M.Sc. Agricultural Engineering

ABSTRACT

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AN AUTOMATIC DRAFT CONTROL FOR SELF PROPELLED VEHICLES

A control was developed for self-propelled farm vehicles. This device automatically controls a self-propelled wagon in order to force the vehicle to supply most of its own draft while being towed.

Field data were accumulated to establish operating parameters for the control. Control was obtained by sensing the draft in the towbar and modifying the signal from the sensor to operate the clutch and throttle of the vehicle's power unit.

Various methods of sensing draft and controlling the clutch and throttle were developed and evaluated.

In the final design the control consisted of: a draft sensor using strain gauges, a signal modifier to process the strain gauge output, and the clutch and throttle operating controls.

AN AUTOMATIC DRAFT CONTROL FOR SELF-PROPELLED VEHICLES

AN AUTOMATIC DRAFT CONTROL FOR SELF-PROPELLED VEHICLES

by

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I. THE PROBLEM

1.1 Introduction

Self-propelled wagons are becoming more common on farms in Eastern Canada. These vehicles may either be assembled by a manufacturer or be farm-built by an enterprising farmer. Either type is essentially a modified standard truck. The modification of a truck into a farm-built wagon consists of removing the truck cab and body and moving the normal driver controls and instruments to the left and to a point as near the front of the vehicle as possible. This leaves available, to the rear of the engine, space on which to mount a self-unloading wagon box. The manufactured type of self-propelled wagon, as shown in plate 1, is similar but the engine may be mounted in the middle of the chassis, below the wagon box, to shorten the vehicle and give better weight distribution.

The normal practice is to use three of these wagons in a harvesting operation with one driver who shuttles the empty and full wagons between the storage area and the field. In the field the driverless wagon is towed behind the forage harvester with the wagon power unit inoperative. The tractor pulling and powering the harvester must supply an increasing amount of extra draft to pull the wagon as it fills with material.

This method of field operation functions well if the tractor is large enough and traction conditions are good. But, in adverse conditions, the tractor often cannot provide the draft required and the entire unit bogs down. The operator, then, has no other choice than to

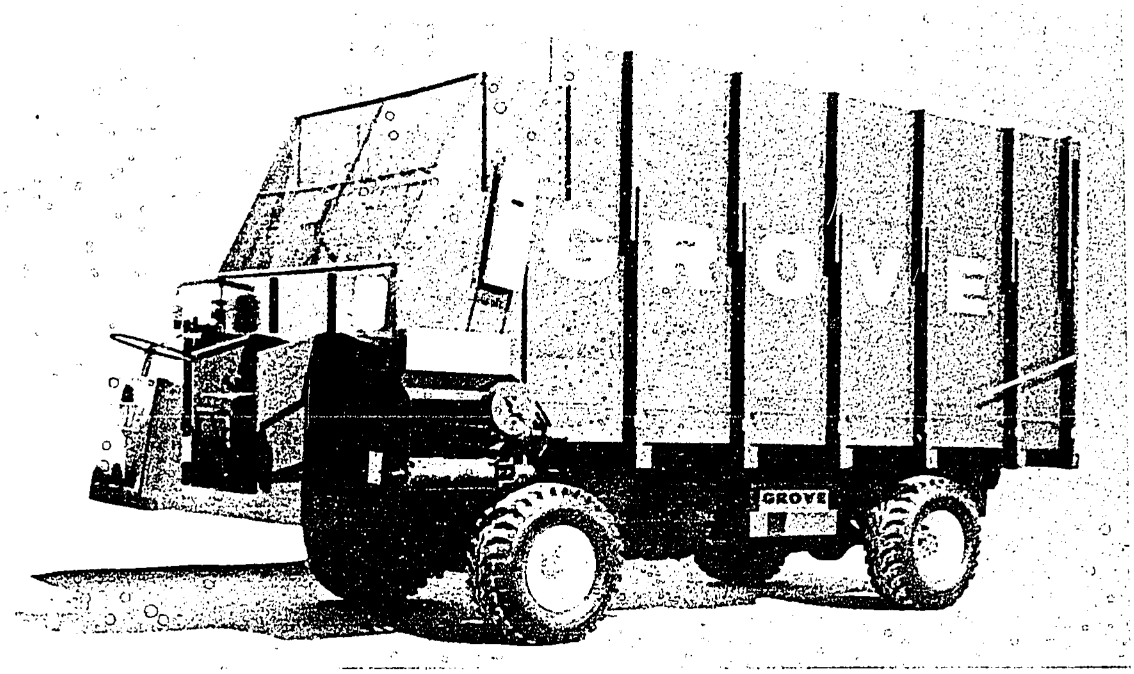


Plate 1. Commercial Self-propelled Wagon.

have the self-propelled wagon driven alongside the harvester while it is being filled. The extra load is removed from the tractor but more labour is required in the form of extra drivers. One unsafe practice that some operators resort to under these conditions is that of towing the wagon with the transmission in gear and the engine running at a preset speed.

A device that would automatically control the power unit of a self-propelled wagon while it is being towed behind the harvester is desirable. Since the wagon would supply most of its own draft, a smaller tractor could be used to power the harvester. The harvesting system would function under poorer traction conditions.

1.2 Pertinent Literature

A search of pertinent literature and an inquiry to each company which might be involved in developing a control of this type have not shown such a device.

1.3 Purpose of Study

It is the purpose of this thesis to report on research done in the course of designing a unit to automatically control the power unit of a self-propelled vehicle during the time that the vehicle is being towed. (It should be noted that the vehicle on which the design is based is a self-propelled wagon and therefore in this thesis all further references, i.e. "vehicle", will signify a self-propelled wagon.)

1.4 Requirements of the Design

The requirements of the design were the following:

i) the unit should automatically force the power unit to supply all the draft requirements for the self-propelled vehicle over a preset minimum amount. The unit would do this by first engaging the clutch and then controlling the throttle of the carburetor.

ii) the unit should be fail-safe, i.e. if the control device fails, the power unit of the self-propelled vehicle should cease functioning and the system revert to a non-powered condition.

iii) the control unit should not interfere with normal driver operation when the vehicle was being driven.

iv) the unit should be as simple as possible yet still fulfill its function.

II. THE CONTROL PROCESS

The whole purpose of any control system is to maintain some variable constant[21]. The variable in this system is the draft force which constantly changes because of the terrain over which the wagon is towed and the load the wagon is carrying.

In certain types of control systems little control is needed since the system, because of the characteristics of the load or the power unit, is more or less self-regulating. An example of such a system is an air fan required to deliver a constant amount of air. Since a small increase in air speed requires a disproportionate increase in power, fan output remains relatively constant over a range of conditions. However, in most other systems, regulation is needed. One method of regulation utilizes the control system output in the form of feedback to influence the input. This is the method employed here.

Because the input signal of a control system does vary, some type of constant reference signal must be used against which the control system can compare the input signal and the output feedback signal to produce the needed control signal.

An automatic feedback control system of this type may be diagrammatically represented as in figure 1. A reference signal is fed to a summing point where there is added to it, or subtracted from it, a feedback signal. The summing point produces an error signal which is processed by the control system to produce a control signal. Part of this control signal is returned to the summing point as a feedback signal.

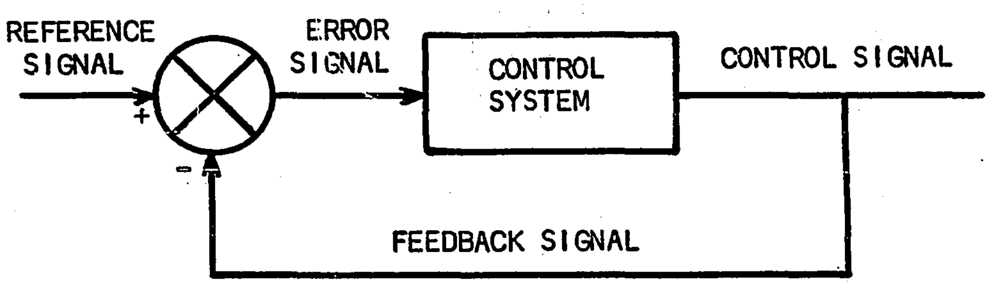


Figure 1. Diagram of an Automatic Feedback Control System

In the control system under development, the reference signal of figure 1 is the signal resulting from the application of a specific amount of draft force to the sensor. When the amount of the reference signal is exceeded, an error signal is produced causing the control system to function. The control elements and the power train of the wagon make up the control system. The control signal is the forward motion resulting from control system action. The forward movement or a change in the forward movement changes the pull on the sensor and is the feedback component of the block diagram.

In order to initiate control action some amount of pull must be applied to the sensor. Pull must exceed a certain minimal amount (the reference signal) in order to meet the fail-safe requirement but if the minimal amount is too small, control complexity and costs are increased, because the system must be more sensitive to react to low values of pull. On the other hand if it is too large, the purpose of the control is partially defeated because the tractor must supply the extra draft. A level of 50 pounds was arbitrarily selected as the reference signal i.e. the amount of pull that must be exceeded before control action would commence. This level is large enough to provide good control and is small enough to avoid loading the tractor appreciably.

An increase or decrease in pull on the sensor results in an increase or decrease in throttle setting with a corresponding change in vehicle speed: if the average value of pull increases, the engine speed will change to bring the amount of pull back to the preset amount; if the average pull decreases to the reference level, the engine is slowed to its idle speed. If the pull remains at this low level for longer than a predetermined time, the clutch is disengaged. The term "average pull" is used because the power unit would not be able to respond to short term variations in draft.

The control process of this system occurs in the following manner. The draft sensing unit, inserted into the connecting link between the forage harvester and the towed wagon, senses the pull exerted and converts this pull into a voltage that is proportional to the magnitude of the pull. When the output voltage of the sensor exceeds the reference signal, control elements engage the clutch and advance the throttle to produce the control signal.

A mathematical model of the complete control system is given in Appendix A.

III. DATA

3.1 Data Prerequisite to the Design

A control system reacts in some method to an input signal to produce an output. As outlined previously, the input is the signal resulting from the varying forces in the wagon drawbar and the output is the varying speed of the vehicle as the control attempts to relate the output to the input. The control has two functions to perform. It must analyze the input signal and, based on the total control response capabilities, create the output signal. Two types of information were therefore required before design of the control could begin: 1) a knowledge of the input signal, and 2) a knowledge of the reaction of the control systems to input signals.

An input signal usually varies in amplitude and in frequency, i.e. in a random manner with respect to time. Such an input signal can be analyzed by the application of probability theory and some concepts of mathematical statistics. Even a partial statistical analysis may reveal that although the input is a random frequency it nevertheless has some dominant frequency about which it varies. It may also be that although the input does have a mean frequency of a particular amplitude, this frequency may also be modulated by other frequencies of lesser magnitude.

The control system is capable of producing an output signal within a certain time after the application of an input signal. This time-delay is called the response time of the control system. If the system response time is known, then the highest frequency of input signal to which the control system is completely capable of responding can be determined. This will be the frequency with a period equal to the response time of the control system. The control system will only partially respond to signals having a period less than the system response time and as the frequency of the input signal rises still farther the output will simply be related to the average magnitude of the input signal. At some still higher input frequency the output may decrease. The frequency response of this control system may be determined by applying a known input of various frequencies and recording the output signals which result.

Data were collected to provide information from which to analyze the input signal with respect to its probable magnitude and frequency. The total response time of a partial control system including the signal modifier, the power unit and the drive train, was measured. The total response time was the sum of the response times of the following components of the partial control system:

i) the signal modifier,

*ii) clutch control circuits,

iii) the carburetor control circuits, and

iv) the power unit, power train and wagon.

3.2 Equipment Used For Data Collection

3.2.1 Force Transducer: Two force transducers, figure 2, were constructed and calibrated (for a description refer to Chapter IV. Electric

*which need only be considered when forward motion of the unit begins or ends

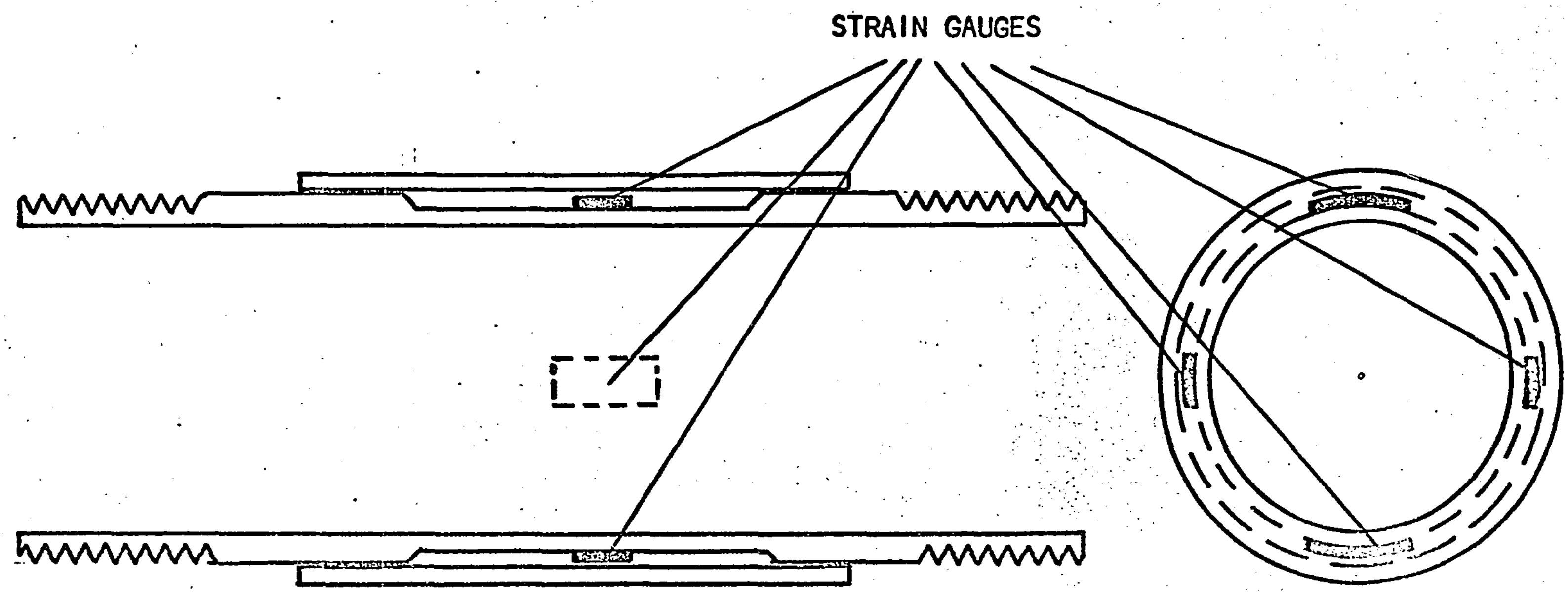


Figure 2. Force Transducer and Electric Draft Sensor

Draft Sensor). The transducers were calibrated by connecting them in series with a calibrated dynamometer and recording the transducer output on an oscillographic recorder as loads were applied in increasing and decreasing steps. The resulting graphs were calibrated with the force read from the dynamometer as the load was changed.

3.2.2 Engine Speed Transducer: The engine speed transducer, figure 3, was derived from an electronic tachometer circuit. Ignition impulses from the engine distributor were shaped, amplified and integrated to provide a DC output voltage, the magnitude of which was proportional to the speed of the engine. For calibration the transducer was connected to an engine, the output voltage recorded and the resulting graph calibrated against an accurate mechanical tachometer connected to the same engine.

3.2.3 Ground Speed Transducer: The transducer, shown in plate 2, was of the "fifth wheel" type and used a bicycle wheel with an AC generator incorporated into its hub as a sensing unit. The AC output was converted to DC and partially filtered to remove most of the ripple without obscuring speed variations. The circuit values for the transducer, figure 4, were obtained experimentally. To attach the wheel to the wagon a frame was made allowing the wheel to move up or down and swivel sideways when operating over uneven terrain. The wheel was then calibrated.

