1.12E-7
C-----
      PMU=5.75E-6
      CSP=4.0E-9
      CSM=4.0E-9
      CDP=2.5E 5
      CDM=2.5E 5
      CFP=0.05
      CFM=0.05
C-----
      PMAX=4000.
C-----
      SEM=315.
      TEFULL=210.
      INDEX=0
C-----
C     CALCULATE LOAD SPEEDS AND TORQUES
C     AT BOTH OPERATION CONDITIONS
C-----
      DO 10 I=1,2
      V(I)=17.6*V(I)
      ALPHA(I)=3.1416/180.*ALPHA(I)
      SL(I)=V(I)/R
   10 TL(I)=R*(W*AS*(1.+V(I)/BS)+0.5*CA*RHO*A*V(I)**2+
     *                                W*SIN(ALPHA(I)))
C-----
C     ITERATE MOTOR GEAR RATIO FOR
C     CALCULATING MOTOR SPEED AND TORQUE
C-----
      DO 100 IGM=10,20,2
      GM=0.1*IGM
      DO 20 I=1,2
      SM(I)=GM*SL(I)
   20 TM(I)=TL(I)/GM
```

```
C-----
C     CALCULATE THE MAXIMUM MOTOR DISPLACEMENT
C-----
      DMM=TM(1)/((1.-CFM)*PMAX-CDM*FMU*SM(1))
C-----
C     ITERATE PUMP GEAR RATIO FOR
C     CALCULATING THE PUMP SPEED
C-----
      DO 100 IGP=34,42,4
      GP=0.1*IGP
      SPM=SEM/GP
C-----
C     ITERATE THE MINIMUM MOTOR DISPLACEMENT FOR
C     CALCULATING THE MAXIMUM PUMP DISPLACEMENT
C-----
      DO 100 J=2,18
      DMMIN=0.05*DMM*J
      DPM=DMMIN*SM(2)/SPM
      P(2)=(TM(2)+CDM*FMU*DMM*SM(2))/(DMMIN-CFM*DMM)
      QST=(CSP*DPM+CSM*DMM)/FMU*P(2)
      DPM=(DMMIN*SM(2)+QST)/SPM
C-----
C     CALCULATE THE MAXIMUM FLOW RATE
C-----
      QST=(CSP*DPM+CSM*DMM)/FMU*P(2)
      Q(2)=DMMIN*SM(2)+QST
C-----
C     CALCULATE THE REQUIRED PUMP TORQUE FOR CHECKING
C     IF THE MAXIMUM ENGING TORGUE EXCEED
C-----
      TP(2)=(1.+CFP)*DPM*P(2)+CDP*FMU*DPM*SPM
      P(1)=PMAX
      QST=(CSP*DPM+CSM*DMM)/FMU*P(1)
      Q(1)=DMM*SM(1)+QST
      DP=Q(1)/SPM
      TP(1)=(DP+CFP*DPM)*P(1)+CDP*FMU*DPM*SPM
      TPMAX=AMAX1(TP(1),TP(2))
      TEMAX=TPMAX/GP
C-----
C     WILL ENGINE STALL ?
C-----
      IF(TEMAX .GT. TEFULL) GO TO 100
C-----
C     CALCULATE THE REQUIRED ENGINE HORSEPOWER
C-----
      HPE=SEM*TEMAX/6600.
      IF(INDEX .GT. 0) GO TO 50
C-----
C     PRINT THE RESULTS
C-----
      WRITE(6,30)
   30 FORMAT(1H1,///,9X,'GP',6X,'GM',5X,'DPM',6X,'DMM',5X,'QMAX',
     * 5X,'HPE',/3X,45(1H-))
   50 WRITE(6,60) GP,GM,DPM,DMM,Q(2),HPE
   60 FORMAT(3X,2(F8.1),2(F9.3),2(F8.1))
      INDEX=1
  100 CONTINUE
      STOP
      END
```

G.2 Program for Optimum Operation Search

The program logic was described in section 2.2. The comment statements are self-explanatory.

```
C*********************************************
C*                                           *
C*    PROGRAM FOR OPTIMUM OPERATION SEARCH    *
C*                                           *
C*********************************************
C
C
      DIMENSION EFE(11,10),TAU(11,10),SED(10),TED(11),FTORQ(11)
      REAL INTERP
C-----
C     READ ENGINE PERFORMANCE DATA
C-----
      READ(5,10) ((EFE(I,J),J=1,10),I=1,11)
      READ(5,10) ((TAU(I,J),J=1,10),I=1,11)
   10 FORMAT(10F7.1)
C
      DATA SED/0.,35.,70.,105.,140.,175.,210.,245.,280.,315./
      DATA TED/0.,30.,60.,90.,120.,150.,180.,210.,240.,270.,300./
      DATA FTORQ/0.,120.,264.,294.,300.,300.,297.,273.,243.,210.,
     *           180./
C-----
C     PRINT THE GIVEN TABLES FOR INTERPOLATION
C-----
      WRITE(6,15)
   15 FORMAT(1H1)
      CALL TABLE(EFE,SED,TED,10,11,'ENGINE EFFICIENCY   ','  SE',
     * '  TE',11)
      CALL TABLE(TAU,SED,TED,10,11,'THROTTLE POSITION   ','  SE',
     * '  TE',11)
C-----
C     SPECIFY
C     NUMBER OF GRADE AND SPEED LEVELS IN THE LOAD PLANE
C     NUMBER OF PUMP/MOTOR DISPLACEMENTS TO BE USED IN SEARCHING
C     MAXIMUM VALUES OF LOAD TORQUE & SPEED AND
C     MAXIMUM VALUES OF ENGINE TORQUE & SPEED
C-----
      NG=6
      NS=66
      NP=40
      NM=40
      SEM=315.
      SLM=66.
      TLM=2680.
      SIDLE=70.
      FMAX=4000.
C-----
C     SPECIFY PUMP AND MOTOR SIZES, COEFFICIENTS AND GEAR RATIOS
C-----
      DPM=0.323
      DMM=0.501
      CSP=4.0E-9
      CSM=4.0E-9
      CDP=2.5E 5
      CDM=2.5E 5
      CFP=0.05
      CFM=0.05
```

```
            GP=3.7
            GM=1.5
            RHO=5.75E-6
      C-----
      C     SPECIFY VEHICLE SPECIFICATION
      C-----
            A=2592.
            R=12.
            W=1700.
            AS=0.01
            BS=1760.
            CA=0.35
            RHO=1.12E-7
            ALPHAM=6.843
      C-----
            DR=DMM/DPM
            C1=CSP+DR*CSM
            PF=R*W*AS
            PA=0.5*R*CA*RHO*A
      C-----
      C     INCREASE ROAD GRADE AND CALCULATE LOAD TORQUE
      C-----
            NG1=NG+1
            DO 80 IG=1,NG1
            ALPHA=(IG-1)/FLOAT(NG)*ALPHAM*3.1416/180.
            PG=R*W*SIN(ALPHA)
            J=0
      C-----
      C     INCREASE LOAD SPEED
      C-----
            DO 70 IS=1,NS,2
            SL=IS*SLM/NS
            SM=GM*SL
            V=R*SL
            TL=PF*(1.+V/BS)+PA*V*V+PG
            TM=TL/GM
            ES1=0.0
      C-----
      C     START SEARCHING THE OPTIMUM SYSTEM OPERATION FOR KNOWN
      C            TL AND SL
      C     INCREASE PUMP DISPLACEMENT
      C-----
            DM=1.0
            DMC=DM-CFM
            IM=NM
            DO 30 IP=1,NP
            DP=IP/FLOAT(NP)
            DPC=DP+CFP
      C-----
      C     START DECREASING MOTOR DISPLACEMENT WHEN
      C     PUMP DISPLACEMENT REACHES FULL
      C-----
            IF(IP .NE. NP) GO TO 24
            IM=0
         22 IM=IM+1
            DM=(NM-IM+1)/FLOAT(NM)
            DMC=DM-CFM
            IF(DMC .LE. 0.0) GO TO 30
```

```
C-----
C     COMPUTE THE SYSTEM OPERATING POINTS FOR KNOWN DP & DM
C-----
   24 SP=1./(DMC*DP)*((DMC*DM*DR+C1*CDM)*SM+C1/(PMU*DMM)*TM)
      TP=PMU*DPM/C1*((DPC*DP+C1*CDP)*SP-DPC*DM*DR*SM)
      P=PMU/C1*(DP*SP-DM*DR*SM)
      IF(P .GT. PMAX) GO TO 26
      SE=GP*SP
      TE=TP/GP
      IF(SE .LT. SIDLE) GO TO 26
      IF(SE .GT. SEM) GO TO 26
      IF(TE .LT. 0.0) GO TO 26
      ISE=SE/35.+1
      PERSE=(SE-(ISE-1)*35.)/35.
      TFULL=FTOFG(ISE)+PERSE*(FTOFG(ISE+1)-FTOFG(ISE))
      IF(TE .GT. TFULL) GO TO 26
C-----
C     MONITOR SYSTEM EFFICIENCY AND STORE THE VALUES OF ALL THE
C     SYSTEM VARIABLES CORRESPONDING TO THE PRESENT MAXIMUM
C     SYSTEM EFFICIENCY
C-----
      HPE=SE*TE/6600.
      EE=INTERP(TE,SE,EFE)
      ET=SM/SP*TM/TP
      ES=EE*ET
      IF(ES .LT. ES1) GO TO 26
      ES1=ES
      EE1=EE
      ET1=ET*100.
      TL1=TL
      SL1=SL
      TE1=TE
      SE1=SE
      HPE1=HPE
      DP1=DP*DPM
      DM1=DM*DMM
      P1=P
      Q1=CMM*(DM*SM+CSM/PMU*P)
   26 IF(IM .NE. NM) GO TO 22
   30 CONTINUE
      IF(IS .GT. 1 .AND. ES1 .LE. 0.) GO TO 70
      J=J+1
      XTA=INTERP(TE1,SE1,TAU)
C-----
C     OPTIMUM OPERATION FOUND
C     PRINT THE VALUES OF ALL THE SYSTEM VARIABLES CORRESPONDING
C     TO EACH PAIR OF LOAD TORQUE & LOAD SPEED
C-----
      IF(IS .GT. 1) GO TO 50
      WRITE(6,40)
   40 FORMAT(1H1,///,3X,'I',2X,'J',4X,'SL',5X,'TL',5X,'TE',5X,
     1 'SE',5X,'HP',4X,'DP',5X,'DM',6X,'P',6X,'Q',4X,'TAU',3X,
     2 'EE',4X,'ET',4X,'ES')
      WRITE(6,45)
   45 FORMAT(3X,90(1H-))
   50 WRITE(6,60) IS,J,SL1,TL1,TE1,SE1,HPE1,DP1,DM1,P1,Q1,XTA,
     * EE1,ET1,ES1
   60 FORMAT(1X,2I3,4F7.1,F6.1,2F7.3,F6.1,5F6.1)
```

```
   70 CONTINUE
   80 CONTINUE
      WRITE(6,15)
      STOP
      END
```

```
C-----
C     SUBROUTINE TABLE
C-----
      SUBROUTINE TABLE(TABCAT,X,Y,NX,NY,TITLE,XLAB,YLAB,NROW)
      DIMENSION TABCAT(NROW,1),X(1),Y(1),TITLE(5),XLAB(1),YLAB(1)
      WRITE(6,10) TITLE
   10 FORMAT(1H0,//,45X,5A4//)
      WRITE(6,20) XLAB,(X(J),J=1,NX)
   20 FORMAT(11X,A4,10F7.0)
      WRITE(6,30) YLAB
   30 FORMAT(8X,A4,1X,72(1H-))
      DO 40 I=1,NY
   40 WRITE(6,50) Y(I),(TABCAT(I,J),J=1,NX)
   50 FORMAT(8X,F5.0,2H I,10F7.1)
      RETURN
      END
```