3.2.4 Oscillograph Recorder and Power Supply: The oscillograph recorder used was a 4 pen Beckman Offner type 504R, powered during field tests by a modified Honda E1000 generator. Generator modification included: 1) the addition of a capacitor to the DC excitation circuit

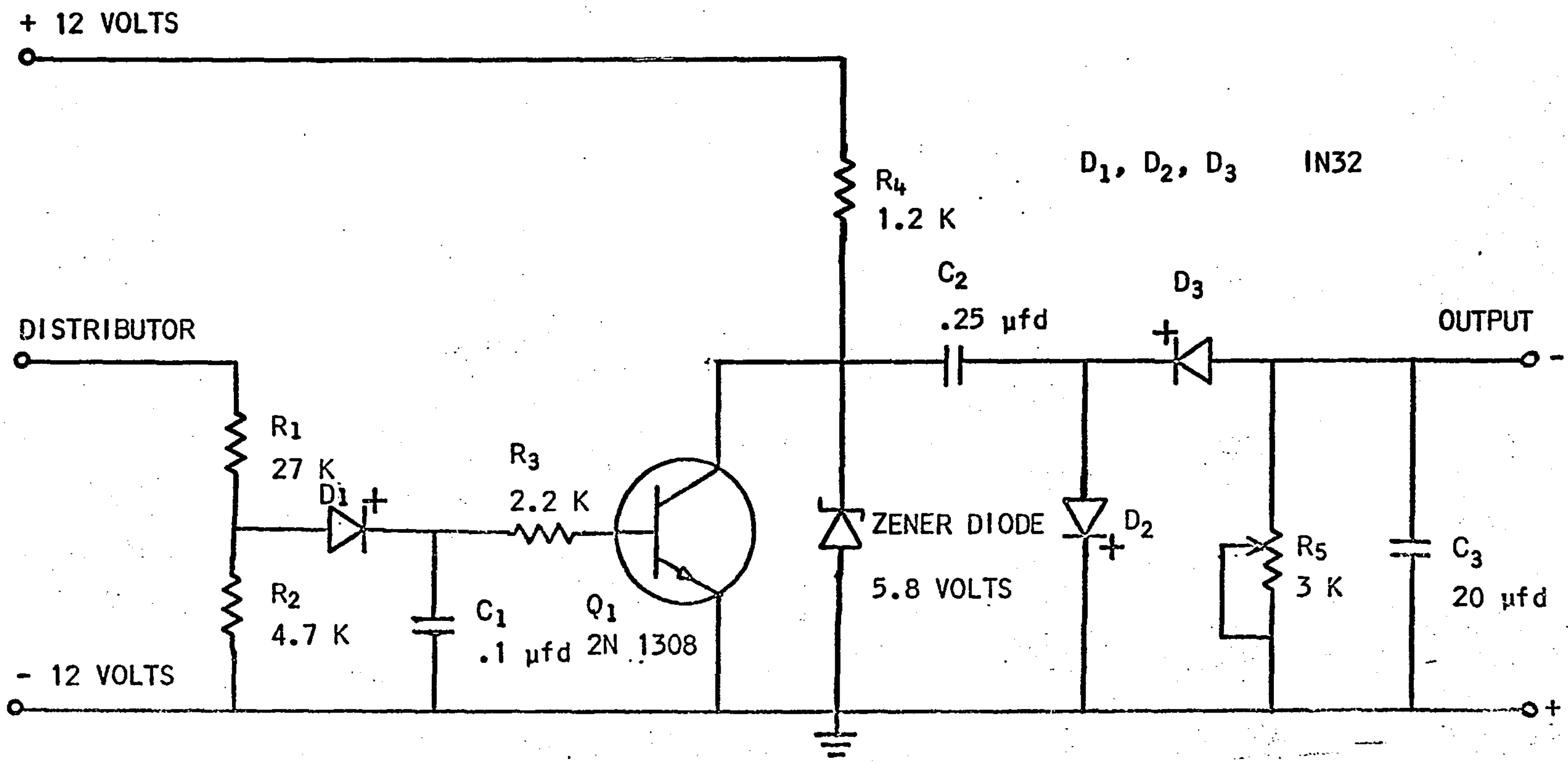


Figure 3. Engine Speed Transducer

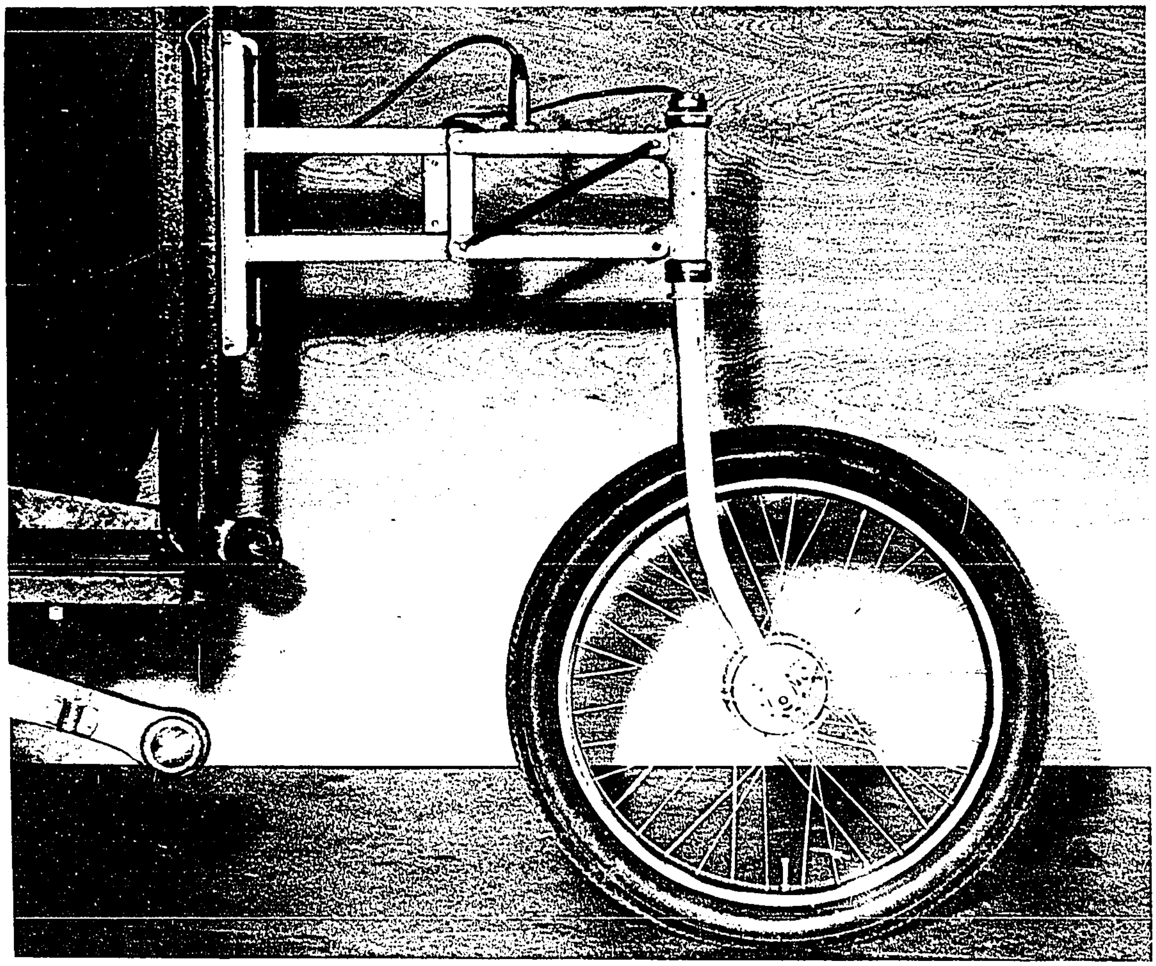


Plate 2. Ground Speed Transducer

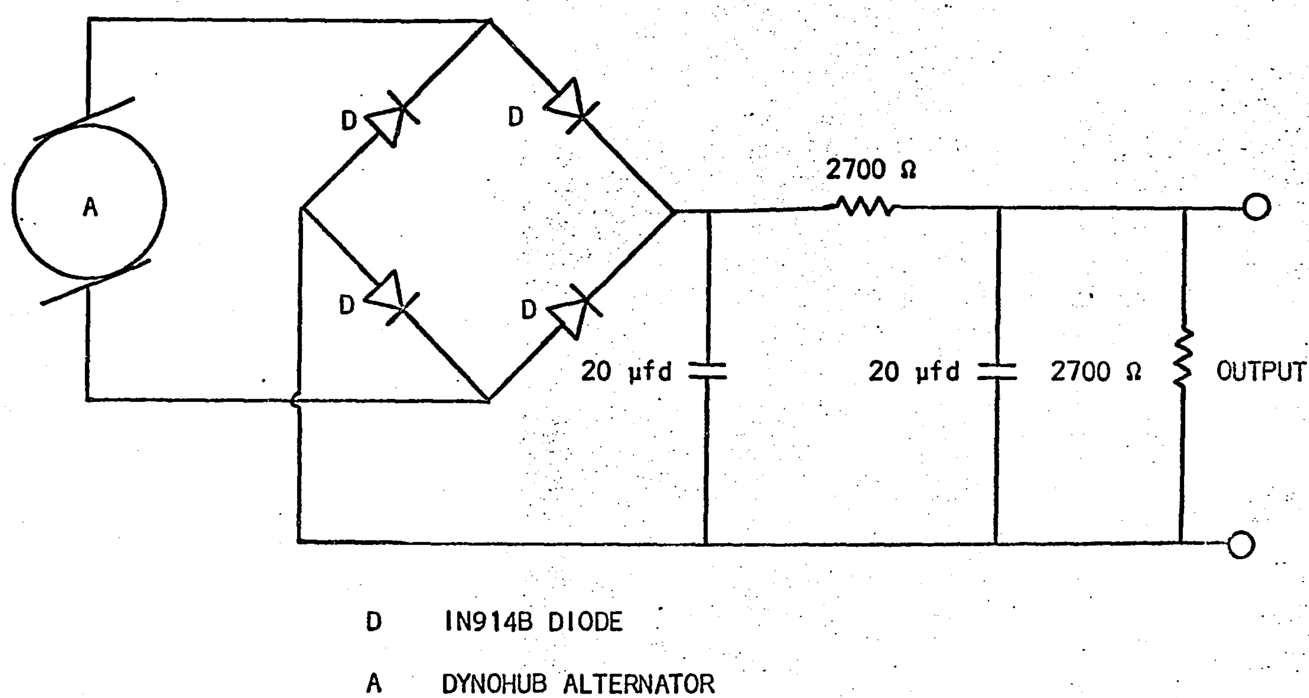


Figure 4. Circuit Diagram for Ground Speed Transducer

to remove a 2 hertz oscillation occurring in the generator output voltage level, and 2) the addition of a frequency meter to provide a means of setting the generator exactly to a frequency of 60 hertz to assure accurate chart speeds.

3.3 Collection of Data

3.3.1 Field Data: One of the force transducers was bolted into the drawbar of a non-powered wagon and the wagon was towed over uneven terrain at various speeds and with various loads. Oscillographic recordings were made of the forces on the sensor as speeds and loads changed. Average ground speeds for the test were obtained by measuring the length of time required for the tractor and wagon to move a known distance.

During a second test conducted to simulate the conditions existing in the drawbar of a self-propelled wagon being towed by a harvester, a combination of two tractors and a loaded wagon was used. The second tractor with its engine governor control set to a fixed speed was attached to the wagon to represent a self-propelled wagon. The first tractor with its engine operating at varying speeds was used to tow the second tractor and its trailing wagon. The towing force between the first and second tractors, the drawbar force between the second tractcr and the wagon, the engine speed of the first tractor and the ground speed of the wagon were recorded on the oscillograph.

3.3.2 Power Train Response Time Data: The data relating time-delay in engine-response to an input signal were obtained in the following way. A function generator fed a square wave signal into the control system signal modifier. A square wave was used rather than a triangular or a sine wave because it was easier to detect changes made to this type of signal by the elements of the control system. During this test period the clutch control was turned off and the tractor was operated in a stationary position.

Recordings were made of the signal modifier input, the output to the solenoid air valve, the change in throttle shaft position and the change in engine speed. Throttle shaft movement was recorded by recording the voltage change as the throttle shaft moved a direct coupled potentiometer to which a DC voltage was fed. The frequency of the square wave input signal was increased incrementally and the results recorded. Chart speed was increased at the higher frequencies to facilitate analysis.

The time-delay in clutch actuation was obtained by measuring the length of time between the beginning of an input pulse and the opening of the micro switch indicating the completion of clutch actuation. These data were correct only for the vehicle used in the test and would vary slightly between vehicles.

3.4 Analysis of Data

Charts 1 and 2 are representative sections of the oscillographic recordings made during field tests. Chart 1 is a recording made of the force in the wagon tongue. Chart 2 shows the results of the application of a unit step to the system. This was achieved by suddenly increasing the engine speed of the first tractor by means of the governor control. Force between the first and second tractors rose sharply but there was little change in the average force between the second tractor and the

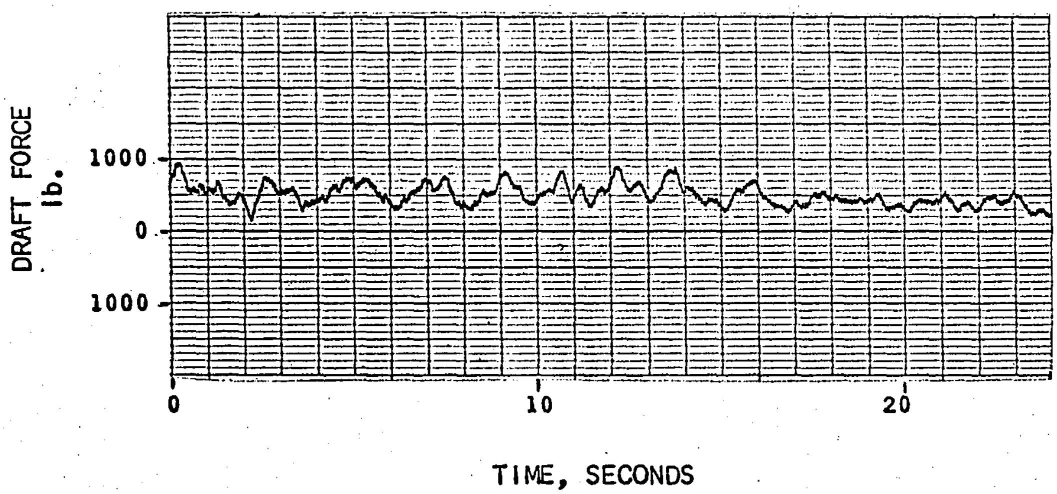


Chart 1. Oscillographic Recording of the Draft Force Between Tractor and Wagon

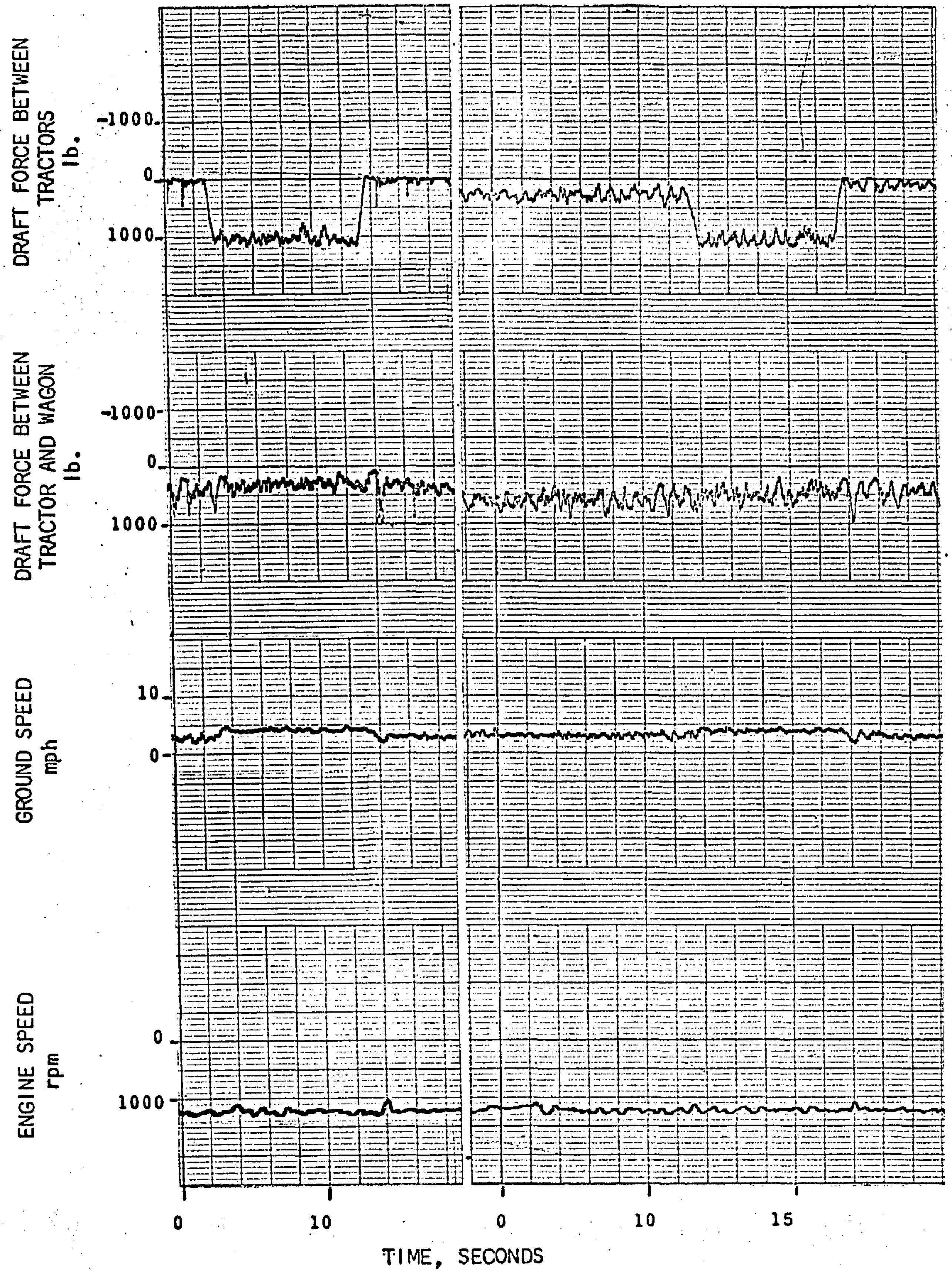


Chart 2. Oscillographic Recordings of Draft Force Between Two Tractors, Draft Force Between Tractor and Wagon, Ground Speed, Engine Speed

wagon. Variations in force in the coupling between the two tractors were much less at high speed than at low speed. The force between the second tractor and wagon also showed fewer variations at high speeds. This was true for all periods of increased speed recorded during the test period.

An analysis of the recordings of the forces between the two tractors and between the tractor and wagon indicated that each recording was comprised of at least three signals, the second and third signal being superimposed on the first. All three signals were a function of the terrain over which the vehicle was operated. The primary signal of lower frequency but higher amplitude was related to the macro changes in the elevation of the terrain. (Macro changes are the upward and downward slopes in the field.) The secondary signal resulted from the intermediate changes in the elevation caused by dead furrows and crop rows while the tertiary signal resulted from the micro changes in elevation due to lumps of ground and stones over which the vehicle was operated.

The frequency of each of the three signals increased with an increase in forward speed. This was to be expected if the above observation was correct. The amplitude of the second and third signals was also found to reduce as vehicle weight or speed increased. This was due to damping which was a function of such variables as vehicle loading, tire inflation pressures, soil properties and wheel parameters. Because the tertiary signal was of very small amplitude and of high frequency in comparison to the primary and secondary signals it was omitted from the analysis of draft force.

This conception of the draft forces existing in the tongue of a self-propelled wagon is more clearly represented by a synthetic reproduction of two of these forces. Chart 3 is an oscillographic recording of a 2.0 hertz signal, a .016 hertz signal and the composite signal made by superimposing the 2.0 hertz signal on the .016 hertz signal. The 2.0 hertz signal represents the secondary draft forces occurring from the intermediate contour changes; the .016 hertz signal represents the primary draft forces resulting from the macro contour changes.

Table 1. Characteristics of the Secondary Frequency Draft Force

Vehicle Speed (ft. per sec.)	Mean Frequency (hertz)	Period (sec.)	Mean Amplitude (lb.)
0.8	1.0	1.0	300
1.9	2.0	0.5	200
5.1	2.5	0.4	150

Maximum draft force during test period	1600 lb.
Minimum draft force during test period	-100 lb.
Total vehicle travel during test period	5500 ft.
Average deceleration time (field speed to zero)	2.0 sec.

Chart 4 is an oscillographic recording of the signal modifier input, the signal to the air valve solenoid, the resultant throttle shaft rotation and the change in engine speed. An analysis of this and other recordings yielded the time-delays in engine control response given in table 2. The clutch engagement time-delay is also included in table 2.

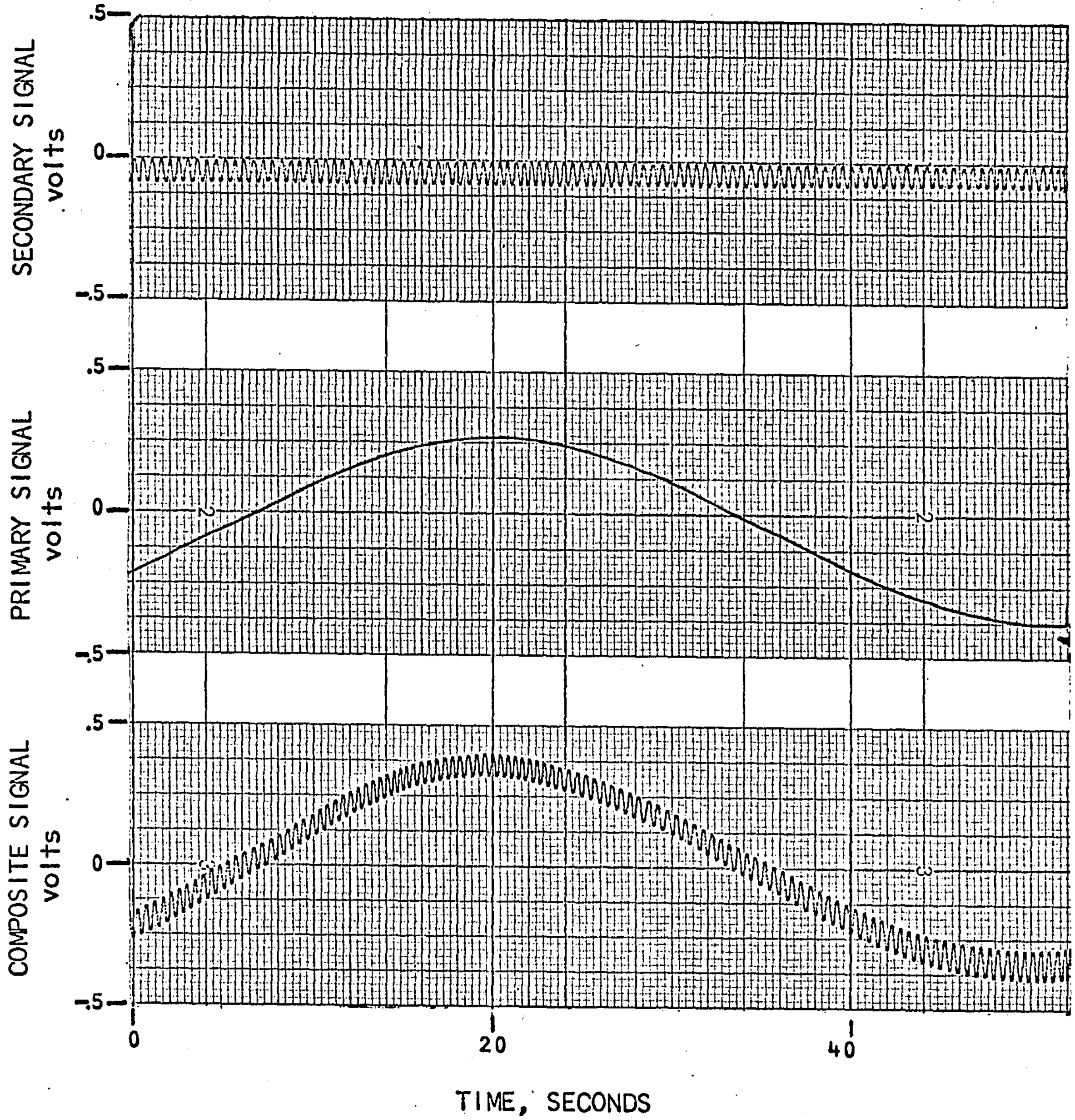


Chart 3. Oscillographic Recording of Synthesized Primary, Secondary and Composite Signals

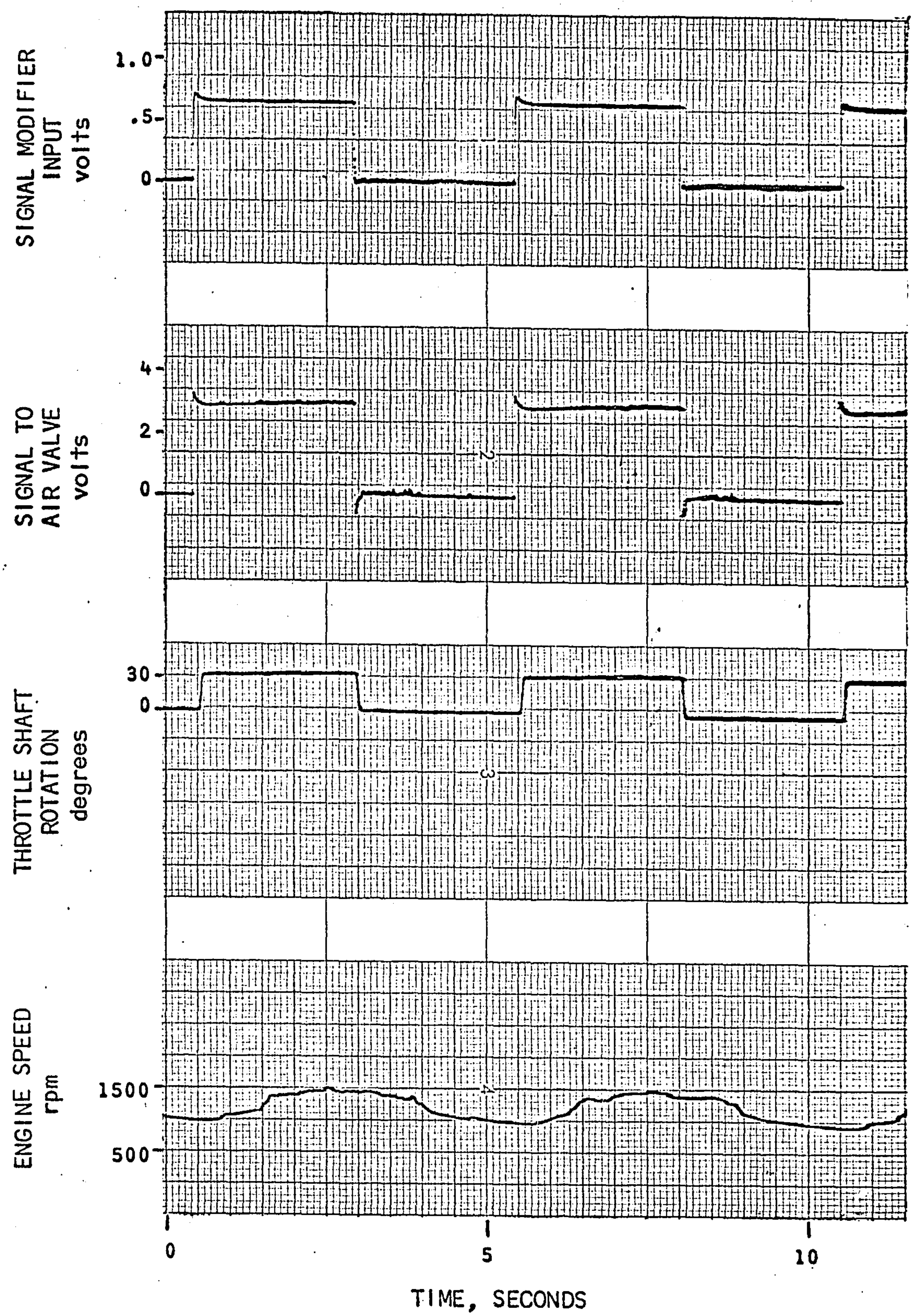


Chart 4.. Oscillographic Recording Showing the Time-Delay Between the Signal Modifier Input Signal, Carburetor Shaft Rotation and Change in Engine Speed

Table 2. Time-Delays in Control

Time-Delay Between	Seconds
Input Signal and Throttle Movement	0.15
Throttle Movement and Change in Engine Speed	0.15
Change in Engine Speed from 550 Minimum (idle) to 66% Maximum (full) Speed Under Light Load	>1.0
Input Signal and Completion of Clutch Engagement	0.5

3.5 Summary

The longest part of the power train time-delay was the time required to effect the change in engine speed in response to a change in throttle setting. Increases in engine load lengthened this time-delay. It was found that the engine would not respond at all to input pulses above 3.0 hertz or respond completely to input pulses above 0.77 hertz. The power train would thus be unable to respond to the changes in the higher frequency secondary draft force signals resulting from vehicle speeds above 5.1 feet per second and instead would operate at the mean value of the signal. It would, however, respond completely to the lower frequency primary draft force signal.

IV. DEVELOPMENT OF CONTROL UNIT DESIGN

The function of the control unit was to generate a control signal. The unit did this by measuring the value of the instantaneous draft force, then comparing this value to the reference signal to create an error signal. The remainder of the control system translated the latter into the correct signal to operate the power train of the self-propelled wagon. To avoid lengthening the total response time each section of the control unit had to generate or respond to the error signal as rapidly as possible.

The control unit was comprised of four sections: the draft sensor, the signal modifying unit, the clutch control, and the carburetor control.

4.1 Draft Sensor

Two forms of draft sensors were studied - a hydraulic-electric unit and an electric unit. Both types created a change in electrical resistance producing a signal which was used to control the throttle position.

4.1.1 Hydraulic-Electric Draft Sensor: This sensor, plate 3 and figure 5, consisted of two sections. The first section, a hydraulic sensor, converted draft into a hydraulic pressure which the second section, a transducer, changed into a specific electrical resistance. Operating pressures were controlled by the second section. Operation was as follows: As pressure in the sensor unit increased, piston 2, forced to the right by

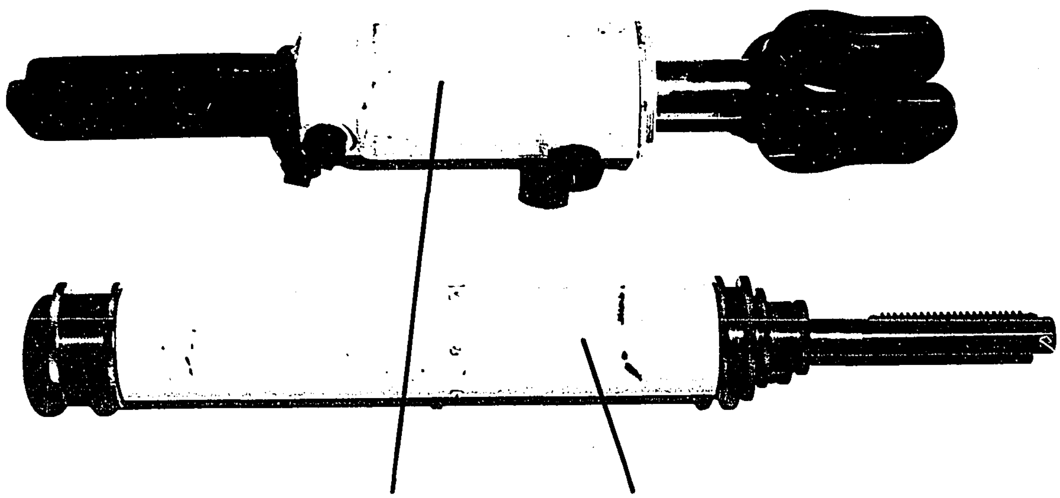


Plate 3. Hydraulic-Electric Draft Sensor

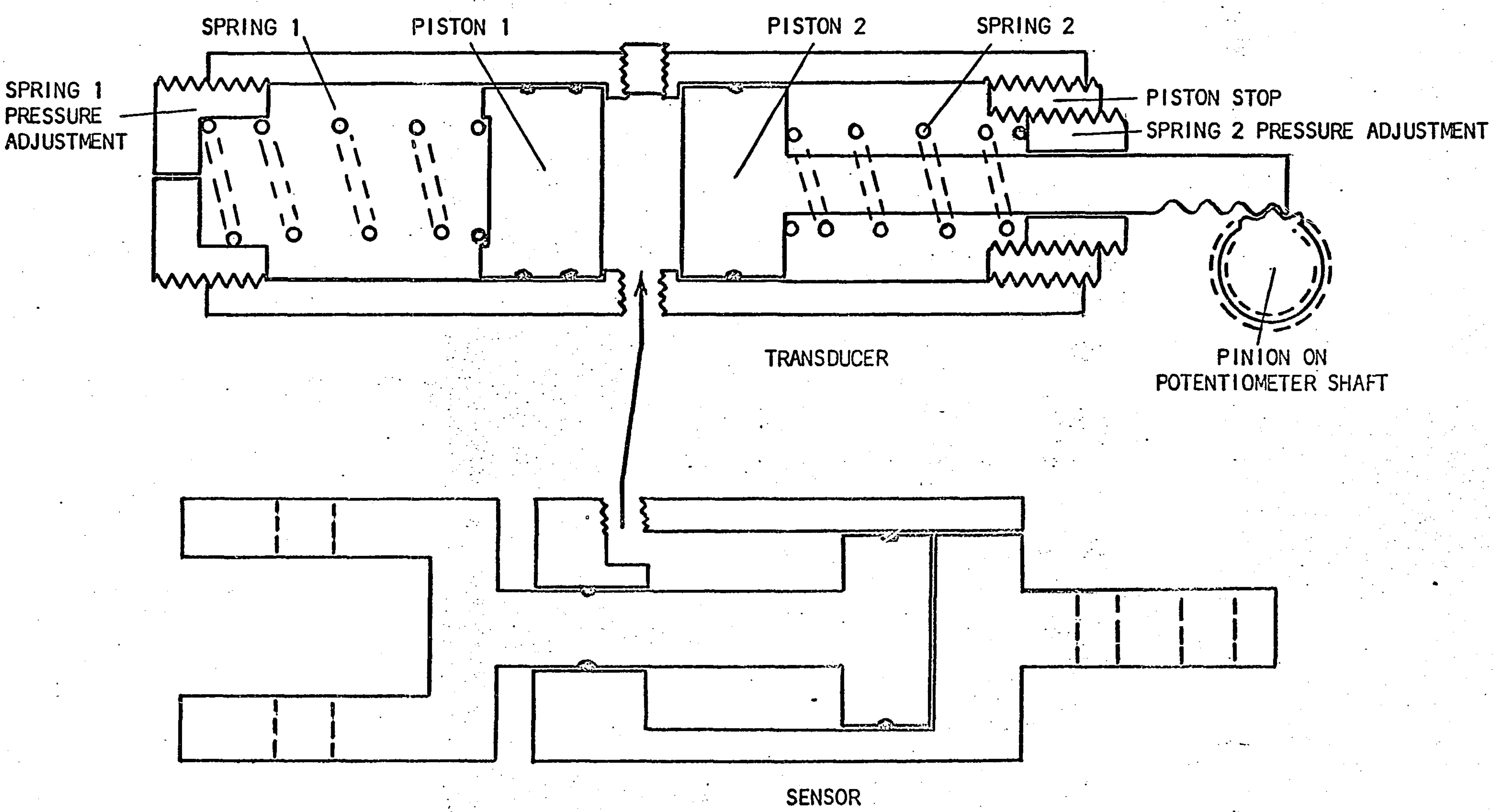


Figure 5. Hydraulic-Electric Sensor Zero pounds Draft

hydraulic fluid being displaced from the sensor, compressed spring 2. At 100 pounds of draft force piston 2 had moved against the adjustable piston stop, which was preset so that the full stroke of the piston moved the rack far enough to rotate the pinion through the full potentiometer travel. If force increased beyond 100 pounds, piston 1 moved to the left as further hydraulic fluid was expelled. At some pressure, determined by the setting of adjustment 1 and spring 1 constant, all the hydraulic fluid would have been expelled from the sensor unit allowing the sensor unit to move to its extreme left position. The sensor would be now mechanically "locked-up", as shown in figure 6, to prevent excessive fluid pressures which would occur if the power unit of the wagon failed to respond to an increase in draft or if the change in draft occurred too rapidly for control compensation to occur.