```
C-----
C     FUNCTION INTERP
C-----
      REAL FUNCTION INTERP(X,Y,Z)
      DIMENSION Z(11,1)
      X0=X/30.+1.
      Y0=Y/35.+1.
      IX=X0
      IY=Y0
      FX=X0-IX
      FY=Y0-IY
      Z1=Z(IX,IY)+FY*(Z(IX,IY+1)-Z(IX,IY))
      Z2=Z(IX+1,IY)+FY*(Z(IX+1,IY+1)-Z(IX+1,IY))
      INTERP=Z1+FX*(Z2-Z1)
      RETURN
      END
```

```
I  J    SL     TL      TE      SE     HP    DP     DM       P       C     TAU    EE     ET     ES
-------------------------------------------------------------------------------------------------
1  1    1.0   205.5    7.4    70.1   0.1  0.048  0.501   290.1    0.9    0.5    9.5   39.4    3.7
1  2    3.0   209.0   13.6    74.1   0.2  0.121  0.501   299.5    2.4    1.0    9.8   62.1    6.1
1  3    5.0   213.1   20.7    72.1   0.2  0.202  0.501   309.9    3.9    1.5    9.9   71.4    7.1
1  4    7.0   218.0   28.4    71.3   0.3  0.283  0.501   321.3    5.4    2.0   10.2   75.5    7.7
1  5    9.0   223.6   33.3    79.7   0.4  0.323  0.501   333.6    6.9    2.3   10.6   75.9    8.0
1  6   11.0   229.9   35.1    97.0   0.5  0.323  0.501   347.0    8.4    2.4   11.1   74.3    8.3
1  7   13.0   236.9   39.6   106.1   0.6  0.323  0.463   392.3    9.2    2.8   11.6   73.4    8.5
1  8   15.0   244.6   47.3   106.4   0.8  0.323  0.401   477.1    9.2    3.4   11.9   72.8    8.6
1  9   17.0   253.0   56.2   106.2   0.9  0.323  0.351   574.4    9.1    4.0   12.2   72.0    8.8
1 10   19.0   262.1   65.8   106.7   1.1  0.323  0.313   677.8    9.2    4.5   12.6   71.0    8.9
1 11   21.0   271.9   71.7   113.3   1.2  0.323  0.301   740.2    9.7    4.8   12.9   70.3    9.1
1 12   23.0   282.4   75.1   123.9   1.4  0.323  0.301   773.5   10.6    5.1   13.3   69.8    9.3
1 13   25.0   293.6   82.0   129.3   1.6  0.323  0.288   846.9   11.1    5.4   13.8   69.2    9.5
1 14   27.0   305.6   85.9   139.5   1.8  0.323  0.288   885.3   12.0    5.5   14.2   68.9    9.8
1 15   29.0   318.2   98.4   137.8   2.1  0.323  0.263  1022.9   11.8    6.2   14.7   68.0   10.0
1 16   31.0   331.5  108.2   140.8   2.3  0.323  0.250  1128.7   12.0    6.9   15.2   67.4   10.2
1 17   33.0   345.5  119.4   143.1   2.6  0.323  0.238  1249.2   12.2    7.9   15.7   66.7   10.5
1 18   35.0   360.2  132.0   144.7   2.9  0.323  0.225  1387.0   12.3    9.0   16.4   66.0   10.8
1 19   37.0   375.6  146.6   145.5   3.2  0.323  0.213  1545.7   12.4   10.1   17.1   65.1   11.2
1 20   39.0   391.8  153.2   153.3   3.6  0.323  0.213  1614.4   13.0   11.4   17.8   65.1   11.6
1 21   41.0   408.6  160.0   161.1   3.9  0.323  0.213  1665.6   13.7   12.7   18.5   65.0   12.0
1 22   43.0   426.1  191.2   152.1   4.4  0.323  0.188  2030.0   12.8   14.3   19.9   63.0   12.5
1 23   45.0   444.4  199.5   159.2   4.8  0.323  0.188  2117.9   13.4   16.1   21.1   63.0   13.3
1 24   47.0   463.3  208.1   166.2   5.2  0.323  0.188  2208.7   14.0   18.0   22.4   62.9   14.1
1 25   49.0   482.9  216.9   173.3   5.7  0.323  0.188  2302.4   14.6   20.1   23.9   62.9   15.0
1 26   51.0   503.3  226.0   180.4   6.2  0.323  0.188  2398.9   15.2   22.5   25.5   63.0   16.1
1 27   53.0   524.3  235.4   187.6   6.7  0.323  0.188  2498.3   15.8   25.2   27.5   63.0   17.3
1 28   55.0   546.1  228.3   208.2   7.1  0.323  0.200  2414.9   17.4   27.4   28.7   64.1   18.4
1 29   57.0   568.5  237.6   212.8   7.7  0.323  0.200  2512.5   18.0   31.3   30.4   64.1   19.5
1 30   59.0   591.7  247.0   220.3   8.2  0.323  0.200  2612.9   18.6   39.0   28.2   64.2   18.1
1 31   61.0   615.5  240.5   239.8   8.7  0.323  0.213  2534.8   20.4   41.9   25.5   65.1   16.6
1 32   63.0   640.1  249.8   247.8   9.4  0.323  0.213  2633.4   21.0   53.5   23.1   65.1   15.1
1 33   65.0   665.3  244.1   268.6   9.9  0.323  0.225  2563.6   22.9   62.5   21.0   65.9   13.9
```

I	J	SL	TL	TE	SE	HP	DF	DM	P	C	TAU	EE	ET	ES
3	1	1.0	1017.4	39.8	71.9	0.4	0.081	0.501	1427.4	1.2	2.6	10.5	35.5	3.7
3	2	3.0	1020.9	71.4	70.5	0.8	0.161	0.501	1436.8	2.8	4.0	11.3	60.8	6.9
3	3	5.0	1025.1	88.1	84.1	1.1	0.202	0.501	1447.2	4.3	5.1	12.4	69.2	8.6
3	4	7.0	1030.0	95.8	103.5	1.5	0.218	0.501	1458.6	5.8	6.1	13.6	72.7	9.9
3	5	9.0	1035.6	115.9	105.6	1.9	0.266	0.501	1470.9	7.3	8.0	14.4	76.1	10.9
3	6	11.0	1041.9	139.6	104.4	2.2	0.323	0.501	1434.3	8.8	9.3	15.1	78.6	11.9
3	7	13.0	1048.8	141.5	121.8	2.6	0.323	0.501	1498.6	10.3	9.3	15.9	79.1	12.6
3	8	15.0	1056.5	143.5	139.1	3.0	0.323	0.501	1513.9	11.8	9.3	16.8	79.4	13.3
3	9	17.0	1064.9	153.1	149.6	3.5	0.323	0.476	1615.3	12.7	11.0	17.6	79.0	13.9
3	10	19.0	1074.0	163.9	158.6	3.9	0.323	0.451	1729.6	13.5	12.8	18.6	78.5	14.6
3	11	21.0	1083.9	193.3	153.6	4.5	0.323	0.388	2051.8	12.9	14.7	20.1	76.7	15.4
3	12	23.0	1094.4	202.7	162.6	5.0	0.323	0.376	2151.2	13.7	16.9	21.6	76.4	16.5
3	13	25.0	1105.6	212.9	170.9	5.5	0.323	0.363	2259.3	14.4	19.3	23.3	76.0	17.7
3	14	27.0	1117.5	232.5	173.1	6.1	0.323	0.338	2472.3	14.6	22.0	25.3	75.0	19.0
3	15	29.0	1130.1	236.0	185.0	6.6	0.323	0.338	2506.1	15.6	24.7	27.2	75.1	20.5
3	16	31.0	1143.4	239.6	196.8	7.1	0.323	0.338	2541.3	16.6	27.8	29.4	75.2	22.1
3	17	33.0	1157.4	243.4	208.7	7.7	0.323	0.338	2578.1	17.6	32.3	30.5	75.2	22.9
3	18	35.0	1172.2	247.3	220.6	8.3	0.323	0.338	2616.3	18.7	39.3	28.1	75.2	21.1
3	19	37.0	1187.6	251.3	232.4	8.9	0.323	0.338	2656.1	19.7	47.5	25.5	75.2	19.2
3	20	39.0	1203.7	246.3	252.0	9.4	0.323	0.351	2593.6	21.4	53.2	22.9	75.6	17.4
3	21	41.0	1220.5	250.5	264.4	10.0	0.323	0.351	2634.6	22.5	62.3	20.9	75.6	15.8

```
I  J     SL      TL       TE       SE      HP     DP      DM       P       G    TAU   EE    ET    ES
-------------------------------------------------------------------------------------------------------
5  1     1.0  1828.1     92.0     72.7    1.0  0.113   0.501   2562.8    1.6    5.1  12.0  27.4   3.3
5  2     3.0  1831.5    110.1    100.5    1.7  0.137   0.501   2572.2    3.2    7.4  13.9  49.7   6.9
5  3     5.0  1835.7    144.5    104.3    2.3  0.186   0.501   2582.6    4.7    9.5  15.3  60.9   9.3
5  4     7.0  1840.6    173.6    110.4    2.9  0.226   0.501   2594.0    6.2   10.5  16.4  67.2  11.0
5  5     9.0  1846.2    191.9    122.1    3.5  0.250   0.501   2606.4    7.7   12.0  17.8  71.0  12.6
5  6    11.0  1852.5    204.7    135.6    4.2  0.266   0.501   2619.8    9.2   13.5  19.4  73.4  14.2
5  7    13.0  1859.5    212.1    152.0    4.9  0.275   0.501   2634.1   10.7   16.2  21.3  75.0  16.0
5  8    15.0  1867.2    219.6    167.5    5.6  0.283   0.501   2649.4   12.2   19.6  23.5  76.2  17.9
5  9    17.0  1875.6    232.9    177.1    6.3  0.299   0.501   2665.7   13.7   22.7  25.9  77.3  20.0
5 10    19.0  1884.7    240.7    190.7    7.0  0.307   0.501   2683.0   15.2   26.9  28.5  78.0  22.2
5 11    21.0  1894.5    242.9    209.0    7.7  0.307   0.501   2701.3   16.7   32.1  30.6  78.4  24.0
5 12    23.0  1905.0    256.7    215.9    8.4  0.323   0.501   2720.5   18.2   42.8  27.3  79.1  21.6
5 13    25.0  1916.2    259.1    233.2    9.2  0.323   0.501   2740.8   19.7   53.9  24.3  79.3  19.3
5 14    27.0  1928.1    261.7    250.6    9.9  0.323   0.501   2762.0   21.3   63.8  21.6  79.4  17.1
```

```
I  J     SL      TL       TE       SE      HP     DP      DM       P       G    TAU   EE    ET    ES
-------------------------------------------------------------------------------------------------------
7  1     1.0  2036.1    124.4    101.1    1.9  0.105   0.501   3694.7    2.0    8.5  14.4  21.0   3.0
7  2     3.0  2039.6    173.3    105.6    2.8  0.153   0.501   3704.1    3.5   10.4  16.2  43.3   7.0
7  3     5.0  2043.8    158.7    122.6    3.7  0.178   0.501   3714.5    5.1   12.5  18.1  54.3   9.8
7  4     7.0  2048.7    208.3    147.3    4.7  0.186   0.501   3725.9    6.6   15.0  20.6  60.4  12.4
7  5     9.0  2054.3    225.0    163.2    5.6  0.202   0.501   3738.3    8.1   19.7  23.5  64.8  15.2
7  6    11.0  2060.6    235.5    183.6    6.5  0.210   0.501   3751.6    9.6   24.4  27.0  67.7  18.3
7  7    13.0  2067.6    237.3    210.2    7.6  0.210   0.501   3766.0   11.1   30.3  30.8  69.5  21.4
7  8    15.0  2075.3    255.0    219.9    8.5  0.226   0.501   3781.3   12.6   43.9  27.0  71.5  19.3
7  9    17.0  2083.7    273.0    228.4    9.4  0.242   0.501   3797.6   14.1   60.1  23.1  73.2  [illegible]
```

G.3 Program for Highest System Frequency Calculation

This program is coded for calculating the highest frequency of the engine-HST system model (refer to Chapter VII). The definitions of the derived coefficients used in the program were presented in Table XIII.