The unit, in this form, was mechanically complicated and would have been expensive to mass produce. It would not react to values of pull of less than 10 pounds because of friction between components. There was the probability that wear in its many moving parts would create problems. (Another simpler version is shown in Appendix B, figure 12.)

4.1.2 Electric Draft Sensor: The electric draft sensor, plate 4 and figure 2, used strain gauge circuitry. In the design of a sensor of this type a compromise had to be made between a unit which was highly sensitive to changes in pull and one which was rugged. In order to have high sensitivity the wall of the sensor had to be relatively thin to impart maximum strain to the strain gauges. But the sensor also formed the link between the wagon and the towing vehicle and was therefore subjected to

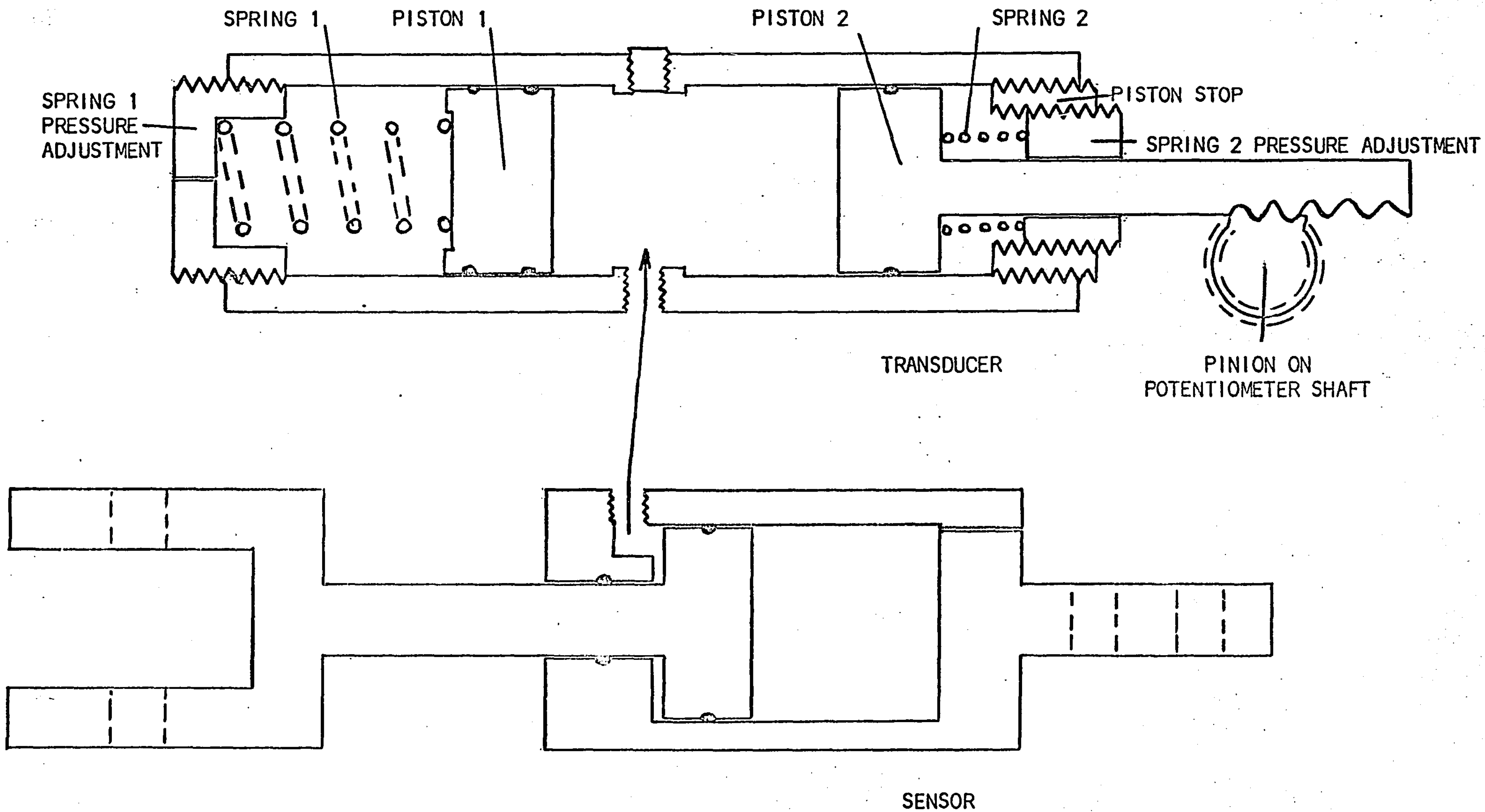


Figure 6. Hydraulic-Electric Sensor 100 pounds Draft

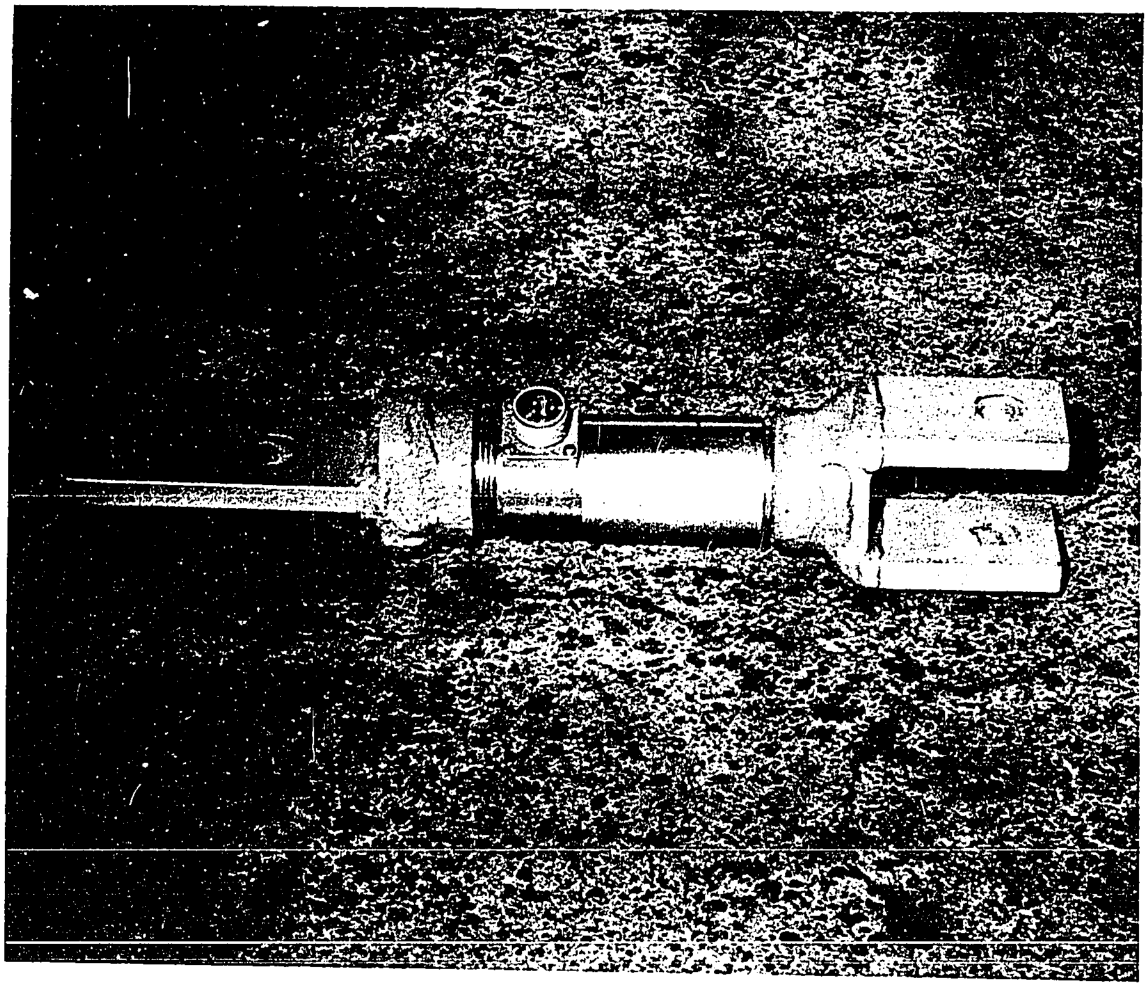


Plate 4. Electric Draft Sensor

various loads such as the load from the pull existing between the two vehicles and the side loads resulting from steering forces. If the power unit functioned properly the pull would be small but the steering loads could still be large. If the power unit failed, the pull on the sensor could rise sharply. Field data showed a maximum pull of only 1600 pounds but peak loads can exceed this amount. The sensor must also withstand abuse from mishandling during coupling or uncoupling the wagon from the towing vehicle.

The sensor used was arbitrarily designed to accept a maximum pull of 10,000 pounds without exceeding the elastic limit of 30,000 pounds per square inch of the mechanical tubing used in construction. The 10,000 pound limit ensured an adequate safety factor to withstand steering and pulling loads, and reasonable sensitivity to changes in pull. Finally, the unit, with the wall thickness chosen, was able to stand a certain amount of rough usage.

The sensor was constructed from a six inch length of mechanical tubing with an interior diameter of 1.595 inches. A two inch section near the mid-point, was reduced to an outside diameter of 1.745 inches to give a cross sectional area of .3934 $inches^2$. The coupling devices which would bolt one end of the sensor to the wagon tongue and pin the other end to the tractor drawbar completed the sensor as shown in plate 4.

In the two-inch section, stress resulting from a 100 pound pull was calculated to be:

$$\sigma = \frac{P}{A} = \frac{100}{.3934} = 254.2 \text{ pounds per square inch}$$

$$\text{Longitudinal strain} = \frac{254.2}{29 \times 10^6} = 8.765 \times 10^{-6} \text{ inches per inch}$$

$$\text{Transverse strain (by Poisson's ratio)} = -2.191 \times 10^{-6} \text{ inches per inch}$$

Four Micro Measurement gauges, type EA09375B8120, were mounted on the sensor. These longer gauges were used because:

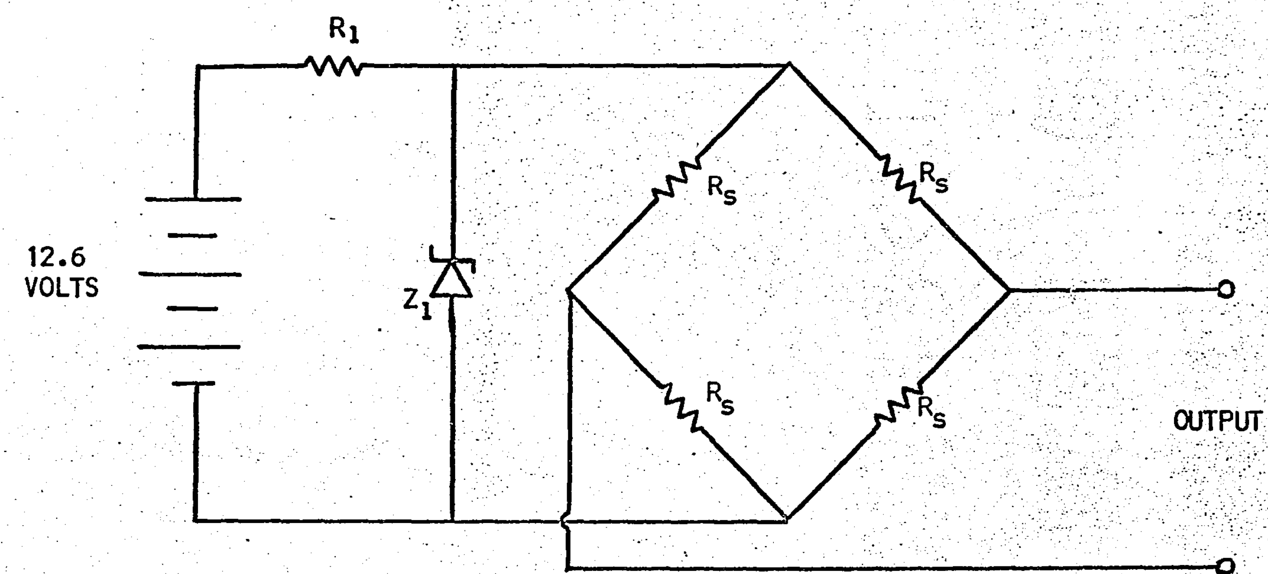
i) when the strain gradient is small a longer gauge has greater sensitivity,

ii) the longer gauge is less sensitive to transverse strain, and

iii) the longer gauge has a greater area in contact with the mounting surface to dissipate heat created by gauge current.

The gauges were mounted in the standard configuration to utilize Poisson's effect, i.e. two gauges measure transverse strain. A metal sleeve, fastened at one end to avoid affecting sensor operation, fitted over the section with the gauges to give mechanical protection. Connections were made to the gauges via a low resistance, low noise connector. (Cannon Part Number MS3102A14S-58(0)).

Since the four gauges, connected as a bridge, figure 7, were mounted in the same temperature environment and carried the same current, the sensor was temperature compensated[7]. A stabilized voltage (12 volts) was applied to the bridge.



R_1 - 10 OHM, 10 WATT

R_s - MICRO MEASUREMENT EA09375B8120 OR BUDD C6-141B STRAIN GAUGES

Z_1 - 12 VOLT 10 WATT ZENER DIODE

Figure 7. Sensor Circuit Diagram

The change in resistance for these gauges was calculated to be:

1) Longitudinal gauge $\Delta R = \varepsilon K R$ where $\varepsilon = \frac{\sigma}{E}$

K = gauge factor

$= 8.765 \times 10^{-6} \times 2.085 \times 120$

$= 2.193 \times 10^{-3}$ ohms

2) Transverse gauge $R = .548 \times 10^{-3}$ ohms

The expected bridge output voltage resulting from the application of 100 pounds of force to the sensor was $.137 \times 10^{-3}$ volts. An amplification of the sensor voltage by approximately 3650 times (71.3 db) was required to provide the correct base current to the transistor controlling the air valve solenoid current. Here db = decibels = 20 log $\frac{E_{out}}{E_{in}}$.

(It may be noted here that, in theory, the sensor output should be zero until some pull is imposed on the sensor but that in practice, there might be some small output voltage because of circuit imbalance resulting from manufacturing tolerances in the strain gauges and from the mounting of the gauges on the sensor. The effect of this voltage can be cancelled at another point in the following circuits.)

A low level DC voltage such as that expected from the sensor is difficult to amplify. In this control system the output from the sensor was fed to a chopper which converted the DC input to a synchronous AC output. The magnitude of the AC voltage was proportional to that of the incoming DC signal and the phase dependent on the DC polarity. This new signal was amplified by an AC amplifier and then converted to DC.