```
C***************************************************************
C*                                                             *
C*      PROGRAM FOR HIGHEST SYSTEM FREQUENCY CALCULATION       *
C*                                                             *
C***************************************************************
C
C
      REAL JC,MC,K1,K2,K3,KY,KP,KM
      DIMENSION ALPHA0(35),SEO(35),DPO(35),DMO(35),FO(35),VO(35),
     1 CA(6),CB(5),CD(4),COFA(6),COFB(5),COFD(4),ROCTRA(5),
     2 ROCTIA(5),ROCTRB(4),ROCTIB(4),ROCTRD(3),ROCTID(3),FREQ(12)
C-----
C     SPECIFY ORDERS OF POLYNOMIALS AND
C             NUMBER OF OPERATING POINTS
C-----
      MA=5
      MB=4
      MD=3
      NP=31
      MAB=MA+MB
      MABC=MAB+MD
C-----
C     SPECIFY SYSTEM CONSTANTS AND PARAMETERS
C-----
      GP=3.7
      GM=1.5
      DPM=0.323
      DMM=0.501
      CSP=4.E-9
      CSM=4.E-9
      CFP=0.05
      CFM=0.05
      CDP=2.5E5
      CDM=2.5E5
      PMU=5.75E-6
      RHC=1.12E-7
      B=2.2E5
      VOL=24.43
      JC=0.18
      K1=455.37
      K2=0.94
      K3=10.9
      W=1700.
      MC=4.533
      A=2592.
      R=12.
      AS=0.01
      BS=1760.
      CA=0.35
      TY=8.E-3
      TD=79.0E-3
      KY=12.22
      KP=3.23
      KM=5.01
C-----
C     SPECIFY INITIAL STEADY STATE OPERATING CONDITIONS
C-----
```

```
      READ(5,10) (ALPHAO(K),SEO(K),DFO(K),DMO(K),PO(K),VO(K),
     *                                                      K=1,NF)
   10 FORMAT(6F10.3)
C
      WRITE(6,20)
   20 FORMAT(1H1,///,7X,'ALPHAI',4X,'SEI',6X,'DFI',6X,'DMI',7X,
     * 'PI',8X,'VI',6X,'FMAX',/,7X,60(1H-))
C
      DO 80 K=1,NF
      ALPHAI=ALPHAO(K)
      SEI=SEO(K)
      DFI=DFO(K)
      DMI=DMO(K)
      PI=PO(K)
      VI=VO(K)
C-----
C     CALCULATE DERIVED AND TRANSFER FUNCTION COEFFICIENTS .
C-----
      TI=K3/SEI
      SPI=SEI/GP
      SMI=GM/R*VI
      ALPHAI=0.017453*ALPHAI
      E1=DFI+CFP*DFM
      E2=DMI-CFM*DMM
      E3=CDP*PMU*DFM
      E4=CDM*PMU*DMM
      E5=VCL/B
      E6=(CSP*DFM+CSM*DMM)/PMU
      E7=W*AS/BS+CA*RHO*A*VI
      E8=W*COS(ALPHAI)
      E9=K2+E3/GP/GP
      E10=E7+E4*(GM/R)**2
      E11=E6*R/GM
      E12=E5*E9+E6*JC
      E13=E6*E9+E1*DFI/GP/GP
      E14=E9*SPI-PI*DFI/GP/GP
      E15=E2*GM*DMI/R
      E16=E2*K1*DFI/GP
      E17=E5*JC*MC*R/GM
      E18=R/GM*(E12*MC+E5*E10*JC)
      E19=R/GM*(E13*MC+E10*E12+E15*JC*GM/R)
      E20=R/GM*(E10*E13+E9*E15*GM/R)
      E21=E2*JC*SPI
      E22=E2*E14
      E23=E5*JC*PI
      E24=E12*PI-E2*JC*SMI
      E25=E13*PI-E2*E9*SMI
      E26=E5*E11*JC
      E27=E11*E12
      E28=E11*E13
      E29=E16*KY
      E30=E17*TY
      E31=E18*TY+E17
      E32=E19*TY+E18
      E33=E20*TY+E19
      DA(1)=E20
      DA(2)=E20*TI+E33
      DA(3)=E33*TI+E32
```

```
      DA(4)=E32*TI+E31
      DA(5)=E31*TI+E30
      DA(6)=E30*TI
      DB(1)=E20
      DB(2)=E20*TD+E19
      DB(3)=E19*TD+E18
      DB(4)=E18*TD+E17
      DB(5)=E17*TD
      DD(1)=E20
      DD(2)=E19
      DD(3)=E18
      DD(4)=E17
C-----
C     COMPUTE THE ROOTS OF CHARACTERISTIC EQUATIONS
C-----
      CALL POLRT(DA,COFA,MA,ROOTRA,ROOTIA,IERA)
      CALL POLRT(DB,COFB,MB,ROOTRB,ROOTIB,IERB)
      CALL POLRT(DD,COFD,MD,ROOTRD,ROOTID,IERD)
C-----
C     IS THERE ANY ERROR ?
C-----
      IF(IERA .GT. 0) GO TO 90
      IF(IERB .GT. 0) GO TO 90
      IF(IERD .GT. 0) GO TO 90
C-----
C     CALCULATE THE CHARACTERISTIC FREQUENCIES
C-----
      DO 30 I=1,MA
   30 FREQ(I)=SQRT(ROOTRA(I)**2+ROOTIA(I)**2)
      DO 40 I=1,MB
      N1=MA+I
   40 FREQ(N1)=SQRT(ROOTRB(I)**2+ROOTIB(I)**2)
      DO 50 I=1,MD
      N2=MAB+I
   50 FREQ(N2)=SQRT(ROOTRD(I)**2+ROOTID(I)**2)
C-----
C     SEARCH THE HIGHEST FREQUENCY
C-----
      FMAX=FREQ(1)
      DO 60 I=2,MABD
   60 IF(FREQ(I) .GT. FMAX) FMAX=FREQ(I)
      FMAX=FMAX/6.283
C-----
C     PRINT INITIAL CONDITIONS AND THE HIGHEST FREQUENCY
C-----
      WRITE(6,70) ALPHAC(K),SEI,DFI,CMI,FI,VI,FMAX
   70 FORMAT(8X,F4.2,4X,F5.1,2(4X,F5.3),4X,F6.1,2(4X,F5.1))
   80 CONTINUE
      GO TO 110
C-----
C     PRINT ERROR MESSAGES
C-----
   90 WRITE(6,100) IERA,IERB,IERD
  100 FORMAT(3X,'IERA=',I3,'IERB=',I3,'IERD=',I3)
  110 STOP
      END
```

G.4 Program for Controller Parameters Adjustment

This program is used for PI controller parameters adjustment. A brief description of the main program and key subroutines follows.

Main Program

This program is used to read engine performance data, information pertinent to HST, e.g. pump, motor displacements, coefficients and parameters, etc., and vehicle specification data. It is also used to read the number of independent variables which will be optimized, side length and initial estimate of the starting simplex, penalty parameter, implicit constraint and the maximum iteration times for minimization process use. The program specifies the numbers of algebraic and state variables, the lengths of arrays XS and YS, and the number of bit for A/D and D/A converters. Sampling time interval and integration control parameters, namely, step size, final time also read in this program. System parameters used in subroutine F are evaluated in this program before the subroutine NELMIN is called.

NELMIN

This subroutine is used for the minimization of a function of N variables. which depends on the comparison of function values at the (N+1) vertices of a general simplex, followed by a replacement of the vertex with the highest value by another point. The simplex adapts itself to the local landscape, and contracts on the final minimum. The program logic has been described in Appendix E.

In the subroutine the reflection, contraction and expansion coefficients are set at 1.0, 0.5 and 2.0 respectively. These are the values recommended by Neldel and Mead [29] as being best for a general situation.

Subroutine FUNC called by this routine, specifies the objective function. The procedure will be terminated if the number of iterations has exceeded the upper limit ITMAX.

The routine prints out values of parameters, intermediate results and the optimum values of the independent variables obtained on the last iteration.

FUNC

This subroutine is used to calculate the objective function at each acceptable vertex of the simplex. It sets up the initial conditions and adjusts the controller parameters before starting integration. The subroutine specifies a pertinent variable value returned from subroutine INTGRL for the objective function and returns it to routine NELMIN.

The implicit constraint is tested in this routine. If the constraint is violated, the objective function is modified to incorporate the influence of constraint by using the penalty function technique [31], which would deflect the trajectories toward the feasible domain.

Other subprograms, i.e., INTGRL, F, PIC, YSHIFT, FG, etc. are the same as those for program 5.

```
              C*****************************************************************
              C*                                                               *
              C*     PROGRAM FOR CONTROLLER PARAMETERS ADJUSTMENT              *
              C*                                                               *
              C*****************************************************************
              C
              C
ISN 0002            REAL MC,ITAE,MITAE
              C
ISN 0003            DIMENSION THROT(21),START(4),DEL(4)
              C
ISN 0004            COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),
                   1P(40),XS(80),YS(40),TS,H,YDELAY,ITAE,MITAE,PP,
                   2KEEP,IEND,NXS,NYS,NBIT,NX,NY
              C-----
              C     READ ENGINE PERFORMANCE DATA
              C-----
ISN 0005            READ(5,10) ((EDATA1(I,J),J=1,15),I=1,9)
ISN 0006         10 FORMAT(15F5.1)
ISN 0007            READ(5,12) ((EDATA2(I,J),J=1,10),I=1,11)
ISN 0008         12 FORMAT(10F7.1)
ISN 0009            READ(5,14) (THROT(I),OPTE1(I),I=1,21)
ISN 0010         14 FORMAT(2F10.3)
              C-----
              C     SPECIFY HST SIZES, COEFFICIENTS AND PARAMETERS
              C-----
ISN 0011            DPM=0.323
ISN 0012            DMM=0.501
ISN 0013            CSP=4.0E-9
ISN 0014            CSM=4.0E-9
ISN 0015            CDP=2.5E5
ISN 0016            CDM=2.5E5
ISN 0017            CFP=0.05
ISN 0018            CFM=0.05
ISN 0019            PMU=5.75E-6
ISN 0020            B=2.2E5
ISN 0021            VOL=12.2
              C-----
              C     SPECIFY VEHICLE SPECIFICATION DATA
              C-----
ISN 0022            MC=4.533
ISN 0023            W=1700.
ISN 0024            A=2592.
ISN 0025            AS=0.01
ISN 0026            CA=0.35
ISN 0027            RHO=1.122E-7
ISN 0028            ALPHA=0.
ISN 0029            VCMAX=45.
              C-----
              C     SPECIFY NUMBER OF VARIABLES, COORDINATES OF STARTING POINT,
              C               AND SIDE LENGTHS OF THE INITIAL SIMPLEX,
              C               ALLOWABLE PERFORMANCE INDEX, PENALTY PARAMETER,
              C               MAXIMUM ITERATION TIMES FOR MINIMIZATION PROCESS
              C-----
ISN 0030            NV=4
ISN 0031            READ(5,16) (START(I), I=1,NV)
ISN 0032            READ(5,16) (DEL(I),I=1,NV)
ISN 0033         16 FORMAT(4F10.5)
```

```
ISN 0034          PP=0.001
ISN 0035          MITAE=3.2E4
ISN 0036          ITMAX=18
               C-----:
               C      SPECIFY THE NUMBER OF ALGEBRAIC VARIABLES,
               C              THE NUMBER OF STATE VARIABLES,
               C              THE LENGTH OF ARRAY XS, USED BY DELAY,
               C              THE LENGTH OF ARRAY YS, USED BY YSHIFT,
               C              THE NUMBER OF BITS FOR A/D AND D/A CONVERTERS
               C-----:
ISN 0037          NX=38
ISN 0038          NY=9
ISN 0039          NXS=80
ISN 0040          NYS=40
ISN 0041          NBIT=12
               C-----:
               C      SPECIFY SAMPLING INTERVAL AND INTEGRATION
               C      CONTROL PARAMETERS
               C----
ISN 0042          TS=0.004
ISN 0043          H=0.002
ISN 0044          TF=150.
ISN 0045          IEND=TF/H+.5
               C-----:
               C      SPECIFY, CALCULATE SYSTEM PARAMETERS
               C-----:
ISN 0046          P(1)=3.7
ISN 0047          P(2)=1.5
ISN 0048          P(3)=12.
ISN 0049          P(4)=CFP*DPM
ISN 0050          P(5)=CDP*PMU*DPM
ISN 0051          P(6)=AS*W
ISN 0052          P(7)=1760.
ISN 0053          P(8)=0.5*CA*RHO*A
ISN 0054          P(9)=W*SIN(0.01745 3*ALPHA)
ISN 0055          P(10)=17.6*VCMAX/P(3)
ISN 0056          P(11)=66.
ISN 0057          P(12)=70.
ISN 0058          P(13)=315.
ISN 0059          P(14)=2680.
ISN 0060          P(15)=300.
ISN 0061          P(20)=0.1575
ISN 0062          P(21)=0.
ISN 0063          P(22)=DPM
ISN 0064          P(23)=DMM
ISN 0065          P(24)=CFM*DMM
ISN 0066          P(25)=CDM*PMU*DMM
ISN 0067          P(26)=8.0E-3
ISN 0068          P(27)=79.6E-3
ISN 0069          P(28)=B/VOL
ISN 0070          P(29)=(CSP*DPM+CSM*DMM)/PMU
ISN 0071          P(30)=0.6
ISN 0072          P(31)=P(6)/P(7)
ISN 0073          P(32)=MC*P(3)
ISN 0074          P(33)=10.9
ISN 0075          P(34)=0.167
               C-----:
ISN 0076          CALL NELMIN(NV,DEL,START,ITMAX)
ISN 0077          STOP
ISN 0078          END
```

```
                C-----:
                C       SUBROUTINE NELMIN
                C-----:
ISN 0002                SUBROUTINE NELMIN(N,DEL,START,ITMAX)
ISN 0003                REAL ITAE,MITAE
                C
ISN 0004                DIMENSION X(5,4),XCEN(5,4),XREF(5,4),XCON(5,4),XEXT(5,4),
                       1 Z(5),AX(5,4),AXCEN(5,4),AXREF(5,4),AXCON(5,4),AXEXT(5,4),
                       2 START(1),DEL(1),AITAE(5)
                C
ISN 0005                COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),
                       1P(40),XS(80),YS(40),TS,H,YDELAY,ITAE,MITAE,PP,
                       2KEEP,IEND,NXS,NYS,NBIT,NX,NY
                C
ISN 0006                DATA ALFA,BETA,GAMA/1.,.5,2./
ISN 0007                NP1=N+1
ISN 0008                ITR=0
ISN 0009                IEVAL=0
                C-----:
                C       CONSTRUCTION OF STARTING SIMPLEX
                C-----:
ISN 0010                DO 20 J=1,N
ISN 0011                TEMP=START(J)
ISN 0012                DO 20 I=1,NP1
ISN 0013             20 X(I,J)=TEMP
ISN 0014                DO 30 I=1,N
ISN 0015             30 X(I,I)=X(I,I)+DEL(I)
                C-----:
                C       PRINT PARAMETERS
                C-----:
ISN 0016                WRITE(6,70)
ISN 0017             70 FORMAT(/,3X,'PARAMETERS')
ISN 0018                WRITE(5,80) N,(I,DEL(I),I=1,N),ALFA,BETA,GAMA
ISN 0019             80 FORMAT(/,3X,'N=',I2,/4(3X,'DEL(',I1,')=',F5.2),/,3X,
                       * 'ALPHA=',F3.1,4X,'BETA=',F3.1,4X,'GAMMA=',F3.1)
ISN 0020                WRITE(6,90) PP,MITAE
ISN 0021             90 FORMAT(3X,'PP=',1PE9.2,4X,'MITAE=',E9.2)
                C-----:
                C       EVALUATE THE OBJECTIVE FUNCTION AT EACH POINT
                C
                C       DETERMINE THE BEST AND THE WORST POINTS
                C-----:
ISN 0022                DO 55 I=1,NP1
ISN 0023                CALL FUNC(I,X,Z(I))
ISN 0024                AITAE(I)=ITAE
ISN 0025                IEVAL=IEVAL+1
ISN 0026             55 CONTINUE
ISN 0027            130 ZLO=Z(1)
ISN 0028                ZHI=Z(1)
ISN 0029                L=1
ISN 0030                K=1
ISN 0031                DO 140 I=2,NP1
ISN 0032                IF(Z(I) .GE. ZLO) GO TO 135
```

```
ISN 0034          ZLO=Z(I)
ISN 0035          L=1
ISN 0036      135 IF(Z(I) .LE. ZHI) GO TO 140
ISN 0038          ZHI=Z(I)
ISN 0039          K=I
ISN 0040      140 CONTINUE
ISN 0041          ITR=ITR+1
            C-----
            C     PRINT THE INTERMEDIATE RESULTS
            C-----
ISN 0042          WRITE(5,150) ITR,IEVAL
ISN 0043      150 FORMAT(//,3X,'ITERATION NUMBER',I3,'      EVALUATION ',
                 * 'NUMBER',I3)
ISN 0044          DO 160 J=1,NP1
ISN 0045      160 WRITE(5,165) (J,I,X(J,I), I=1,N)
ISN 0046      165 FORMAT(/,4(3X,'X(',I1,',',I1,') =',F6.2))
ISN 0047          DO 170 I=1,NP1
ISN 0048      170 WRITE(6,180) I,Z(I),I,AITAE(I)
ISN 0049      180 FORMAT(/,3X,'F(',I1,') =',1PE10.3,5X,'ITAE(',I1,') =',
                 * 1PE10.3)
            C-----
            C     HAS THE SPECIFIED NUMBER OF ITERATIONS REACHED ?
            C-----
ISN 0050          IF(ITR.GE.ITMAX) GO TO 400
            C-----
            C     CALCULATE THE CENTROID OF THE SIMPLEX VERTICES
            C     EXCEPTING THE WORST POINT
            C-----
ISN 0052          DO 220 J=1,N
ISN 0053          SUM=0.
ISN 0054          DO 210 I=1,NP1
ISN 0055          IF(I.EQ.K) GO TO 210
ISN 0057          SUM=SUM+X(I,J)
ISN 0058      210 CONTINUE
ISN 0059          XCEN(K,J)=SUM/FLOAT(N)
ISN 0060      220 AXCEN(K,J)=ABS(XCEN(K,J))
            C-----
            C     REFLECTION THROUGH THE CENTROID
            C-----
ISN 0061          DO 240 J=1,N
ISN 0062          XREF(K,J)=XCEN(K,J)+ALFA*(XCEN(K,J)-X(K,J))
ISN 0063      240 AXREF(K,J)=ABS(XREF(K,J))
ISN 0064          CALL FUNC(K,AXREF,Y)
ISN 0065          ZREF=Y
ISN 0066          RITAE=ITAE
ISN 0067          IEVAL=IEVAL+1
            C-----
            C     EXTENSION, RETAIN REFLECTION OR CONTRACTION ?
            C-----
ISN 0068          IF(ZREF.LT.Z(L)) GO TO 355
ISN 0070          J=0
ISN 0071          DO 250 I=1,NP1
ISN 0072          IF(Z(I) .GT. ZREF ) J=J+1
ISN 0074      250 CONTINUE
ISN 0075          IF(J .EQ. 0) GO TO 260
ISN 0077          IF(J .GT. 1) GO TO 365
            C-----
            C     CONTRACTION ON THE REFLECTION SIDE OF THE CENTROID
```

```
                C-----
ISN 0079              DO 255 J=1,N
ISN 0080          255 X(K,J)=XREF(K,J)
                C-----
                C     CONTRACTION ON THE WORST POINT SIDE OF THE CENTROID
                C-----
ISN 0081          260 DO 270 J=1,N
ISN 0082              XCON(K,J)=XCEN(K,J)+BETA*(X(K,J)-XCEN(K,J))
ISN 0083          270 AXCON(K,J)=ABS(XCON(K,J))
ISN 0084              CALL FUNC(K,AXCON,Y)
ISN 0085              ZCON=Y
ISN 0086              CITAE=ITAE
ISN 0087              IEVAL=IEVAL+1
ISN 0088              IF(ZCON.LE.Z(K)) GO TO 340
                C-----
                C     CONTRACT WHOLE SIMPLEX
                C-----
ISN 0090              DO 320 J=1,N
ISN 0091              DO 320 I=1,NP1
ISN 0092              X(I,J)=(X(I,J)+X(L,J))*0.5
ISN 0093          320 AX(I,J)=ABS(X(I,J))
ISN 0094              DO 330 I=1,NP1
ISN 0095              IF(I .EQ. L) GO TO 330
ISN 0097              CALL FUNC(I,AX,Z(I))
ISN 0098              AITAE(I)=ITAE
ISN 0099              IEVAL=IEVAL+1
ISN 0100          330 CONTINUE
ISN 0101              GO TO 130
ISN 0102          340 DO 350 J=1,N
ISN 0103          350 X(K,J)=XCON(K,J)
ISN 0104              Z(K)=ZCON
ISN 0105              AITAE(K)=CITAE
ISN 0106              GO TO 130
                C-----
                C     SUCCESSFUL REFLECTION, SO EXTENSION
                C-----
ISN 0107          355 DO 360 J=1,N
ISN 0108              XEXT(K,J)=XCEN(K,J)+GAMA*(XREF(K,J)-XCEN(K,J))
ISN 0109          360 AXEXT(K,J)=ABS(XEXT(K,J))
ISN 0110              CALL FUNC(K,AXEXT,Y)
ISN 0111              ZEXT=Y
ISN 0112              EITAE=ITAE
ISN 0113              IEVAL=IEVAL+1
                C-----
                C     RETAIN EXTENSION OR REFLECTION ?
                C-----
ISN 0114              IF(ZEXT.LT.ZREF) GO TO 380
ISN 0116          365 DO 370 J=1,N
ISN 0117          370 X(K,J)=XREF(K,J)
ISN 0118              Z(K)=ZREF
ISN 0119              AITAE(K)=RITAE
ISN 0120              GO TO 130
                C-----
                C     RETAIN EXTENSION
                C-----
ISN 0121          380 DO 390 J=1,N
ISN 0122          390 X(K,J)=XEXT(K,J)
ISN 0123              Z(K)=ZEXT
```