Choppers have generally been elaborate, bulky mechanical relays operated from a 400 hertz source. Bipolar transistors can be used in a chopping circuit but these require a special transformer to isolate the driving voltage from the DC voltage being chopped[11]. On the other hand, field effect transistors (FETs) do not need the special transformer but care must be taken in the choice of the circuit. There is a certain inherent capacity and resistance between components within the transistor and because switching occurs at a high speed a differentiating circuit may exist which would produce unwanted output spikes. In certain circuits the spike voltages could exceed the value of the DC voltage being chopped thereby limiting the minimum value of usable DC input voltage. The circuit chosen[14] had a usable minimum input voltage of $\pm 10\mu v$ which was well below the sensor output of $137\mu v$.

The chopper was driven by an astable multivibrator[13] at a switching speed of 100 kilohertz. The output of the chopper was then amplified by an integrated circuit operational amplifier, IC_1, (Texas Instruments' SN724N), which had a gain of 30 dbs. Finally, the AC output of the amplifier was converted to DC and applied to one of the inputs of the differential amplifier, IC_2, (Texas Instruments' 2N725), as shown in figure 8.

Now a voltage regulated by the zenor diode Z_1, was applied to the potentiometer R_8. The potentiometer output voltage, e_2, was connected to the second input of the differential amplifier which

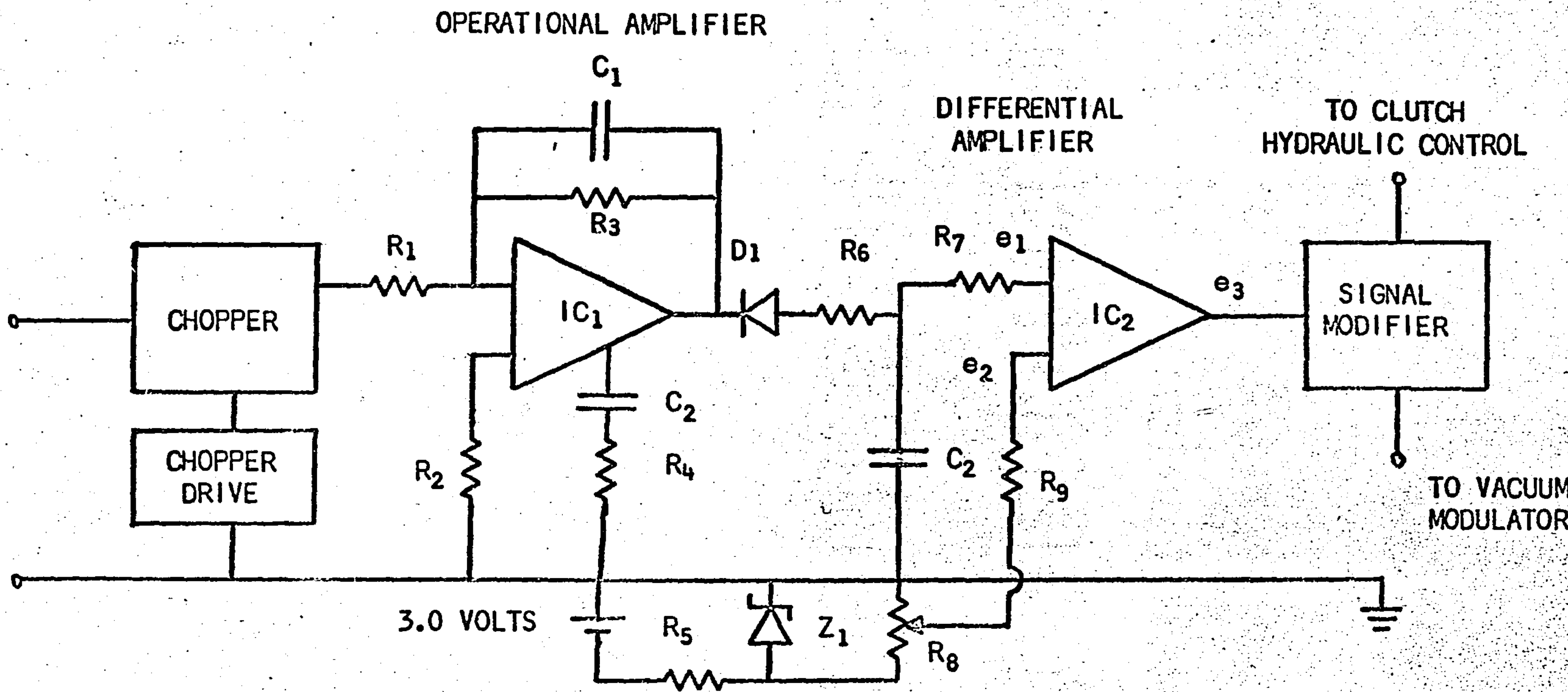


Figure 8. Diagram of Strain Gauge Output Amplifier

amplified the difference between the two voltages, e_1 and e_2, to produce voltage e_3. When voltage e_3 was of the correct polarity it became the error signal and was processed by the signal modifier circuits. If voltage e_3 was equal to zero or of the wrong polarity the control was quiescent. In this way the value of voltage e_2 set the draft reference level referred to in Chapter II, establishing the amount of draft force necessary to start control action.

4.2 Signal Modifier

Initially, the clutch and throttle controls responded to the same error signal but this signal required modification to match the characteristics of both A, the function and B, the operating parameters of each control. These characteristics were as follows:

A. Function: 1) Clutch Control. The clutch, like an electric switch, has two operating states either engaged or disengaged. It does not have any intermediate operating state but does have an unavoidable transition period between the two states. As a result, the function of the clutch control requires that the signal be either on or off.

2) Throttle Control. The throttle control must be able to produce a low or high or any intermediate engine speed proportionate to the strength of the error signal.

B. Operating Parameters: a) Starting

1) Clutch Control. The clutch control relay must energize as soon as the error signal appears.

2) Throttle Control. The throttle control must also react to the error

signal but the amount of reaction must be limited until clutch engagement occurs. Without some limit being imposed, the engine, during the transition period of the clutch, might race, producing an undesirable abrupt shift from standstill to a high forward speed.

b) Movement - Based on the field data the average draft force was well above the amount chosen as the reference level. But the draft signal was a constantly varying signal which would only momentarily drop below the reference level unless the vehicle was descending a slope.

1) Clutch Control. The elapsed time while the draft forces remain below the reference signal level is normally much shorter than the time required for clutch operation. The clutch must then be prevented from trying to disengage under these conditions by inhibiting clutch control relay deenergization by means of a time-delay. This time-delay must be longer than the period of the secondary frequency draft forces. Descent of a slope affects the clutch control in a similar manner to that of stopping movement. During this period there would not be an error signal present.

2) Throttle Control. The throttle must follow changes in the draft force as closely as possible within the limitations imposed by control and power train reaction times.

c) Stopping Movement - Stopping may occur as the result of normal deceleration or rapid deceleration; for example, through the application of brakes. In either case the error signal will disappear.

1) Clutch Control. The clutch control relay will deenergize on completion of the time-delay built into the clutch control relay circuitry. Some vehicle braking effect will occur from the engine until the engine idle speed is equal to or greater than that required to move the vehicle at

that particular instantaneous speed. If the clutch control relay time-delay is too short, part of this effect is lost. Time-delay was set to 2.0 seconds on the basis of average deceleration times obtained from field data.

2) Throttle Control. The throttle control will reduce the engine speed to an idle as deceleration occurs. Throttle response time was less than deceleration time.

The signal modifier, figure 9, consisted of two sections, the clutch control and the throttle control. Both sections had a common input.

The clutch control section was a switching circuit preceded by a DC amplifier and signal inverter. There was a 2.0 second time-delay on deenergization. The transistor controlling the relay conducted current as soon as an error signal voltage appeared at the input and stopped conducting at the conclusion of the time-delay.

The throttle control section was a DC amplifier which generated a change in the final amplifier collector current to change the position of the air valve in the vacuum modulator as the error signal changed. A clamp circuit, disconnected on completion of clutch engagement, limited the value of current in the final amplifier collector and thus the amount of the air valve closure. (Fully closed gave maximum engine speed.)

A circuit diagram and a detailed description of the operation of the signal modifier are given in Appendix C.

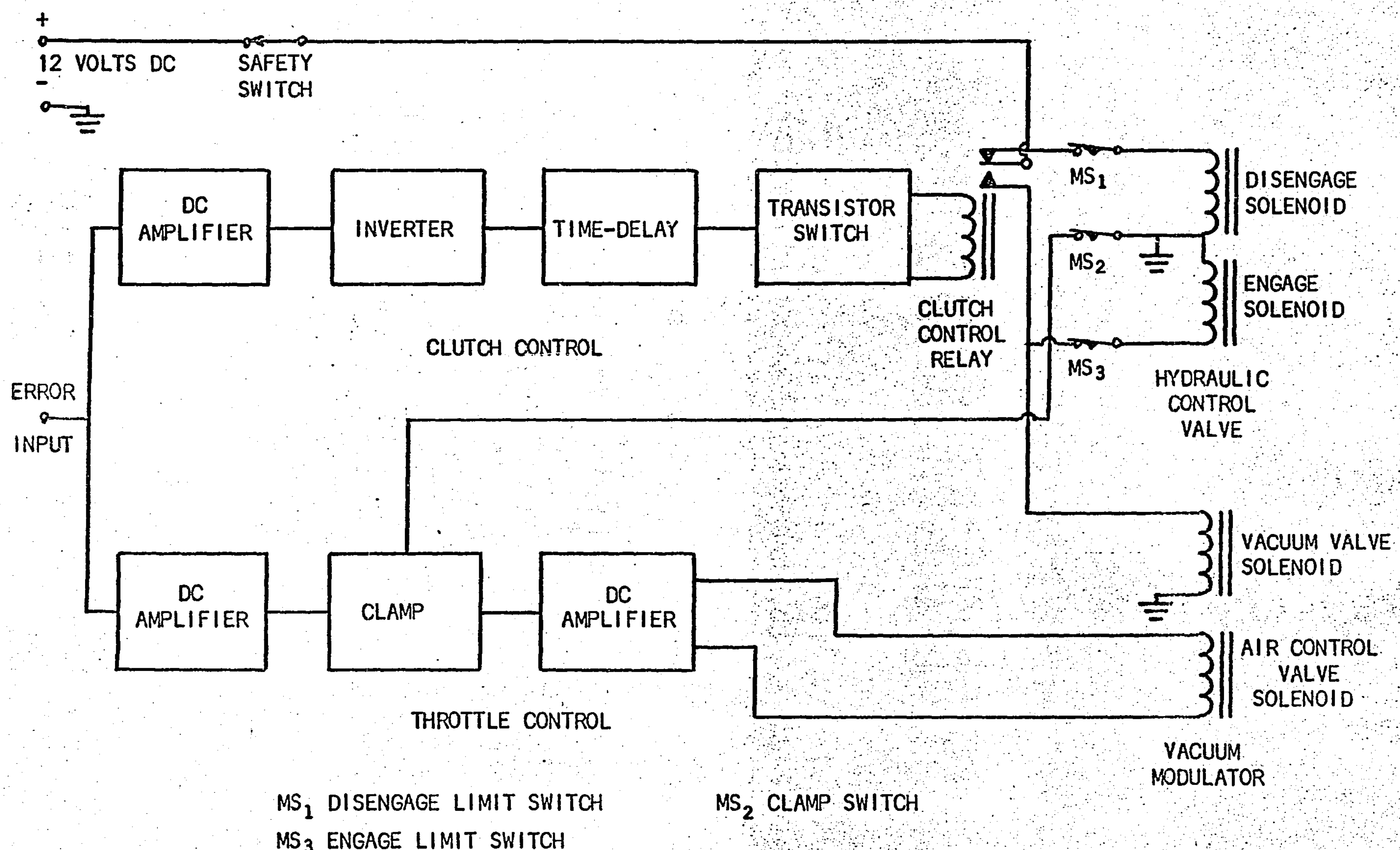


Figure 9. Diagram of Signal Modifier and Control Circuits

4.3 Throttle Control

Three methods of controlling the throttle were tested: an electric motor driven control, a solenoid operated control, and a vacuum servo control.

4.3.1 Electric Motor Driven Control: This method of positioning the throttle used a reversible DC motor. A gear reducer converted high motor shaft speed to a very low speed to drive a crank mechanism connected to the throttle, whose position could be controlled by running the motor forward or backward. Microswitches, actuated by the throttle control at its minimum or maximum position, limited travel. The motor also drove a small DC generator to provide a feedback signal.

This method of control was rejected after testing. There was a time-delay between an input signal and the subsequent change in carburetor setting. Backlash in the gear train created positioning problems. The unit was complex and more expensive than other systems.

4.3.2 Solenoid Position Control: A solenoid is an electro-mechanical device normally intended to move some mechanism from one position to another as rapidly as possible without stopping at any intermediate point. The mechanical force is not linear. Once the solenoid is fully energized, less current will hold it closed (energized). This effect is called hysteresis. A standard solenoid is thus not a positioning device unless modifications are made.

Most of the undesirable hysteresis effect was reduced by removing the armature stop from the core of the solenoid and making an opening in the bottom of the case through which a longer armature could extend. A further reduction in hysteresis was made when travel of the armature was limited to prevent the end of the armature from leaving the core and entering the hole through the case. A certain current now moved the armature against spring tension to a specific position.

The force developed by the armature, however, was still not linear even with the modifications. Force and rate of movement increased non-linearly as the plunger moved into the solenoid. Unless compensation was made for this fact, throttle positioning was still difficult. Compensation could have been affected by causing the opposing mechanical force to increase at the same rate of increase as the solenoid force by using a return spring with a rising spring constant or by using a mechanical linkage which provided a decreasing mechanical advantage as the throttle moved towards its wide open position. This latter technique was the one under investigation. Ideally a cam should have been used but an offset lever arm, figure 10, was used as a compromise.

As the throttle control moved it could also have been made to move a permanent magnet plunger inside a coil of wire to generate an electric current that would provide a feedback signal.

The solenoid position control gave precise control under optimum conditions but any small amount of extra friction at a key point created problems in positioning. Under field conditions of dust and wear these problems would increase. The measured force of the laboratory model was 16 ounces, which was sufficient to operate a carburetor with its

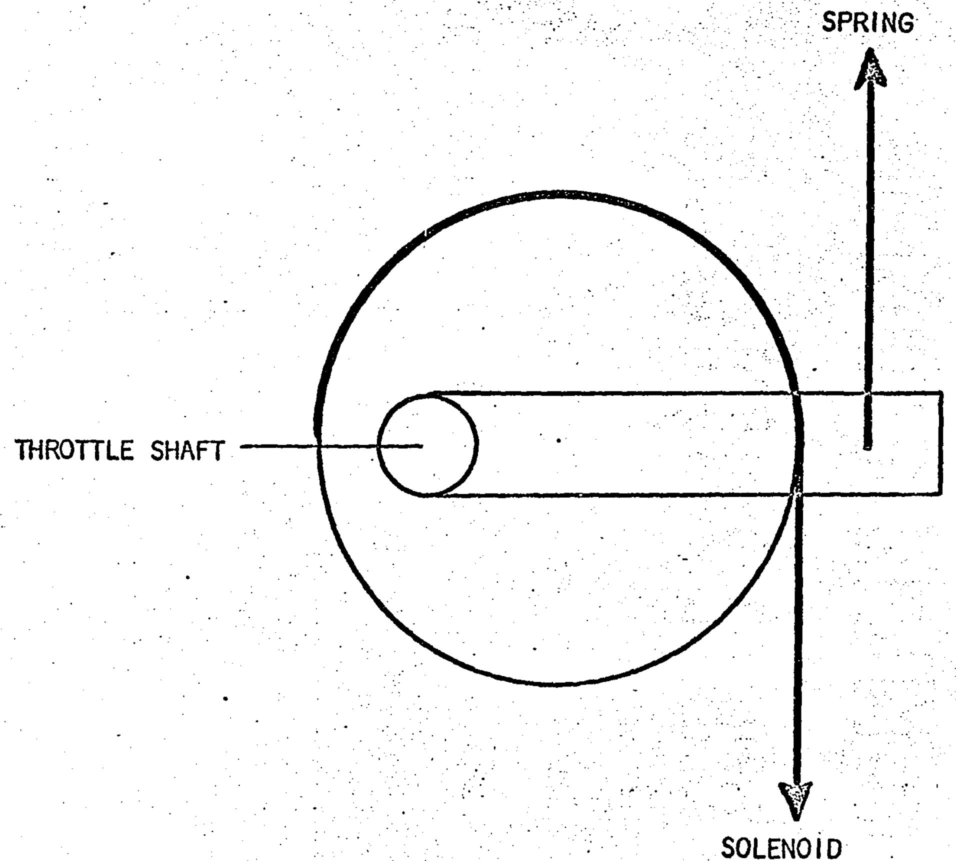


Figure 10. Offset Lever Arm

external linkage removed. A larger solenoid would have given greater force, nevertheless this method of control was rejected in favour of the vacuum servo unit modulator control.

4.3.3 Vacuum Servo Control: Car manufacturers offer automatic speed control units as an option. These units are generally of two types. Both types use a fly-ball sensor driven from the speedometer linkage. One control[10] uses an all-electric carburetor control system which is part of the fly-ball unit and the other[1] uses a separate vacuum servo unit controlled by a vacuum modulator which, in turn, is controlled by the fly-ball sensor.