```
ISN 0124              AITAE(K)=EITAE
ISN 0125              GO TO 130
                C-----
                C     PRINT THE OPTIMUM VALUES OF THE FUNCTION AND VARIABLES
                C-----
ISN 0126          400 WRITE(6,430) ITR,ZLO
ISN 0127          430 FORMAT(//,3X,'AFTER ',I2,' ITERATIONS,',
                     *//,3X,'THE IMPROVED VALUE OF F =',1PE10.3)
ISN 0128              WRITE(6,440)
ISN 0129          440 FORMAT(/,3X,'IMPROVED VALUES OF VARIABLES')
ISN 0130              DO 450 I=1,N
ISN 0131          450 WRITE(6,460) I,X(L,I)
ISN 0132          460 FORMAT(/,3X,'X(',I1,') =',F6.2)
ISN 0133              RETURN
ISN 0134              END
```

```
                    C------
                    C      SUBROUTINE FUNC
                    C------
ISN 0002                   SUBROUTINE FUNC(I,X,Y)
ISN 0003                   REAL ITAE,MITAE
                    C
ISN 0004                   DIMENSION X(5,1), XO(38),YO(9),T(251),XP(251,38), YP(251,9)
                    C
ISN 0005                   COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),
                          1P(40),XS(80),YS(40),TS,H,YDELAY,ITAE,MITAE,PP,
                          2KEEP,IEND,NXS,NYS,NBIT,NX,NY
                    C------
                    C      SET UP INITIAL CONDITIONS
                    C------
ISN 0006                   DO 10 J=1,NX
ISN 0007                10 XO(J)=0.
ISN 0008                   DO 20 J=1,NY
ISN 0009                20 YO(J)=0.
ISN 0010                   XO(16)=P(20)
ISN 0011                   XO(17)=P(20)
ISN 0012                   YO(1)=P(34)
ISN 0013                   YO(5)=18.92
ISN 0014                   YDELAY=P(34)
ISN 0015                   DO 30 J=1,NXS
ISN 0016                30 XS(J)=P(34)
ISN 0017                   DO 40 J=1,NYS
ISN 0018                40 YS(J)=0.1357
                    C------
                    C      ADJUST CONTROLLER PARAMETERS
                    C------
ISN 0019                   P(16)=X(I,1)
ISN 0020                   P(17)=X(I,2)
ISN 0021                   P(18)=X(I,3)
ISN 0022                   P(19)=X(I,4)
                    C------
ISN 0023                   CALL INTGRL(XO,YO,T,XP,YP)
                    C------
                    C      CHECK AGAINST EXPLICIT CONSTRAINT
                    C------
ISN 0024                   ITAE=YP(250,9)
ISN 0025                   IF(ITAE .GT. MITAE) GO TO 50
                    C------
                    C      OUTPUT  OBJECTIVE FUNCTION VALUE
                    C------
ISN 0027                   Y=YP(250,7)/YP(250,8)
ISN 0028                   RETURN
                    C------
                    C      CONSTRAINT IS VIOLATED, OUTPUT PENALTY FUNCTION VALUE
                    C------
ISN 0029                50 Y=YP(250,7)/YP(250,8)+PP*(ITAE-MITAE)**2
ISN 0030                   RETURN
ISN 0031                   END
```

```
PARAMETERS

N= 4
DEL(1)= 0.03    DEL(2)= 1.10    DEL(3)= 0.68    DEL(4)=-0.34
ALPHA=1.0     BETA=0.5     GAMMA=2.0
PP= 1.00E-03     MITLE= 3.20E+04

ITERATION NUMBER  1.      EVALUATION NUMBER  5

X(1,1) =  0.35   X(1,2) = 18.20   X(1,3) =   1.00   X( 1,4) =   5.00

X(2,1) =  0.33   X(2,2) = 19.30   X(2,3) =   1.00   X( 2,4) =   5.00

X(3,1) =  0.33   X(3,2) = 18.20   X(3,3) =   1.68   X( 3,4) =   5.00

X(4,1) =  0.33   X(4,2) = 18.20   X(4,3) =   1.00   X( 4,4) =   4.66

X(5,1) =  0.33   X(5,2) = 18.20   X(5,3) =   1.00   X( 5,4) =   5.00

F(1) = 4.750E+00      ITAE(1) = 2.856E+04

F(2) = 4.708E+00      ITAE(2) = 3.013E+04

F(3) = 4.744E+00      ITAE(3) = 2.857E+04

F(4) = 4.737E+00      ITAE(4) = 2.880E+04

F(5) = 4.747E+00      ITAE(5) = 2.877E+04

ITERATION NUMBER  2.      EVALUATION NUMBER  6

X(1,1) =  0.30   X(1,2) = 18.75   X(1,3) =   1.34   X( 1,4) =   4.83

X(2,1) =  0.33   X(2,2) = 19.30   X(2,3) =   1.00   X( 2,4) =   5.00

X(3,1) =  0.33   X(3,2) = 18.20   X(3,3) =   1.68   X( 3,4) =   5.00

X(4,1) =  0.33   X(4,2) = 18.20   X(4,3) =   1.00   X( 4,4) =   4.66

X(5,1) =  0.33   X(5,2) = 18.20   X(5,3) =   1.00   X( 5,4) =   5.00

F(1) = 4.718E+00      ITAE(1) = 2.955E+04

F(2) = 4.708E+00      ITAE(2) = 3.013E+04

F(3) = 4.744E+00      ITAE(3) = 2.857E+04

F(4) = 4.737E+00      ITAE(4) = 2.880E+04

F(5) = 4.747E+00      ITAE(5) = 2.877E+04

ITERATION NUMBER  3.      EVALUATION NUMBER  8

X(1,1) =  0.30   X(1,2) = 18.75   X(1,3) =   1.34   X( 1,4) =   4.83

X(2,1) =  0.33   X(2,2) = 19.30   X(2,3) =   1.00   X( 2,4) =   5.00

X(3,1) =  0.33   X(3,2) = 18.20   X(3,3) =   1.68   X( 3,4) =   5.00

X(4,1) =  0.33   X(4,2) = 18.20   X(4,3) =   1.00   X( 4,4) =   4.66
```

```
X(5,1) =  0.31   X(5,2) = 19.44   X(5,3) =  1.76   X( 5,4) =  4.62

F(1) = 4.718E+00      ITAE(1) = 2.955E+04

F(2) = 4.708E+00      ITAE(2) = 3.013E+04

F(3) = 4.744E+00      ITAE(3) = 2.857E+04

F(4) = 4.737E+00      ITAE(4) = 2.880E+04

F(5) = 4.687E+00      ITAE(5) = 3.037E+04

ITERATION NUMBER  4,      EVALUATION NUMBER 10

X(1,1) =  0.30   X(1,2) = 18.75   X(1,3) =  1.34   X( 1,4) =  4.83

X(2,1) =  0.33   X(2,2) = 19.30   X(2,3) =  1.00   X( 2,4) =  5.00

X(3,1) =  0.30   X(3,2) = 19.64   X(3,3) =  0.87   X( 3,4) =  4.55

X(4,1) =  0.33   X(4,2) = 18.20   X(4,3) =  1.00   X( 4,4) =  4.66

X(5,1) =  0.31   X(5,2) = 19.44   X(5,3) =  1.76   X( 5,4) =  4.62

F(1) = 4.718E+00      ITAE(1) = 2.955E+04

F(2) = 4.708E+00      ITAE(2) = 3.013E+04

F(3) = 4.683E+00      ITAE(3) = 3.087E+04

F(4) = 4.737E+00      ITAE(4) = 2.880E+04

F(5) = 4.687E+00      ITAE(5) = 3.037E+04

ITERATION NUMBER  5,      EVALUATION NUMBER 12

X(1,1) =  0.30   X(1,2) = 18.75   X(1,3) =  1.34   X( 1,4) =  4.83

X(2,1) =  0.33   X(2,2) = 19.30   X(2,3) =  1.00   X( 2,4) =  5.00

X(3,1) =  0.30   X(3,2) = 19.64   X(3,3) =  0.87   X( 3,4) =  4.55

X(4,1) =  0.32   X(4,2) = 18.74   X(4,3) =  1.12   X( 4,4) =  4.71

X(5,1) =  0.31   X(5,2) = 19.44   X(5,3) =  1.76   X( 5,4) =  4.62

F(1) = 4.718E+00      ITAE(1) = 2.955E+04

F(2) = 4.708E+00      ITAE(2) = 3.013E+04

F(3) = 4.683E+00      ITAE(3) = 3.087E+04

F(4) = 4.718E+00      ITAE(4) = 2.947E+04

F(5) = 4.687E+00      ITAE(5) = 3.037E+04
```

(Skip 9 iterations)

```
ITERATION NUMBER 15,      EVALUATION NUMBER 30
X(1,1) =  0.28   X(1,2) = 20.27   X(1,3) =  1.69   X( 1,4) =  4.23
X(2,1) =  0.25   X(2,2) = 19.94   X(2,3) =  1.97   X( 2,4) =  4.06
X(3,1) =  0.27   X(3,2) = 20.13   X(3,3) =  2.14   X( 3,4) =  4.25
X(4,1) =  0.28   X(4,2) = 20.02   X(4,3) =  1.75   X( 4,4) =  4.45
X(5,1) =  0.28   X(5,2) = 19.92   X(5,3) =  1.89   X( 5,4) =  4.29
F(1) = 4.644E+00      ITAE(1) = 3.197E+04
F(2) = 4.657E+00      ITAE(2) = 3.152E+04
F(3) = 4.652E+00      ITAE(3) = 3.169E+04
F(4) = 4.661E+00      ITAE(4) = 3.146E+04
F(5) = 4.661E+00      ITAE(5) = 3.132E+04

ITERATION NUMBER 16,      EVALUATION NUMBER 31
X(1,1) =  0.28   X(1,2) = 20.27   X(1,3) =  1.69   X( 1,4) =  4.23
X(2,1) =  0.25   X(2,2) = 19.94   X(2,3) =  1.97   X( 2,4) =  4.06
X(3,1) =  0.27   X(3,2) = 20.13   X(3,3) =  2.14   X( 3,4) =  4.25
X(4,1) =  0.28   X(4,2) = 20.02   X(4,3) =  1.75   X( 4,4) =  4.45
X(5,1) =  0.26   X(5,2) = 20.26   X(5,3) =  1.89   X( 5,4) =  4.21
F(1) = 4.644E+00      ITAE(1) = 3.197E+04
F(2) = 4.657E+00      ITAE(2) = 3.152E+04
F(3) = 4.652E+00      ITAE(3) = 3.169E+04
F(4) = 4.661E+00      ITAE(4) = 3.146E+04
F(5) = 4.646E+00      ITAE(5) = 3.198E+04

ITERATION NUMBER 17,      EVALUATION NUMBER 33
X(1,1) =  0.28   X(1,2) = 20.27   X(1,3) =  1.69   X( 1,4) =  4.23
X(2,1) =  0.25   X(2,2) = 19.94   X(2,3) =  1.97   X( 2,4) =  4.06
X(3,1) =  0.27   X(3,2) = 20.13   X(3,3) =  2.14   X( 3,4) =  4.25
X(4,1) =  0.27   X(4,2) = 20.08   X(4,3) =  1.84   X( 4,4) =  4.32
X(5,1) =  0.26   X(5,2) = 20.26   X(5,3) =  1.89   X( 5,4) =  4.21
F(1) = 4.644E+00      ITAE(1) = 3.197E+04
F(2) = 4.657E+00      ITAE(2) = 3.152E+04
F(3) = 4.652E+00      ITAE(3) = 3.169E+04
```

```
F(4) = 4.655E+00      ITAE(4) = 3.163E+04

F(5) = 4.646E+00      ITAE(5) = 3.198E+04

ITERATION NUMBER 18.      EVALUATION NUMBER 35

X(1,1) =  0.28   X(1,2) = 20.27   X(1,3) =  1.69   X(1,4) =  4.23

X(2,1) =  0.25   X(2,2) = 20.05   X(2,3) =  1.93   X(2,4) =  4.16

X(3,1) =  0.27   X(3,2) = 20.13   X(3,3) =  2.14   X(3,4) =  4.25

X(4,1) =  0.27   X(4,2) = 20.08   X(4,3) =  1.84   X(4,4) =  4.32

X(5,1) =  0.25   X(5,2) = 20.25   X(5,3) =  1.89   X(5,4) =  4.21

F(1) = 4.644E+00      ITAE(1) = 3.197E+04

F(2) = 4.654E+00      ITAE(2) = 3.166E+04

F(3) = 4.652E+00      ITAE(3) = 3.169E+04

F(4) = 4.655E+00      ITAE(4) = 3.163E+04

F(5) = 4.646E+00      ITAE(5) = 3.198E+04

AFTER 18 ITERATIONS.