The vacuum servo unit is a bellows with one side anchored and the other connected by a short chain to the regular driver-operated throttle control linkage. The chain, being flexible, allows normal driver operation. If air is drawn from the bellows the servo collapses. The amount of collapse is determined by a) internal air pressure, and b) spring tension both on the throttle control linkage and inside the bellows.

The vacuum servo seemed to be capable of the type of carburetor control needed for this unit. It was simpler, had a minimum of moving parts, was not affected by dust, and was capable of producing sufficient pull. Rate feedback could be obtained in a similar way to that described for the solenoid control.

The key to effective control of the servo was the vacuum modulator. A vacuum modulator, figure 11, different from that used in

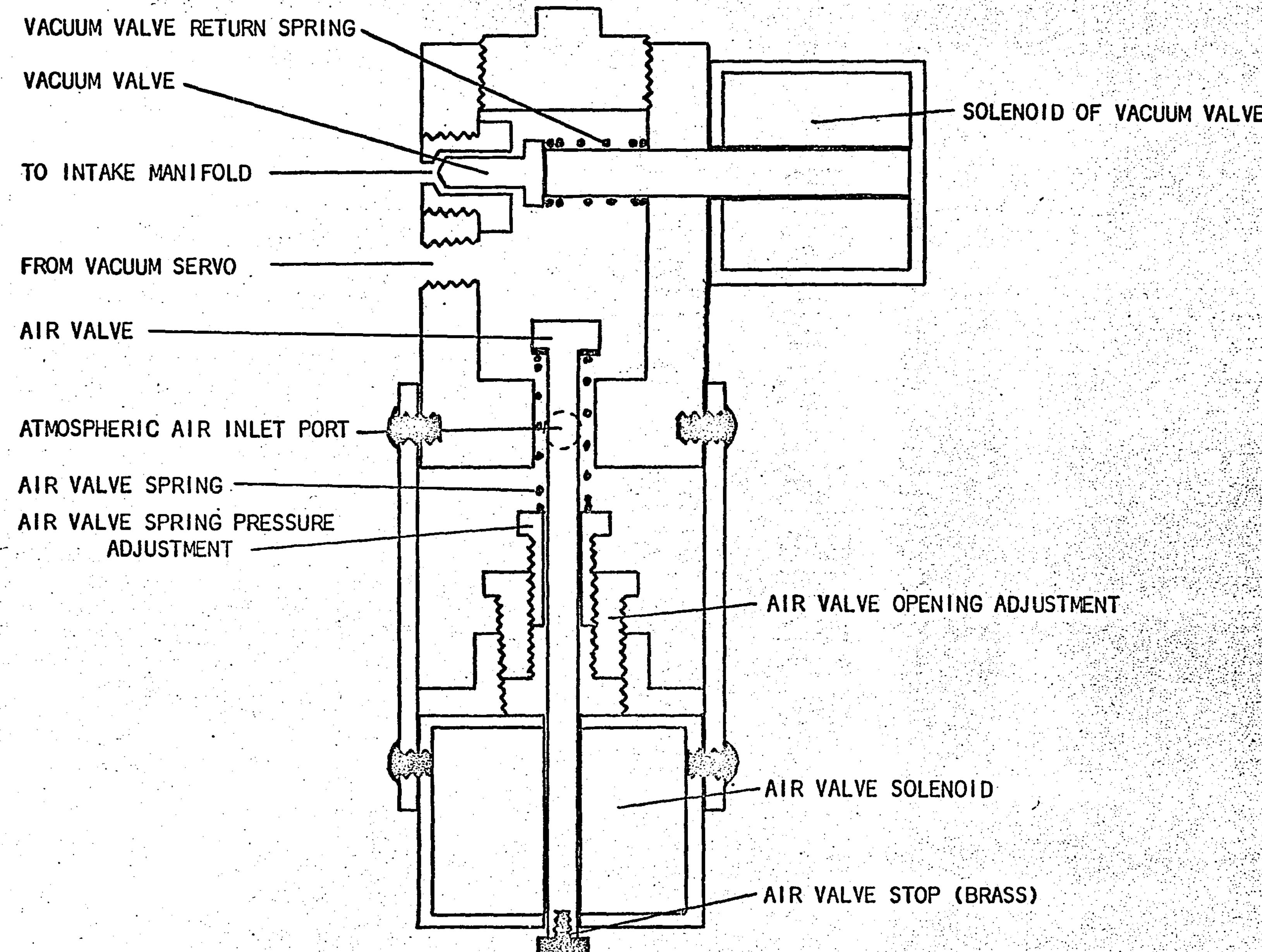


Figure 11. Vacuum Modulator

the car speed control was constructed. Its operation was as follows: When the solenoid vacuum valve of the modulator was energized by the clutch control relay, air pressure inside the modulator dropped to that of the intake manifold. The amount of air flow to the intake manifold was adjusted by means of a valve in the connecting air line. The solenoid operated air valve controlled the flow of outside air into the modulator and thus its internal pressure. The unit is shown in plate 5.

The shape and size of the face of the air valve were important to its operation. The mechanical force of the solenoid, modified as discussed previously, was opposed by the valve spring and by air pressure operating against the flat under face of this valve. Air pressure on the valve face increased as the valve moved towards the closed position. Thus the force opposing the solenoid increased non-linearly, effectively offsetting non-linearity in the solenoid force characteristics. Collector current of the DC amplifier controlled the air valve solenoid.

4.4 Clutch Control

Gilmour[12], in developing his automatic control system for farm tractors, used a solenoid clutch control with a dashpot. In the unit under development a short stroke, double acting, hydraulic cylinder was coupled to the clutch linkage in such a way that either it or the normal foot pedal would control the clutch, plate 6. Hydraulic fluid flow to the cylinder was controlled by a solenoid operated, open centre control valve. The valve solenoids were energized by the clutch control relay of the signal modifier. When the engage-solenoid was energized the control valve supplied hydraulic fluid causing the cylinder to retract.

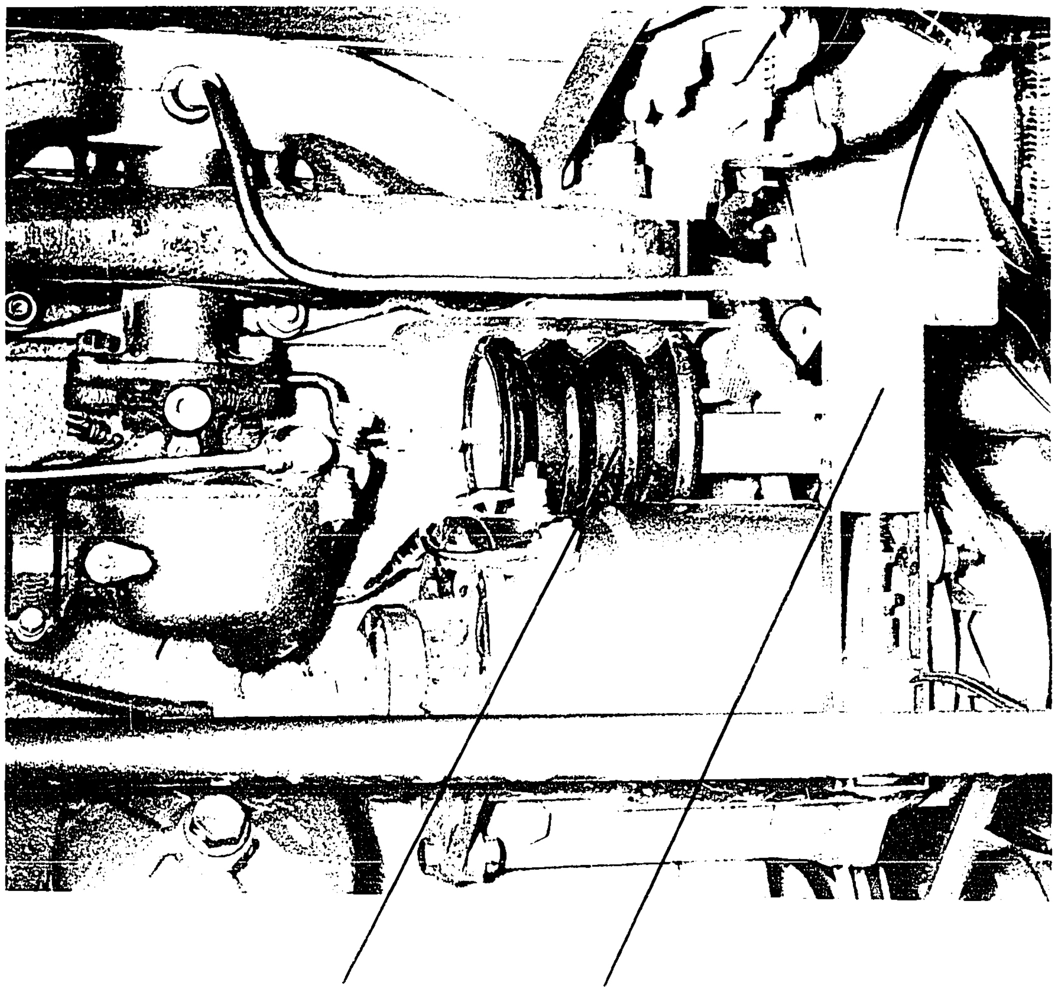


Plate 5. Vacuum Servo and Vacuum Modulator

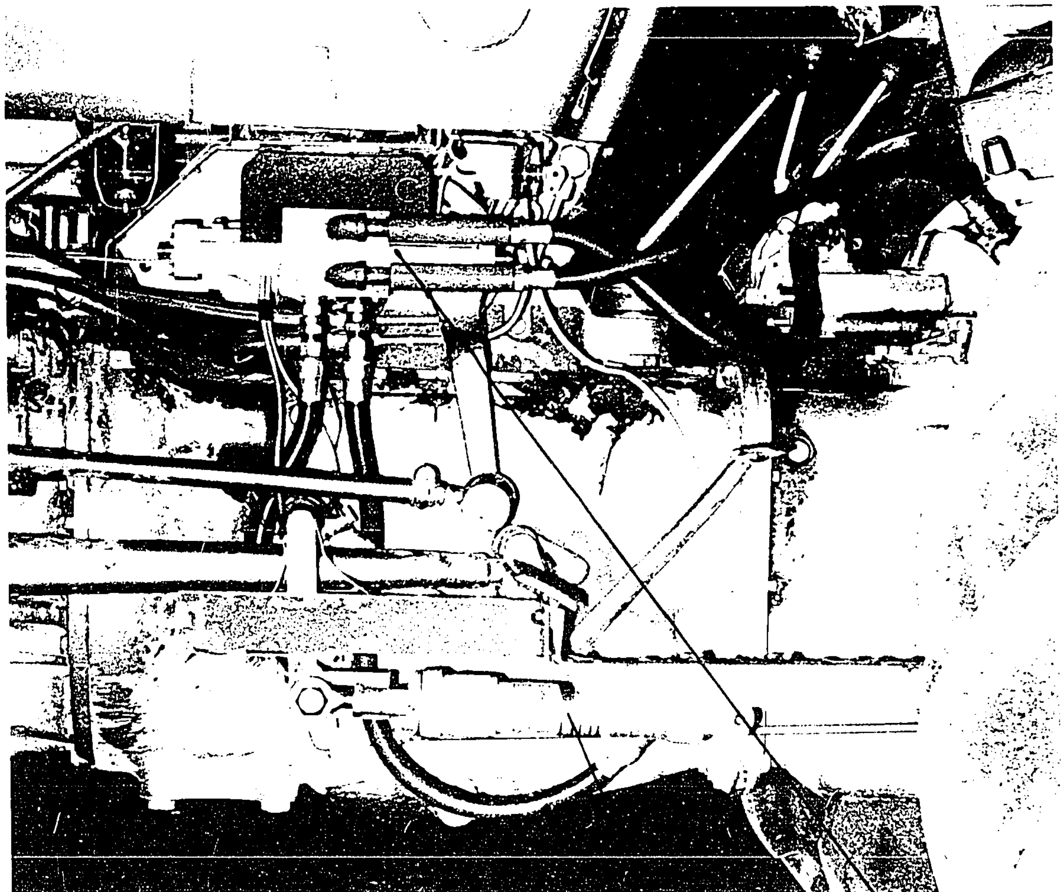


Plate 6. Clutch Control - Clutch operating cylinder
Solenoid operated hydraulic valve

When the clutch was fully engaged the clutch arm depressed a microswitch to open the engage-solenoid circuit, allowing the hydraulic control valve to return to its open-centre position. Hydraulic pressure was still maintained inside the cylinder but hydraulic fluid flow was by-passed into the reservoir. This was done to prevent pressure and heat build-up which would occur if the engage-solenoid remained energized and the system pressure relief valve controlled pressure. A safety switch was provided to disconnect the clutch controls. The hydraulic control valve could also be operated manually if desired.

4.5 Summary

The completed draft control system consisted of:

i) a sensor using strain gauges

ii) an amplifier for the sensor output

iii) a signal modifier to produce the separate clutch and vacuum modulator control signals

iv) a vacuum modulator to change the signal modifier output into a change in air pressure, and

v) the vacuum servo to control the throttle position.

Automatic feedback in the control unit was obtained through the changes in the draft force on the sensor as a result of power train reaction to sensor control.

V. TESTING OF CONTROL UNIT

5.1 Preliminary Evaluation

Each section of the control was constructed and tested for operation. After preliminary testing some components were rejected, e.g., the electric motor driven throttle control. On the tractor being used to simulate the power unit and power train of a self-propelled wagon the components were mounted in place and retested. In some cases test data were collected to determine response times to be used in developing other control components.

In addition to rejecting certain components, changes were made to other components after initial testing. It was found for example that a small change in air pressure inside the vacuum modulator made a large change in the movement of the vacuum servo and in the throttle setting. Because of this, the adjustment of air control valve both mechanically and electrically was not only critical but also difficult to maintain. This problem was corrected by increasing the amount of vacuum servo movement necessary to effect a specific throttle change.

5.2 Laboratory Testing

All this testing of the control unit was confined to the laboratory. To determine probable operation and time-delay two series of tests were conducted.

The first series was used to evaluate overall control unit operation. During this test the draft sensor was manually loaded, with the inputs of simulated draft kept as uniform as possible.

The second series of tests were used to evaluate the total time-delay between the application of an input and the resulting change in vehicle movement. It was difficult to load the draft sensor in such a way that it would provide a square wave output at a constant frequency. However, because the draft sensor in use converted an input draft force almost instantaneously into an output signal, the function generator could be substituted to simulate the controlled output signal necessary.

During the first series of tests the draft sensor was connected to the oscillographic recorder and the output of the recorder was fed to the signal modifier. Recordings were made of the draft force on the sensor, the engine speed, the ground speed of the tractor and the clutch actuation signal. A sample section of the oscillograph chart is shown in Chart 5.

Recordings were made during the second series of tests, with the function generator replacing the draft sensor, of the function generator output, the engine speed, the ground speed and, the signal modifier output to the air valve solenoid. The clutch control relay was disconnected and a separate switch used to control the operation of the solenoid valve to keep the moving tractor within reach of the interconnecting cables but still allow maximum recording time. Clutch actuation was not recorded but can be determined from the recording of ground speed. A section of the oscillograph chart is shown in Chart 6.

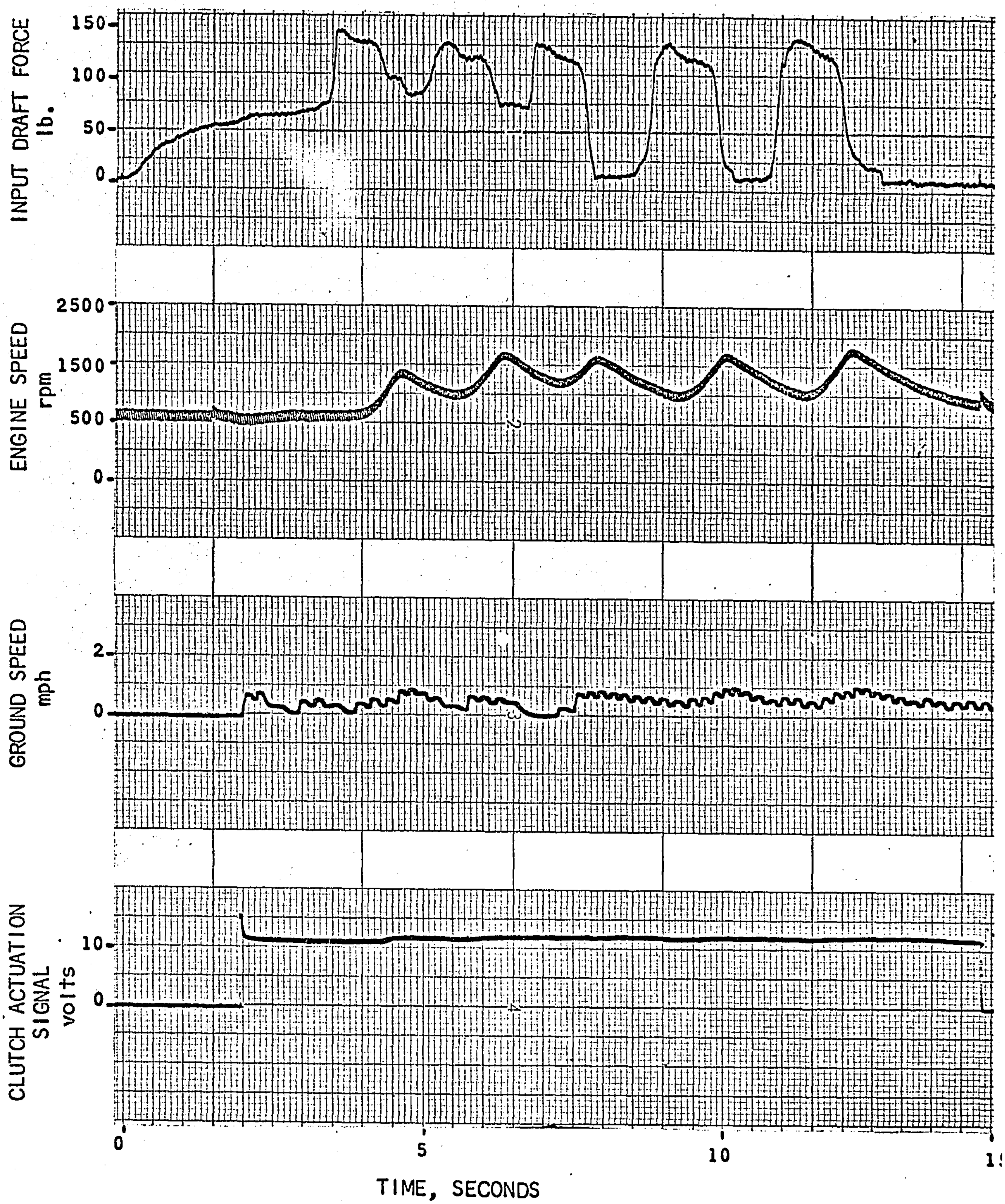


Chart 5. Oscillographic Recording of Response of Engine Speed, Ground Speed and Clutch to Draft Force on Sensor

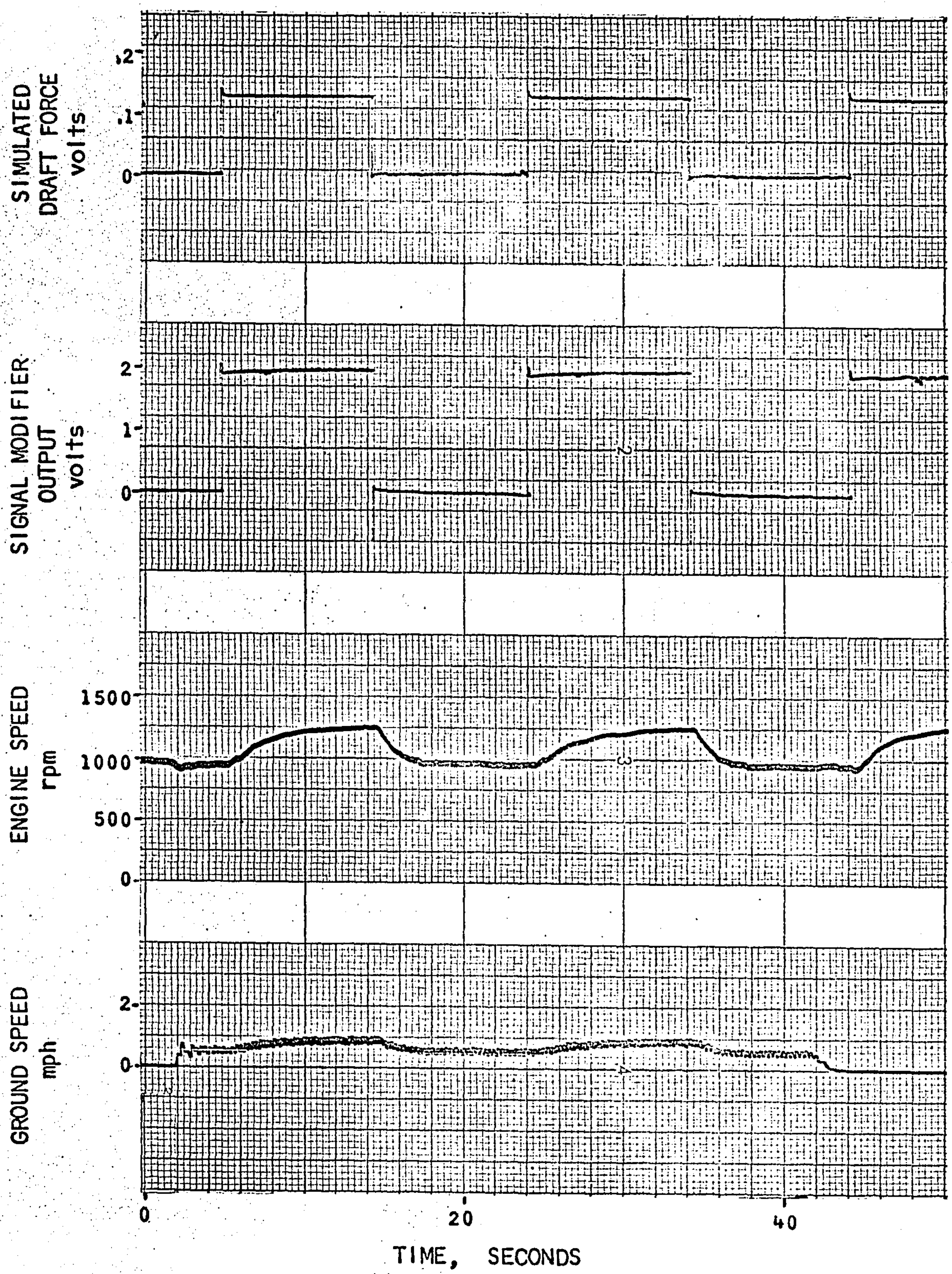


Chart 6. Oscillographic Recording of Response of Signal Modifier, Engine Speed and Ground Speed to a Simulated Draft Force

5.3 Analysis of Tests

Some comments should be made regarding the graphs of engine speed. This type of graph results from the method used to record the engine speed. As stated before, the transducer acted on the ignition pulses from the engine distributor and integrated these to produce a graph of engine speed. At high sensitivity and high paper speeds the recorder would record the original ignition pulses as part of the graph. This effect could have been removed with better filtering but it was considered advantageous to be able to count the pulses from the recording.

During the tests conducted, of which chart 5 was part, the clamp circuit was not used. Therefore the engine speed should have begun to rise with the increasing input force consistent with the expected time-delays. This did not occur thus indicating that during this test period the throttle control did not produce sufficient movement of the throttle. As a result the chart gives the impression that there was a considerable time-delay. If the point (time = 3.5 seconds) at which the initial input pulse begins increasing rapidly is considered then the time-delay in the change in engine speed from that point on is consistent with the expected time-delay.

The vacuum servo had to overcome high spring pressure in order to initiate throttle movement and this required a considerable change in internal air pressure of the servo to develop the required force. A reduction of spring force should therefore correct this should it be a problem during field tests.

The time of the beginning of the clutch actuation is indicated by a "pip" on the recording of the engine speed. This effect is created by the energization of the engage solenoid. A similar effect occurs on deenergization.

5.4 Results of Laboratory Tests

Applications of simulated draft force during the first test series were not equal but the change in engine speed and forward speed were proportional to the draft force. It would thus appear that the control system is stable at this frequency of draft input.

If a higher input of draft resulted in a much higher peak in engine speed -- indicating that the speed was tending to overshoot the application of draft -- instability would have been suspected.

The time-delay feature of the clutch control section of the signal modifier functioned as intended in preventing unnecessary clutch disengagement. This is evident from chart 5. On two occasions, (at 7.7 seconds and 9.7 seconds), the draft force dropped below 55 pounds but the time-delay prevented disengagement.

The results of tests are given in table 3.

Table 3. Results of Tests

Time-Delay in Seconds Between Application of Input and:	Expected	Actual
Clutch Engagement (completion)	0.5	0.5
Change in Engine Speed	0.3	0.6
Maximum Engine Speed*	>1.0	>1.1
Time-Delay in Seconds Between Completion of Input and:		
Clutch Disengagement	2.0	2.2
Draft Force (in pounds) Required to Initiate Clutch Engagement	50	55

*Depends on load and amount of throttle opening

VI. SUMMARY

The tests performed in the laboratory showed that the control met the requirements of the design. The control automatically forced the power unit to supply the draft requirements above a preset minimum by engaging the clutch and advancing the throttle.

Indications were that the fail-safe requirement was met in the following ways: 1) if failure of the vacuum system occurred the vacuum servo would relax returning the throttle to an idle, 2) if the clutch relay failed to operate to engage the clutch, the vacuum valve solenoid would not open and the engine speed remained at an idle, and 3) if the air valve solenoid closed because of high collector current the resulting high engine speed would produce a negative draft component on the sensor, a zero error signal and clutch disengagement cutting off the vacuum in the vacuum modulator and returning the engine speed to idle. However, if a signal other than the correct error signal should develop because of a failure in the system there would be an increase in forward motion of the vehicle about which the unit could do nothing. An override circuit would have to be added to the control if there was a possibility that this problem would develop.

Little interference to driver operation resulted from the control system installation. Turning one switch off in the power supply circuit restored control of the throttle and the clutch to normal.

It may be argued whether the unit was as simple as possible consistent with fulfilling its requirement. Future investigation of the modified hydraulic-electric sensor or of a sensor wherein draft operated directly on a spring loaded rheostat, using damping if necessary, may produce a simpler form of control. The strain gauge type of sensor is simple but the necessary chopper and high gain amplifier is not. Because of the gain necessary any circuit noise when amplified along with the strain gauge output voltage could become a problem. The two sensors suggested as alternatives would produce the necessary voltage to operate the signal modifier without the need for amplification.

Results of the tests indicate that the design has some merit. However, operation under field conditions can be often quite different than in the laboratory and may reveal deficiencies in parts of the control system.

VII. RECOMMENDATIONS FOR FURTHER RESEARCH

It is recommended that the control described in this thesis be field tested under a variety of conditions. Other changes to the design may be suggested by such a testing program. One immediate addition which might be a necessity in rolling terrain would be an automatic braking system. A system which might be readily incorporated, with some modification, is the one developed by Douglass and Burdette[6], to automatically apply the brakes of a house trailer towed behind an automobile as the automobile stops. As suggested, some of the simpler draft sensors should be evaluated in comparison with the electric draft sensor and its elaborate amplifier.

The automatic draft control unit, as reported in this thesis, was required to control the clutch. The process of clutch engagement forced a time-delay in the operation of the power unit. If the self-propelled wagon had been equipped with an automatic transmission much better control would probably have been obtained, for as soon as load was placed on the sensor the throttle would be advanced and the wagon would move forward without the time-delay of clutch engagement. It may be argued that an automatic transmission would raise the cost of a self-propelled vehicle but this would be partially offset by the reduction in the cost of the automatic draft control unit: the expensive solenoid operated hydraulic valve, hydraulic cylinder and attendant hydraulic circuitry would all be eliminated.

It is recommended that a further study be made of the behaviour of wagons and other wheeled vehicles under field conditions.

Only sufficient data to develop the design of this control unit were collected. More work should be done in this area on the analysis of draft required to overcome the rolling resistance of wheeled vehicles over the ground under various conditions. Involved would be a study of the effects of: tires, tire spacing, tire pressures, tire size, vehicle loading, topography, and soil conditions. From the literature studied, there appears to be a lack of this information.

BIBLIOGRAPHY

1. American Motors Corporation, Technical Service Manual 1969, Section 4, pp. 42-45, American Motors Corporation, Milwaukee, Wisconsin.

2. Buchele, W. F., Design and Operation of MSU Tandem Tractor, Transactions of American Society of Agricultural Engineers, St. Joseph, Michigan, Vol. 2, No. 1, 1957, pp. 11, 12, 15.

3. Clark, Robert N., Introduction to Automatic Control Systems, John Wiley and Sons, Inc., New York, 1962, p. 467.

4. Collins, E. V., Tandem Tractor Features, Transactions of American Society of Agricultural Engineers, St. Joseph, Michigan, Vol. 2, No. 1, 1959, pp. 13-15.

5. Conaway, Philip and Delhom, Louis, Shunt and Series FET Choppers Texas Instruments Incorporated, Semiconductor-Components Div., P.O. Box 5012, Dallas 22, Texas.

6. Douglass, Burdette, Surge Brakes Keep Trailer Braking Synchronized with Tow Car Braking, Journal of Society of Automotive Engineers, New York, February 1968, pp. 64, 65.

7. Dove, R.C. and Adams, Paul H., Experimental Stress Analysis and Motion Measurement, Charles E. Merrill Books, Inc., Columbus, Ohio, p. 108.

8. Frederick, J. E., Engine Control in 0.006 Seconds Claimed for Electronic Governor, Journal of Society of Automotive Engineers, New York, March 1960, pp. 64, 65.

9. Garman, J. A., Tandem Tractor Studies, Transactions of American Society of Agricultural Engineers, St. Joseph, Michigan, Vol. 2, No. 1, 1959, pp. 18-20.

10. General Motors Products of Canada Limited, 1967 Service Manual for Oldsmobile, Section 15, pp. 18-29, Electric Control, pp. 29-34, Vacuum Control, General Motors Products of Canada Limited, Oshawa, Ontario.

11. General Electric Company, Semiconductor Products Dept., Transistor Manual Seventh Edition, pp. 88-94, General Electric Company, Syracuse, New York.

12. Gilmour, W. D., An Automatic Control System for Farm Tractors, Journal of Agricultural Engineering Research, United Kingdom, Vol. 5, No. 4, 1960.

13. Motorola Incorporated, Semiconductor Products Division, Pheonix, Arizona, High Speed Switching Transistor Handbook, 4th Printing, Section 8 - 4, p. 276.

14. Motorola Incorporated, Semiconductor Products Division, Pheonix, Arizona, The Semiconductor Data Book, 3rd Edition, January 1968, Section 16, p. 72.

15. National Institute of Agricultural Engineering, Wrest Park, Silsoe, Bedfordshire, England, Doe 'Triple D' Tractor No. 396/BS, No. 413/O.E.C.D., Report 408, October 1964.

16. Ristenbatt, Marlin P. and Riddle, Robert L., Transistor Physics & Circuits, 2nd Edition, Prentice-Hall Inc., Syracuse, New York.

17. Strauss, Leonard, Wave Generation and Shaping, McGraw-Hill Book Co., New York.

18. Stout, M. B., Basic Electrical Measurements, Prentice-Hall Inc., Syracuse, New York.

19. Texas Instruments, Semiconductor and Components Data, Book 1, 1968, Texas Instruments, Bedford, England.

20. Texas Instruments, Series 52 Application Report, Texas Instruments, Dallas, Texas.

21. Welbourn, D. B., Essentials of Control Theory for Mechanical Engineers, 1963, Edward Arnold (Publishers) Ltd., London.

22. Wendenborn, J. G., The Irregularities of Farm Roads and Fields as Sources of Farm Vehicle Vibrations, Journal of Terramechanics, United Kingdom, Vol. 3, No. 3, 1966, pp. 9 - 40.

23. Wujek, Joseph H. and McGee, Max R., Field Effect Transistor Circuits, Electronics World, Vol. 77, No. 5, May 1967, pp. 32, 33, 75.

APPENDIX "A"

There are other methods of designing and evaluating control systems other than the one followed in this thesis. One of these is a mathematical approach wherein a transfer function is derived for the complete control system and then is analyzed.

The physical properties of the system are related to the transfer function. The transfer function is the ratio of the Laplace transform of the output quantity to the Laplace transform of the input with the restriction that the initial conditions are all zero.

The purpose of a control system is to convert some variable to a constant. It is of interest then to know the system dynamic response to a variable. This can be determined by applying a variable to the system and observing the system reaction. In the testing program for the control this was accomplished by applying a variable in the form of a draft pulse or a square wave and recording the reaction to the system to the input.

Control reaction to an input pulse takes place in three stages if one considers what the system was doing before the input pulse arrived as the first stage. The second stage is the period while the control system is reacting to the pulse. This reaction is called the transient response. The third stage is the operation of the control system after the transient stage when it has reached its final value.

Once the transient response has been obtained the system behaviour can be calculated. Ideally the system should respond as rapidly as possible to the input by moving from the initial condition state to the final condition state. System damping determines the rapidity of movement and the probability of overshoot. From a graph of the response, the time of maximum overshoot and the amount of overshoot can be determined and be applied to equations to enable prediction of system operation.