THE IMPROVED VALUE OF F = 4.644E+00

IMPROVED VALUES OF VARIABLES

X(1) =  0.28

X(2) = 20.27

X(3) =  1.69

X(4) =  4.23
```

G.5 Program for Simulation

This program is used to evaluate the system performance and to study the parametric effects on the proposed vehicle drive system. In the MAIN program, engine, HST, and vehicle data are read; system parameters are specified and calculated; initial conditions are set up; and simulation results are plotted. All variables in the MAIN program have the same definitions as those in program 4.

Subprograms used in this program are described as follows:

INTGRL

This is the integration routine which develops the trajectories of the state and the algebraic variables. On the consideration of accuracy and efficiency, the fourth-order Adams Predictor/corrector numerical integration method is used with the fourth-order Runge-Kutta method as a "starting" step.

The variable KEEP is used to indicate when the numerical technique has reached the end of an integration step. KEEP is set equal to 1 when a valid integration step has been completed. For intermediate steps, KEEP is specified to 0. KEEP will be used in subroutine F as an indicator.

The values of the input vector $\overline{DY}$ at any prescribed time are obtained by calling subroutine F. In addition to subroutine F, two other subprograms, CHECK and DELAY, are called each time when a valid integration has been done. CHECK is used to check the hard constraints on the state variables. DELAY is used to simulate the engine transport delay.

The program logic of subroutine DELAY is substantially the same as that of the subprogram YSHIFT (recall section 6.5.2). The only difference is that the sampling time interval used in YSHIFT now is replaced by the step size of integration H.

The trajectories are stored after a prescribed number of integration steps as specified by INDEX in line 66. The integration will be terminated by the control parameter IEND in line 83.

F

This subroutine contains the dynamic system model (see Chapter IV) in the forms of algebraic equations and first order differential equations. The definitions of variables and parameters used in this subroutine are presented in Table XIV.

The routine evaluates the algebraic variables $\overline{X}$ and state derivatives $\overline{DY}$ based on the state variables $\overline{Y}$, parameters $\overline{P}$ and the independent variable time, TT. (Computation procedure was given in Appendix F).

The values of state variables are furnished by the calling routine INTGRL. Parameters and the independent variable are furnished via common storages.

The statement in line 12 allows the algorithms in lines 14 through 41 to be executed only at each sampling instant. This simulates that the data acquisition unit can only sense signals at each sampling time.

The statement in line 13 is used to insure that the same algorithms mentioned earlier can only be executed when a valid integration is performed.

A number of subprograms are called in this subroutine; they are:

STEP → simulates a step input

AMPULS → simulates an ideal sampler

SIGIN → simulates transducer, A/D converter, involves data scaling

PIC

YSHIFT (see descriptions in section 6.5.2)

FG

SIGOUT → simulates D/A converter, involves data scaling

ZHOLD → simulates a zero order hold

LIMIT

simulate the crossover control circuit (see section 4.7)

DEADSP

INTERP → for table lookup and bi-linear interpolation (see Appendix B)

TABLE XIV

DEFINITIONS OF PARAMETERS AND VARIABLES

P(1) = G_p

P(2) = G_m

P(3) = R

P(4) = $C_{fp}\ D_{pm}$

P(5) = $C_{dp}\ \mu\ D_{pm}$

P(6) = wa

P(7) = b

P(8) = $0.5\ C_a\ \rho A$

P(9) = $W \sin \phi$

P(10) = $17.6\ V_{cmax}/R$

P(11) = $S_{\ell max}$

P(12) = Y_{max}

P(13) = S_{emax}

P(14) = $T_{\ell max}$

P(15) = T_{emax}

P(16) = c_1

P(17) = τ_1

P(18) = c_2

P(19) = τ_2

P(20) = YI_{min}

P(21) = DI_{min}

P(22) = D_{pm}

P(23 = D_{mm}

P(24) = $C_{fm}\ D_{mm}$

P(25) = $C_{dm}\ \mu\ D_{mm}$

P(26) = τ_y

P(27) = τ_d

P(28) = B/v

P(29) = $(C_{sp}\ D_{pm} + C_{sm}\ D_{mm})/\mu$

P(30) = J_c

P(31) = Wa/b

P(32) = $M_c\ R$

P(33) = K_3

P(34) = Y_{idle}

X(1) = S_e

X(2) = S_m

X(3) = V

X(4) = T_p

X(5) = T_e

X(6) = $T_{\ell s}$

X(7) = ISAMP

X(8) = S_c

X(9) = S_{cd}

X(10) = $S_{\ell d}$

X(11) = Y_d

TABLE XIV (Continued)

X(12) = S_{ed}

X(13) = $T_{\ell sd}$

X(14) = T_{ed}

X(15) = ΔS

X(16) = YI

X(17) = Y_{rd}

X(18) = Y_s

X(19) = T_{op}

X(20) = ΔT

X(21) = DI

X(22) = D_{rd}

X(23) = Y_{ra}

X(24) = Y_{rh}

X(25) = Y_r

X(26) = D_{ra}

X(27) = D_{rh}

X(28) = D_r

X(29) = T_{out}

X(30) = D_m

X(31) = T_m

X(32) = T_ℓ

X(33) = F_{acc}

X(34) = D_{rp}

X(35) = D_{rm}

X(36) = η_e

X(37) = HP_e

X(38) = HP_ℓ

Y(1) = Y

Y(2) = D_p

Y(3) = $\tilde{D}_m$

Y(4) = P

Y(5) = S_p

Y(6) = S_ℓ

Y(7) = f

X(8) = L

X(9) = ITAE

```
C*********************************
C*                               *
C*     PROGRAM FOR SIMULATION    *
C*                               *
C*********************************
C
C
      REAL MC
      DIMENSION SEDAT1(9),SEDAT2(10),TEDATA(11),THROT1(15),
     1 THROT2(21),X(38),Y(9),DY(9),T(251),XP(251,38),YP(251,9),
     2 T1(84),YY(84,6),ZZ(84,6),FORMA1(4),FORMA2(5),FORMA3(6),
     3 FORMB1(4),FORMB2(5),FORMB3(6),TITLEA(6),TITLEB(6)
C
      COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C-----
C     READ ENGINE PERFORMANCE DATA
C-----
      READ(5,10) ((EDATA1(I,J),J=1,15),I=1,9)
   10 FORMAT(15F5.1)
      READ(5,12) ((EDATA2(I,J),J=1,10),I=1,11)
   12 FORMAT(10F7.1)
      READ(5,14) (THROT2(I),OPTE1(I),OPTE2(I),OPTE3(I),OPTE4(I),
     * OPTE5(I),OPTE6(I),OPTE7(I),I=1,21)
   14 FORMAT(8F10.3)
C-----
      DATA SEDAT1/35.,70.,105.,140.,175.,210.,245.,280.,315./
      DATA SEDAT2/0.,35.,70.,105.,140.,175.,210.,245.,280.,315./
      DATA TEDATA/0.,30.,60.,90.,120.,150.,180.,210.,240.,270.,
     *            300./
      DATA THROT1/0.,5.,10.,15.,20.,25.,30.,35.,40.,45.,50.,55.,
     *            60.,65.,70./
      DATA FORMA1/'(10X',',A4,','15F6','.0) '/
      DATA FORMA2/'(8X,',A4,1','X,91','(1H-','))  '/
      DATA FORMA3/'(7X,','F5.0',',2H ','I,15','F6.0',')   '/
      DATA FORMB1/'(10X',',A4,','10F7','.0) '/
      DATA FORMB2/'(8X,','A4,1','X,71','(1H-','))  '/
      DATA FORMB3/'(7X,','F5.0',',2H ','I,10','F7.1',')   '/
      DATA TITLEA/'EDAT','A1(T','E .V','S. Y',' & S','E)  '/
      DATA TITLEB/'EDAT','A2(E','FF .','VS. ','SE &',' TE)'/
C-----
C     SPECIFY HST SIZES, COEFFICIENTS AND PARAMETERS
C-----
      DPM=0.323
      DMM=0.501
      CSP=4.0E-9
      CSM=4.0E-9
      CDP=2.5E5
      CDM=2.5E5
      CFP=0.05
      CFM=0.05
      PMU=3.75E-6
      B=2.2E5
      VCL=12.2
C-----
```

```
C      SPECIFY VEHICLE SPECIFICATION DATA
C-----
       MC=4.533
       W=1700.
       A=2592.
       AS=0.01
       CA=0.35
       RHC=1.122E-7
       ALPHA=0.
       VCMAX=45.
C-----
C      SPECIFY THE NUMBER OF ALGEBRAIC VARIABLES.
C              THE NUMBER OF STATE VARIABLES.
C              THE LENGTH OF ARRAY XS, USED BY DELAY,
C              THE LENGTH OF ARRAY YS, USED BY YSHIFT,
C              THE NUMBER OF BITS FOR A/D AND D/A CONVERTERS
C-----
       NX=38
       NY=9
       NXS=80
       NYS=40
       NBIT=12
C-----
C      SPECIFY SAMPLING INTERVAL AND INTEGRATION
C      CONTROL PARAMETERS
C-----
       TS=0.004
       H=0.002
       TF=150.
       IEND=TF/H+.5
C-----
C      SPECIFY, CALCULATE SYSTEM PARAMETERS
C-----
       P(1)=3.7
       P(2)=1.5
       P(3)=12.
       P(4)=CFP*DFM
       P(5)=CDP*FMU*DFM
       P(6)=AS*W
       P(7)=1760.
       P(8)=0.5*CA*RHC*A
       P(9)=W*SIN(0.017453*ALPHA)
       P(10)=17.6*VCMAX/P(3)
       P(11)=66.
       P(12)=70.
       P(13)=315.
       P(14)=2680.
       P(15)=300.
       P(16)=0.327
       P(17)=20.3
       P(18)=1.12
       P(19)=4.3
       P(20)=0.1575
       P(21)=0.
       P(22)=DFM
       P(23)=DMM
       P(24)=CFM*DMM
       P(25)=CDM*FMU*DMM
```