The behaviour of the system during its transient stage can also be predicted from a mathematical analysis of the transfer function once this function has been derived for the system. The control system may be diagramatically represented as in figure 12. The Laplace transforms for the control elements are:

$R(s)$ is the reference input, i.e. the preset input draft,
$G_1(s)$ is the transfer function for the amplifier,
$G_2(s)$, for the signal modifier,
$G_3(s)$, for the vacuum modulator,
$G_4(s)$, for the vacuum servo,
$G_5(s)$, for the power unit,
$H_1(s)$, for the feedback of the carburetor control,
$H_2(s)$, for the feedback signal provided by the movement of the vehicle, and
$C(s)$, the output variable.

Figure 12 shows an inner feedback loop which, had it been necessary, would have been rate feedback obtained as the result of carburetor control action.

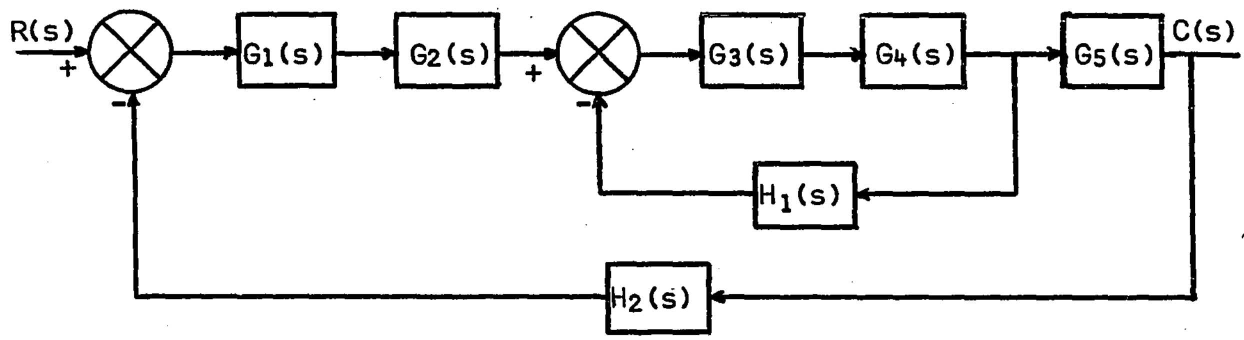


Figure 12. Diagram of Automatic Draft Control System

The transfer function for the system is:

$$W(s) = \frac{C(s)}{R(s)} = \frac{G_1(s)G_2(s)G_3(s)G_4(s)G_5(s)}{1 + H_2(s)G_1(s)G_2(s)G_3(s)G_4(s)G_5(s)} \quad (1)$$

and since H (s) = 1 this becomes

$$W(s) = \frac{C(s)}{R(s)} = \frac{G_1(s)G_2(s)G_3(s)G_4(s)G_5(s)}{1 + G_1(s)G_2(s)G_3(s)G_4(s)G_5(s)} \quad (2)$$

This is a generalized transfer function so that the component parts represented by $G_1(s)$, $G_2(s)$, $G_3(s)$, $G_4(s)$, and $G_5(s)$, must each be replaced with the appropriate equation. One problem with transfer functions is that sometimes the equations for some of the control parts can be derived only from empirical data obtained after the control has been completed. A second problem is that the transfer function as in this case can become a high order equation which would be difficult to factor.

As a system is driven still harder it may eventually reach a point where its operation is no longer predictable and the system is said to be unstable. Again the probable stability can be predicted from the transfer function for the entire control. This can be done by applying Routh's stability criterion to the unfactored polynomial. A more complete study can be made by the Root Locus Method but this requires factoring and/or simplification of the polynomial. But one advantage of the Root Locus Method is that it does give a graphic display of the system and the way in which the system operation changes as alterations are made to the physical parameters. If there are problems in the completed control the root locus method can indicate how the required control system response can be obtained.

The results obtained from the use of the mathematical approach are only as accurate as the transfer function is itself. There are some complications in the development of a transfer function for the control system as described. For example, in the assigning of gain to the components, the overall system gain is approximately 32 times if the change from the 50 pound reference signal to the maximum recorded draft of 1600 pounds is used. On the other hand a gain of 3650 times was required to convert the draft sensor output to a usable signal for the transistor controlling the air valve solenoid. Another example of difficulty would be involved in the writing of a transfer function for certain sections such as the vacuum servo.

APPENDIX "B"

The complete operation of signal modifier circuits, figure 13, was as follows.

B1 Clutch Control Circuit

The application of e_3 to transistor Q_1 turns the transistor on, and the voltage between the collector and emitter, V_{ce}, drops to a low value turning transistor Q_2 off. The voltage V_{ce} of Q_2 drops to -10 volts turning transistor Q_3 on. The voltage V_{ce} of Q_3 becomes a very low value and, because the collector of Q_3 is tied to $-V_{ce}$, the emitter voltage of Q_3 becomes equal to $-V_{ce} + V_{be}$ which is approximately -9.1 volts. The capacitor C_1 charges to -9.0 volts via diode D_1 which is forward biased and conducts. The instant C1 begins to charge transistor, Q_4, an N channel field effect transistor, turns off causing the base voltage of transistor Q_5 to become more negative. Transistor Q_5 conducts resulting in the emitter voltage of Q_5 dropping from -.07 volts to -.27 volts. Since the emitter voltage of Q_5 is the base voltage of transistor Q_6, Q_6 conducts and the relay operates opening the disengage solenoid circuit and closing the engage-solenoid circuit of the clutch control.

If voltage e_3 is removed from the base of transistor Q_1, the circuit reverts to its original state except transistors Q_4, Q_5 and Q_6. When transistor Q_3 stops conducting, diode D_1 is back biased and opens but the charge voltage on capacitor C_1 remains. The input impedance of the FET, Q_4, is now very high so that the charge on C_1 must be drained

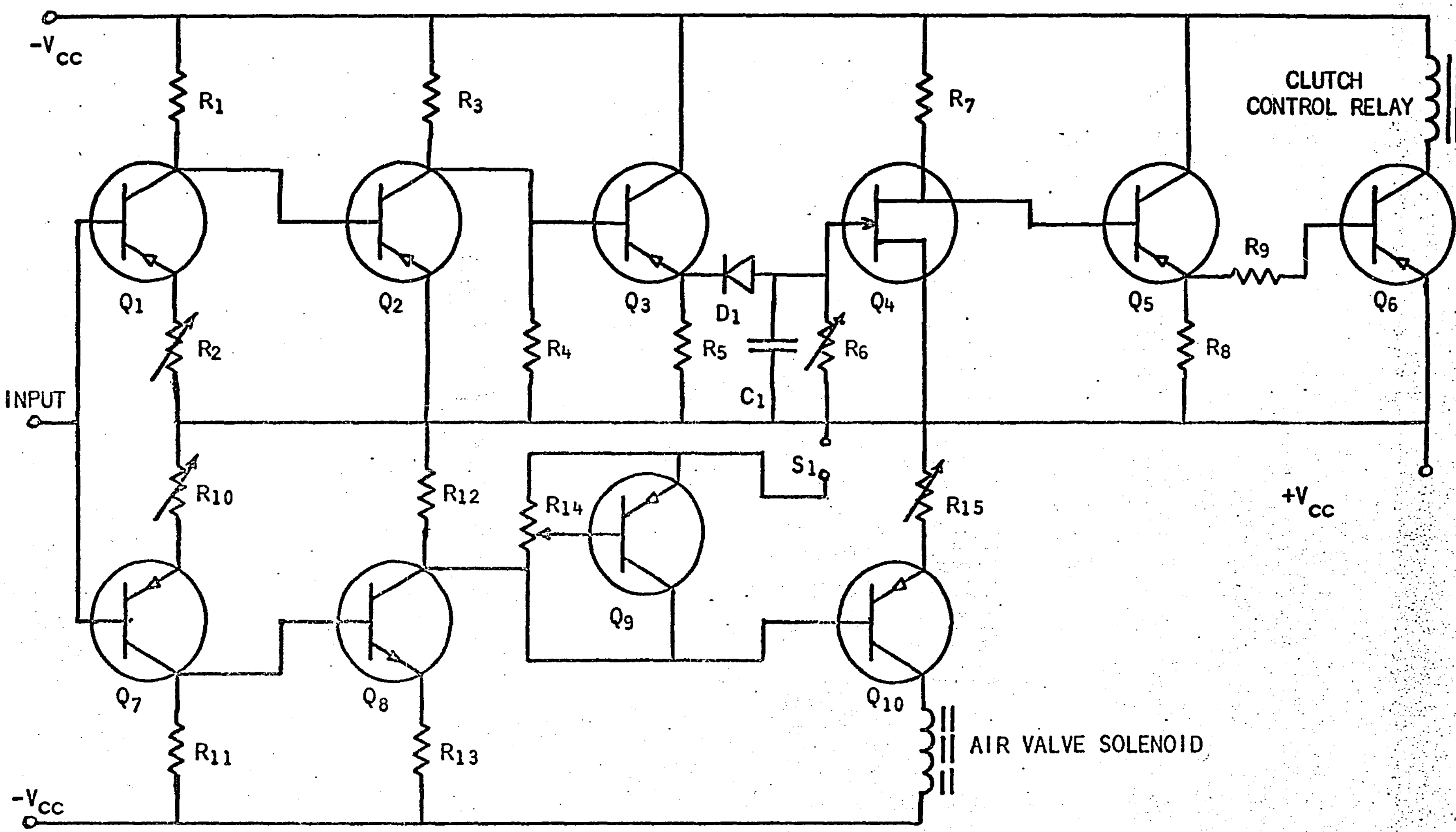


Figure 13. Circuit Diagram of the Signal Modifier

PARTS LIST FOR SIGNAL MODIFIER

R_1, R_5, R_{11}, R_{12}	10K ohm	½ watt resistor
R_2, R_{10}	200 ohm	potentiometer
R_4	100K ohm	½ watt resistor
R_6	100K ohm	potentiometer
R_7	220K ohm	½ watt resistor
R_8	5.1K ohm	½ watt resistor
R_9	470 ohm	½ watt resistor
R_{13}	560 ohm	½ watt resistor
R_{14}	5000 ohm	potentiometer
R_{15}	10 ohm	10 watt potentiometer

*Q_1, Q_2, Q_3, Q_5, Q_7, Q_9	2N404A transistor
*Q_4	2N3369 transistor
*Q_6, Q_{10}	GE 3 transistor
*Q_8	2N1086 transistor
C_1	5 μfd capacitor
*D_1	IN914 diode
S_1	Clutch engaged limit switch
Air Valve Solenoid - Part of Vacuum Modulator	
Clutch Control Relay	12 volt DPDT Contacts

*Polarity of unit may be reversed by using equivalent transistors of the opposite polarity and reversing the diode D_1.

off by the 100 kilohm potentiometer. As long as the charge remains, the FET is biased off holding transistors Q_4 and Q_5 on and the relay closed. Proper adjustment of the potentiometer provides the 2.0 second time-delay from the time voltage e_3 is cut off until the relay opens.

B2 Throttle Control Circuit

Voltage e_3 applied to the base of transistor Q_7 turns it on causing its collector voltage to rise toward zero. Potentiometer R_8 determines the level of e_3 required to turn on Q_7. Transistor Q_8 conducts and emitter voltage rises causing transistor Q_{10} to conduct. The value of the base voltage of transistor Q_{10} determines its collector current which in turn sets the position of the air control valve in the vacuum modulator. As voltage e_3 changes, the position of the air control valve changes.

When the forage harvester moves ahead it will pull the self-propelled wagon with it. Since the components of the power train cannot act instantaneously considerable pull will develop in the sensor before the wagon propels itself. The strain resulting from this pulling force will produce a high voltage e_3 and, as a result, a high throttle setting which would cause the engine to race before the clutch could be engaged. A transistor clamp, Q_9, is connected by a switch S_1 from the base of transistor Q_{10} to the emitter supply voltage, $+V_{cc}$, of Q_{10}. When a transistor conducts the voltage between the collector and emitter, V_{ce}, drops to a very small amount. The amount of voltage V_{ce} is set by the base current. The base voltage of transistor Q_{10} is limited to V_{ce} of transistor Q_9. The amount of collector current of transistor Q_{10} and hence the movement of the air valve controlled by the collector current is limited by this method. The 5000 ohm potentiometer, R_{12}, sets the base current of transistor Q_9 and thus the amount of collector current of transistor Q_{10}. The 10 ohm potentiometer, R_{13}, in the emitter circuit of transistor Q_{10} sets the range of collector current. The two potentiometers determine the limit of operation and the range of operation of the air valve. When the clutch engages the switch in the emitter circuit of transistor Q_9 opens and removes the clamping action.

B3 Throttle Circuit Performance

The gain of the throttle control circuit in db, where db = decibel = 10 log $\frac{W_{out}}{W_{in}}$, was 34 db at 20 hertz.

APPENDIX "C"

The modified sensor, figure 14, combines in one section, most of the functions of the two separate sections of the hydraulic-electric sensor, figures 5 and 6. Its operation was as follows: With an increase in pull on the sensor piston 2 moved to the right increasing pressure against the pressure transducer increasing the input voltage to transistors Q_1 and Q_7 of the signal modifier circuit, figure 9. If the power unit failed to respond, the pressure would increase further until the pressure relief valve 1 opened allowing hydraulic fluid to flow into fluid chamber 1. Piston 1 was thus forced to the left against spring 1. At some pressure all the fluid in chamber 2 was expelled and piston 2 would be against its stop. The sensor would then mechanically lock up. Maximum fluid pressure could be preset by the constant of spring 1 and the ratio of piston areas regardless of the final force on the sensor.

If pull on the sensor decreased spring 1 forced piston 1 to the right and the fluid flowed past check valve 1 (which offered little restriction to fluid flow) back into fluid chamber 2. Although fluid pressures were equal on both sides of piston 2 the force on the right side of piston 2 would be greater then than that on the left and piston 2 was forced to the left.

The force transducer was simply a material whose conductivity changed with pressure rather than the more elaborate transducer, figure 5.

Preliminary tests indicated that the design had merit.

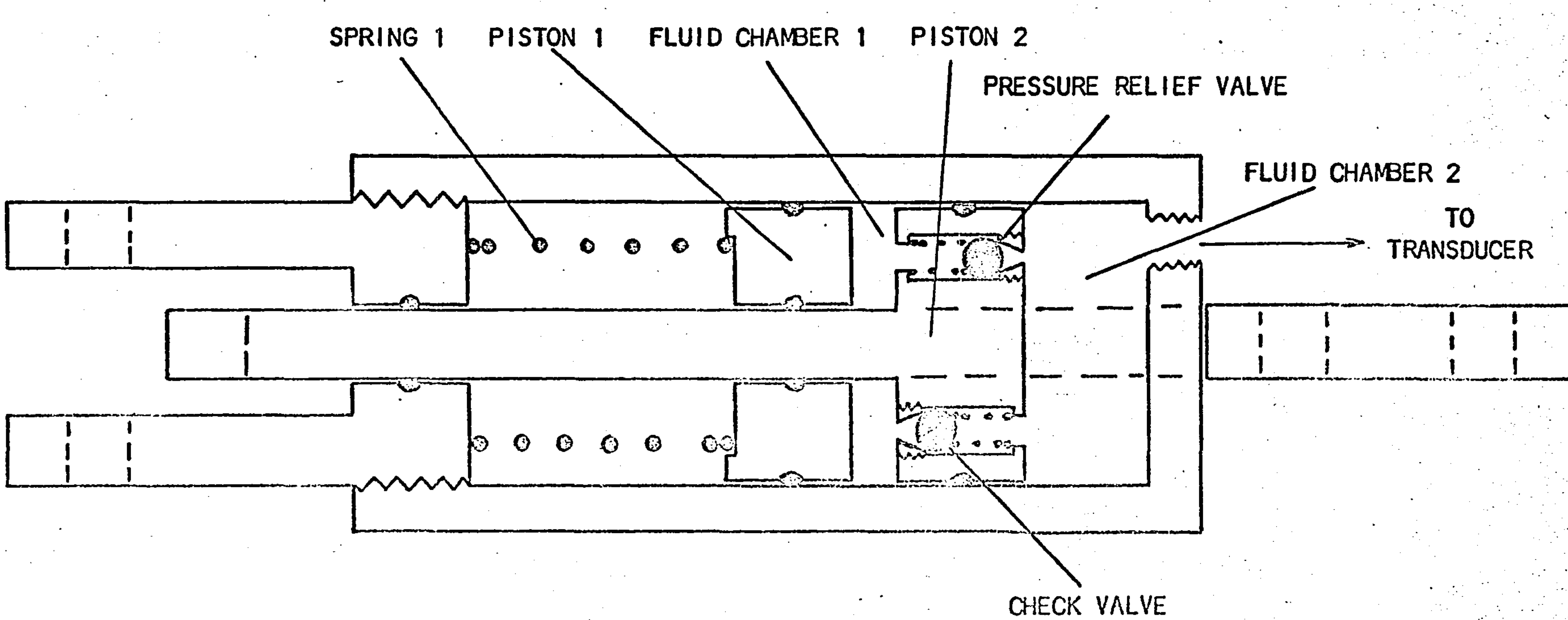


Figure 14. Modified Hydraulic-Electric Sensor