```
      P(26)=8.0E-3
      P(27)=79.6E-3
      P(28)=B/VCL
      P(29)=(CSP*DPM+CSM*DMM)/FMU
      P(30)=0.6
      P(31)=P(6)/P(7)
      P(32)=MC*P(3)
      P(33)=10.9
      P(34)=0.167
C-----
C     SET UP INITIAL CONDITIONS
C-----
      DO 20 I=1,NX
   20 X(I)=0.
      DO 22 I=1,NY
   22 Y(I)=0.
      X(15)=P(20)
      X(17)=P(20)
      Y(1)=P(34)
      Y(5)=18.92
      YDELAY=P(34)
      DO 24 I=1,NXS
   24 XS(I)=P(34)
      DO 26 I=1,NYS
   26 YS(I)=0.1367
C-----
C     PRINT ENGINE PERFORMANCE DATA AND
C            OPTIMUM OPERATING SCHEDULES
C-----
      WRITE(6,40)
   40 FORMAT(1H1)
      CALL TABLE(EDATA1,THFCT1,SEDAT1,15,9,TITLEA,'    Y',
     * '   SE',9,FORMA1,FORMA2,FORMA3)
      CALL TABLE(EDATA2,SEDAT2,TEDATA,10,11,TITLEB,'   SE',
     * '   TE',11,FORMB1,FORMB2,FORMB3)
      WRITE(6,50)
   50 FORMAT(1H0,///,10X,'TAU',5X,'OPTE1',5X,'OPTE2',5X,'OPTE3',
     * 5X,'OPTE4',5X,'OPTE5',5X,'OPTE6',5X,'OPTE7'/9X,75(1H-))
      DO 60 I=1,21
   60 WRITE(6,70) THFCT2(I),OPTE1(I),OPTE2(I),OPTE3(I),OPTE4(I),
     * OPTE5(I),OPTE6(I),OPTE7(I)
   70 FORMAT(9X,F4.1,7(F10.1))
C-----
      CALL INTGRL(X,Y,T,XP,YP)
C-----
      WRITE(6,80)
   80 FORMAT(1H1,///, 9X,'TIME',9X,'Y',10X,'SE',10X,'TE',10X,
     1 'DF',10X,'DM',11X,'P',9X,'FUEL',9X,'SL',9X,'ESL',3X,
     2 'ETE',/,6X,127(1H-))
      DO 82 I=1,251
   82 WRITE(6,84) T(I),YP(I,1),XP(I,1),XP(I,5),YP(I,2),XP(I,30),
     *YP(I,4),YP(I,7),YP(I,6),XP(I,15),XP(I,20)
   84 FORMAT(3X,9(1PE12.3),2(1PE11.3))
      FPD=YP(250,7)/YP(250,8)
      WRITE(6,86) FPD,YP(250,9)
   86 FORMAT(//,6X,'FPD= ',1PE11.3/5X,'ITAE= ',E11.3)
C-----
C     SCALE VARIABLES AND PLOT TRAJECTORIES
```

```
C-----
      DO 90 J=1,250,3
      K=(J+2)/3
      T1(K)=T(J)
      YY(K,1)=XP(J,3)/792.
      YY(K,2)=XP(J,1)/315.
      YY(K,3)=XP(J,29)/300.
      YY(K,4)=XP(J,37)/14.32
      YY(K,5)=XP(J,38)/14.32
      YY(K,6)=YP(J,7)/5.E5
      ZZ(K,1)=YP(J,1)/70.
      ZZ(K,2)=YP(J,2)/0.323
      ZZ(K,3)=XP(J,30)/0.501
      ZZ(K,4)=YP(J,4)/5000.
      ZZ(K,5)=XP(J,15)/66.
      ZZ(K,6)=XP(J,20)/300.
   90 CONTINUE
      CALL PLOTS(2048,2048)
      CALL PLOT(2.0,1.0,-3)
      CALL GRAPH(T1,YY,84,6,'TIME','V    ', 8.0,6.0)
      CALL GRAPH(T1,ZZ,84,6,'TIME','Y    ', 8.0,6.0)
      STOP
      END
```

```
C-----
C     SUBROUTINE TABLE
C-----
      SUBROUTINE TABLE(TABDAT,X,Y,NX,NY,TITLE,XLAB,YLAB,NROW,
     * FORM1,FORM2,FORM3)
      DIMENSION TABDAT(NROW,1),X(1),Y(1),TITLE(6),XLAB(1),
     * YLAB(1),FORM1(4),FORM2(5),FORM3(6)
      WRITE(6,10) TITLE
   10 FORMAT(1H0,//,16X,9A4//)
      WRITE(6,FORM1) XLAB,(X(I),I=1,NX)
      WRITE(6,FORM2) YLAB
      DO 20 I=1,NY
   20 WRITE(6,FORM3) Y(I),(TABDAT(I,J),J=1,NX)
      RETURN
      END
```

```
C-----
C      SUBROUTINE INTGRL
C-----
       SUBROUTINE INTGRL(XO,YO,T,X,Y)
       REAL K1,K2,K3,K4
C
       DIMENSION XO(1),YO(1),T(1),X(251,1),Y(251,1),DYO(9),K1(9),
     1 K2(9),K3(9),K4(9),YY(9),DY(251,9),Y4(9),Y5(9),DY1(9),
     2 DY2(9),DY3(9),DY4(9),DY5(9)
C
       COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C-----
C      COMPUTE FOUR VALUES BY RUNGE-KUTTA METHOD
C-----
       TW=0.
       TT=TW
       KEEP=1
       CALL F(XO,YO,DYO)
       KEEP=0
       T(1)=TW
       DO 10 I=1,NX
    10 X(1,I)=XO(I)
       DO 12 J=1,NY
       Y(1,J)=YO(J)
    12 DY(1,J)=DYO(J)
       DO 34 KK=2,4
       DO 20 J=1,NY
       K1(J)=H*DYO(J)
    20 YY(J)=YO(J)+.5*K1(J)
       TT=TW+0.5*H
       CALL F(XO,YY,DYO)
       DO 22 J=1,NY
       K2(J)=H*DYO(J)
    22 YY(J)=YO(J)+.5*K2(J)
       CALL F(XO,YY,DYO)
       DO 24 J=1,NY
       K3(J)=H*DYO(J)
    24 YY(J)=YO(J)+K3(J)
       TT=(KK-1)*H
       CALL F(XO,YY,DYO)
       DO 26 J=1,NY
    26 K4(J)=H*DYO(J)
       DO 28 J=1,NY
    28 YO(J)=YO(J)+(K1(J)+2.*K2(J)+2.*K3(J)+K4(J))/6.
       CALL CHECK(YO)
       KEEP=1
       CALL F(XO,YO,DYO)
       KEEP=0
C-----
C      ENGINE TRANSPORT TIME DELAY
C-----
       TDELAY=P(33)/XO(1)
       YDELAY=DELAY(YO(1),TDELAY)
       DO 32 J=1,NY
       Y(KK,J)=YO(J)
    32 DY(KK,J)=DYO(J)
```

```
      TW=TT
   34 CONTINUE
      DO 36 J=1,NY
      Y4(J)=Y(4,J)
      DY1(J)=DY(1,J)
      DY2(J)=DY(2,J)
      DY3(J)=DY(3,J)
   36 DY4(J)=DY(4,J)
      INDEX=4
      JJ=2
C-----
C     ADVANCE THE SOLUTION BY ADAMS-MOULTON METHOD
C-----
   40 DO 42 J=1,NY
   42 Y5(J)=Y4(J)+H*(55.*DY4(J)-59.*DY3(J)+37.*DY2(J)-9.*DY1(J))
     *                                                          /24.
      TT=KK*H
      CALL F(XO,Y5,DY5)
      DO 44 J=1,NY
   44 Y5(J)=Y4(J)+H*(9.*DY5(J)+19.*DY4(J)-5.*DY3(J)+DY2(J))/24.
      CALL CHECK(Y5)
      KEEP=1
      CALL F(XO,Y5,DY5)
      KEEP=0
C-----
C     ENGINE TRANSPORT TIME DELAY
C-----
      TDELAY=P(33)/XC(1)
      YDELAY=DELAY(Y5(1),TDELAY)
      IF(INDEX .LT.300) GO TO 54
      T(JJ)=TT
      DO 50 I=1,NX
   50 X(JJ,I)=XC(I)
      DO 52 J=1,NY
   52 Y(JJ,J)=Y5(J)
      JJ=JJ+1
      INDEX=1
      GO TO 60
   54 INDEX=INDEX+1
C-----
C     RESUBSCRIPT DY VALUES AND REPEAT ADAMS-MOULTON CALCULATION
C-----
   60 DO 62 J=1,NY
      DY1(J)=DY2(J)
      DY2(J)=DY3(J)
      DY3(J)=DY4(J)
      DY4(J)=DY5(J)
   62 Y4(J)=Y5(J)
      KK=KK+1
      IF(KK .LE. IEND) GO TO 40
      RETURN
      END
```

```
C-----
C       SUBROUTINE F
C-----
        SUBROUTINE F(X,Y,DY)
        REAL LIMIT,INTERP
        DIMENSION X(1),Y(1),DY(1)
C
        COMMON TT,EDATA1(9,19),EDATA2(11,10),OPTE1(21),OPTE2(21),
      1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
      2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C-----
        X(1)=P(1)*Y(5)
        X(2)=P(2)*Y(6)
        X(3)=P(3)*Y(6)
        X(4)=(Y(2)+P(4))*Y(4)+P(5)*Y(5)
        X(5)=X(4)/P(1)
        X(6)=P(3)*(P(6)*(1+X(3)/P(7))+P(8)*X(3)*X(3)+P(9))
C-----
C       SAMPLER
C-----
        X(7)=AMPULS(TS)
C-----
C       SAMPLING OR NOT ?
C-----
        IF(X(7) .NE. 1) GO TO 10
C-----
C       IS AN INTEGRATION PERFORMED ?
C-----
        IF(KEEP .NE. 1) GO TO 10
C-----
C       SENSING AND SCALING SIGNALS
C-----
        X(8)=P(10)*STEP(0.0)
        X(9)=SIGIN(X(8),P(11))
        X(10)=SIGIN(Y(6),P(11))
        X(11)=SIGIN(Y(1),P(12))
        X(12)=SIGIN(X(1),P(13))
        X(13)=SIGIN(X(6),P(14))
        X(14)=SIGIN(X(5),P(15))
C-----
C       CALCULATE CONTROL ALGORITHMS
C-----
        X(15)=X(9)-X(10)
        IF(ABS(X(15)) .LT. 1.25E-1) X(15)=0.
        CALL PID(P(16),P(17),X(16),P(11),P(20),X(15),X(17))
        X(18)=YSHIFT(X(11),X(12))
        IF(X(10).LT.1.) X(19)=FG(X(18),OPTE1)
        IF(X(10).GE.1. .AND. X(13).LT.680.) X(19)=FG(X(18),OPTE1)
        IF(X(10).GE.1. .AND. (X(13).GE.680. .AND. X(13).LT.1000.))
      1                                         X(19)=FG(X(18),OPTE2)
        IF(X(10).GE.1. .AND. (X(13).GE.1000. .AND. X(13).LT.1300.))
      2                                         X(19)=FG(X(18),OPTE3)
        IF(X(10).GE.1. .AND. (X(13).GE.1300. .AND. X(13).LT.1700.))
      3                                         X(19)=FG(X(18),OPTE4)
        IF(X(10).GE.1. .AND. (X(13).GE.1700. .AND. X(13).LT.2090.))
      4                                         X(19)=FG(X(18),OPTE5)
        IF(X(10).GE.1. .AND. (X(13).GE.2090. .AND. X(13).LT.2470.))
      5                                         X(19)=FG(X(18),OPTE6)
```

```
0032                  IF(X(10).GE.1. .AND. X(13).GE.2470.) X(19)=FG(X(18),OPTE7)
0033                  X(20)=X(19)-X(14)
0034                  IF(ABS(X(20)) .LT. 4.50E-3) X(20)=0.
0035                  CALL PIC(P(18),P(19),X(21),P(15),P(21),X(20),X(22))
                C-----
                C     OUTPUT CONTROL SIGNALS
                C-----
0036                  X(23)=SIGOUT(X(17),P(11))
0037                  X(24)=ZHOLD(X(7),X(23),X(24))
0038                  X(25)=X(24)/100.
0039                  X(26)=SIGOUT(X(22),P(15))
0040                  X(27)=ZHOLD(X(7),X(26),X(27))
0041                  X(28)=X(27)/50.
0042               10 X(29)=INTERP(X(1),YDELAY,EDATA1,35.,0.,35.,5.,9,15)
0043                  X(30)=P(23)-Y(3)
0044                  X(31)=(X(30)-P(24))*Y(4)-P(25)*X(2)
0045                  X(32)=P(2)*X(31)
0046                  X(33)=X(32)/P(3)-P(6)-P(9)
                C-----
                C     CROSSOVER CONTROLLER
                C-----
0047                  X(34)=1.2755*LIMIT(X(28),0.0784)
0048                  X(35)=0.8224*DEADSP(X(28),0.0784)
                C-----
                C     ENGINE EFFICIENCY
                C-----
0049                  X(36)=INTERP(X(29),X(1),EDATA2,0.,0.,30.,35.,11,10)
                C-----
                C     ENGINE OUTPUT HP
                C-----
0050                  X(37)=X(1)*X(29)/6600.
                C-----
                C     LOAD REQUIRED HP
                C-----
0051                  X(38)=Y(6)*X(6)/6600.
                C-----
                C     THROTTLE POSITION
                C-----
0052                  DY(1)=(P(12)/0.1*X(25)-Y(1))/P(26)
                C-----
                C     PUMP DISPLACEMENT
                C-----
0053                  DY(2)=(P(22)/0.1*X(34)-Y(2))/P(27)
                C-----
                C     MOTOR DISPLACEMENT
                C-----
0054                  DY(3)=(P(23)/0.1*X(35)-Y(3))/P(27)
                C-----
                C     HYDRAULIC PRESSURE
                C-----
0055                  DY(4)=P(28)*(Y(2)*Y(5)-X(30)*X(2)-P(29)*Y(4))
                C-----
                C     PUMP SPEED
                C-----
0056                  DY(5)=(X(29)-X(5))/P(30)
                C-----
                C     VEHICLE SPEED
                C-----
```

```
      DY(6)=0.
      IF(X(3) .EQ. 0. .AND. X(33) .LE. 0.) GO TO 20
      DY(6)=(X(33)-P(31)*X(3)-P(8)*X(3)*X(3))/P(32)
C-----
C     FUEL CONSUMPTION RATE
C-----
   20 DY(7)=X(1)*X(29)/X(36)
C-----
C     DISTANCE TRAVELLED
C-----
      DY(8)=X(3)
C-----
C     DRIVE SYSTEM PERFORMANCE INDEX
C-----
      DY(9)=TT*ABS(X(15))
      RETURN
      END
```

```
C-----
C     SUBROUTINE CHECK
C-----
      SUBROUTINE CHECK(YC)
      DIMENSION YO(1)
      IF(YC(1) .GT. 70.) YO(1)=70.
      IF(YC(1) .LT. 0.167) YC(1)=0.167
      IF(YC(2) .GT. 0.323) YC(2)=0.323
      IF(YC(2) .LT.-0.323) YC(2)=-0.323
      IF(YC(3) .GT. 0.501) YC(3)=0.501
      IF(YC(3) .LT.-0.501) YO(3)=-0.501
      IF(YC(4) .GT. 5000.) YC(4)=5000.
      IF(YC(4) .LT. 0.) YO(4)=0.
      RETURN
      END
```

```
C-----
C     FUNCTION DELAY
C-----
      FUNCTION DELAY(X,TDELAY)
      COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C
      XS(1)=X
      ICUT=TDELAY/H+1.5
      DELAY=XS(ICUT)
      I=NXS-1
      DO 10 J=1,I
      K=NXS-J
   10 XS(K+1)=XS(K)
      RETURN
      END
```

```
C-----
C      FUNCTION AMPULS
C-----
      FUNCTION AMPULS(PERIOD)
      DOUBLE PRECISION TEST1,TEST2,DTT,DPERIO,CHECK,TCHECK,FCHECK
C
      COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C
      DATA TEST1,TEST2/0.01D0,0.99D0/
      AMPULS=0.
      DTT=TT
      DPERIO=PERIOD
      CHECK=DTT/DPERIO
      ICHECK=CHECK
      TCHECK=DFLOAT(ICHECK)
      FCHECK=CHECK-TCHECK
      IF(FCHECK .LE. TEST1 .OR. FCHECK .GE. TEST2) AMPULS=1.
      RETURN
      END
```

```
C-----
C      FUNCTION STEP
C-----
      FUNCTION STEP(TSTART)
      COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C
      STEP=0.
      IF(TT .GE. TSTART) STEP=1.
      RETURN
      END
```

```
C-----
C      FUNCTION SIGIN
C-----
      FUNCTION SIGIN(X,XMAX)
      COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C
      TVOLT=10./XMAX*X
      QUANT=2.**(NBIT-1)-1.
      LDIGIT=QUANT/10.*TVOLT
      SIGIN=XMAX/QUANT*FLOAT(LDIGIT)
      RETURN
      END
```

```
C-----
C     SUBROUTINE PIC
C-----
      SUBROUTINE PIC(GAIN,TCONST,XI,YMAX,YMIN,X,Y)
      COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C
      IF((Y.GE.YMAX .AND. X.GT.0.) .OR. (Y.LE.YMIN .AND.
     * X.LT.0.)) GO TO 10
      XI=XI+X*TS/TCONST
   10 Y=GAIN*X+XI
      RETURN
      END
```

```
C-----
C     FUNCTION YSHIFT
C-----
      FUNCTION YSHIFT(YIN,SE)
      COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),P(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C
      YS(1)=YIN
      TDELAY=P(33)/SE
      IOUT=TDELAY/TS+1.5
      YSHIFT=YS(IOUT)
      I=NYS-1
      DO 10 J=1,I
      K=NYS-J
   10 YS(K+1)=YS(K)
      RETURN
      END
```

```
C-----
C     FUNCTION FG
C-----
      FUNCTION FG(X,Z)
      DIMENSION Z(1)
      XMIN=0.1367
      XDEL=3.492
      XC=(X-XMIN)/XDEL+1
      IX=XC
      FX=XC-IX
      IF(IX .EQ. 21) GO TO 10
      FG=Z(IX)+FX*(Z(IX+1)-Z(IX))
      RETURN
   10 FG=Z(IX)
      RETURN
      END
```

```
C-----
C      FUNCTION SIGOUT
C-----
      FUNCTION SIGOUT(X,XMAX)
      COMMON TT,EDATA1(9,15),EDATA2(11,10),OPTE1(21),OPTE2(21),
     1 OPTE3(21),OPTE4(21),OPTE5(21),OPTE6(21),OPTE7(21),F(40),
     2 XS(80),YS(40),TS,H,YDELAY,NX,NY,NXS,NYS,NBIT,KEEP,IEND
C
      QUANT=2.**(NBIT-1)-1.
      X1=QUANT/XMAX*X
      IF(X1 .GT. QUANT) X1=QUANT
      SIGOUT=10./QUANT*X1
      RETURN
      END
```

```
C-----
C      FUNCTION ZHOLD
C-----
      FUNCTION ZHOLD(TRIG,X,XHELD)
      ZHOLD=XHELD
      IF(TRIG .EQ. 1.) ZHOLD=X
      RETURN
      END
```

```
C-----
C      FUNCTION INTERP
C-----
      REAL FUNCTION INTERP(X,Y,Z,XMIN,YMIN,XDEL,YDEL,NROW,NCOL)
      DIMENSION Z(NROW,1)
      X0=(X-XMIN)/XDEL+1.
      Y0=(Y-YMIN)/YDEL+1.
      IX=X0
      IY=Y0
      FX=X0-IX
      FY=Y0-IY
      IF(IX .EQ. NROW) GO TO 10
      IF(IY .EQ. NCOL) GO TO 20
      Z1=Z(IX,IY)+FY*(Z(IX,IY+1)-Z(IX,IY))
      Z2=Z(IX+1,IY)+FY*(Z(IX+1,IY+1)-Z(IX+1,IY))
      INTERP=Z1+FX*(Z2-Z1)
      RETURN
   10 INTERP=Z(IX,IY)+FY*(Z(IX,IY+1)-Z(IX,IY))
      RETURN
   20 INTERP=Z(IX,IY)+FX*(Z(IX+1,IY)-Z(IX,IY))
      RETURN
      END
```

```
C-----
C      FUNCTION LIMIT
C-----
       REAL FUNCTION LIMIT(X,XC)
       LIMIT=X
       IF(X .GT. XC) LIMIT=XC
       IF(X .LT. -XC) LIMIT=-XC
       RETURN
       END
```

```
C------
C      FUNCTION DEADSP
C------
       FUNCTION DEADSP(X,XC)
       DEADSP=0.
       IF(X .GT. XC) DEADSP=X-XC
       IF(X .LT. -XC) DEADSP=X+XC
       RETURN
       END
```

```
C-----
C     SUBROUTINE GRAPH
C-----
      SUBROUTINE GRAPH(X,Y,NPT,NLI,XLAB,YLAB,AXLEN,AYLEN)
      DIMENSION X(1),Y(NPT,1),XSCAL(4),YSCAL(4),ISYMB(9),
     *X1(86),Y1(86,6)
      LOGICAL*1 XLAB(1),YLAB(1)
      DATA ISYMB/113,114,115,116,117,118,119,120,121/
      CALL PLOT(0.0,-19.0,-3)
      CALL PLOT(2.0,1.0,-3)
      DO 10 J=1,NPT
      X1(J)=X(J)
      DO 10 I=1,NLI
   10 Y1(J,I)=Y(J,I)
      VXMAX=X1(1)
      VXMIN=X1(1)
      VYMAX=Y1(1,1)
      VYMIN=Y1(1,1)
      DO 20 J=1,NPT
      VXMAX=AMAX1(VXMAX,X1(J))
      VXMIN=AMIN1(VXMIN,X1(J))
      DO 20 I=1,NLI
      VYMAX=AMAX1(VYMAX,Y1(J,I))
   20 VYMIN=AMIN1(VYMIN,Y1(J,I))
      XSCAL(1)=VXMAX
      XSCAL(2)=VXMIN
      YSCAL(1)=VYMAX
      YSCAL(2)=VYMIN
      CALL SCALE(XSCAL,AXLEN,2,1)
      CALL SCALE(YSCAL,AYLEN,2,1)
      X1(NPT+1)=XSCAL(3)
      X1(NPT+2)=XSCAL(4)
      DO 30 I=1,NLI
      Y1(NPT+1,I)=YSCAL(3)
   30 Y1(NPT+2,I)=YSCAL(4)
      CALL AXIS(0.,0.,XLAB,-4,AXLEN,0.,XSCAL(3),XSCAL(4))
      CALL AXIS(0.,0.,YLAB,4,AYLEN,90.,YSCAL(3),YSCAL(4))
      DO 40 I=1,NLI
   40 CALL LINE(X1,Y1(1,I),NPT,1,-1,ISYMB(I))
      CALL PLOT(0.,0.,999)
      RETURN
      END
```

VITA 2

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Doctor of Philosophy

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