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The Design and Development of an Automatic Guiding System for a Tractor

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THE DESIGN AND DEVELOPMENT OF AN AUTOMATIC GUIDING SYSTEM FOR A TRACTOR

BY

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This thesis is approved as a creditable, independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser

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INTRODUCTION

Mechanization and Automation are very fashionable words in present day Agriculture. Both imply a reduction in the amount of human effort necessary to achieve certain ends, and to accept the need for either of them is to assume that it will lead to some financial gain.

Mechanization is concerned with the reduction of human physical effort, but automation aims mainly at the reduction of mental effort, and the small amount of physical effort still remaining after mechanization. Automation implies the control of machines installed in the mechanization phase, so that close investigation is required not only of what men do, but also of how they do it.

The human machine has the essential features of a controlling device, sensing mechanisms such as eyes and ears, a versatile nervous signalling system, and an impressive number of servomechanisms such as fingers and toes. The problems of sensing and interpreting the resultant signal, presumably lead nature to the production of the brain, and lead the man into the interesting sphere of instrumentation which is often an essential precursor to automation.

Automation as applied to Agriculture is to improve many limited factors which affect the final yield of any agricultural crop. One of these factors, the mechanical operation, requires considerable care and attention to more nearly insure maximum yield and high quality.

Every year approximately 10 to 20 percent of the corn crop is lost because of one or a combination of factors such as weather conditions, faulty harvest or inadequate storage. Prevention of such a loss would probably increase the average harvest by 300 to 600 million bushels. In other words, such a saving could increase the total farm income from 500 million to one billion dollars annually.

Numerous methods have been adopted through research and development to minimize field losses of a crop and to improve the quality of the product. More adaptable and accurate machines are constantly being manufactured to cut down the losses and also to reduce the amount of man-hour labor involved.

In most field operations there are various jobs that an operator must perform simultaneously. He must guide the tractor properly across the field without damaging the plants, while constantly watching the performance of whatever implement the tractor is pulling. Therefore, a device which enables the tractor to steer itself down the crop row automatically would not only reduce the driver's fatigue, but at the same time would result in more efficient, and sometimes more accurate operation. Thus the operator would be free to watch closely how his equipment is performing. Therefore an important advantage of the automatic steering over conventional or human steering of a machine or tractor would be to prevent and correct any improper operation of the equipment as it occurs, thus saving a considerable amount of time and labor. On the other hand, since any reduction in the amount of labor involved usually means a higher income to the farmer, the trend is toward more automation and automatic controls.

Considering the factors which have been mentioned above, resulted in the possibility of devising a system to help a tractor to steer more accurately. It was believed that such a system could be well adapted to many field operations such as row crop cultivation, where accurate steering could result in a good weed coverage without reducing stands or injuring the crop.

Specifically the objective of this study was:

1. To design, develop, and construct an automatic steering device which would enable a tractor to guide itself down the crop row accurately. The system was to be designed in a manner that would make it possible for the tractor to be used for a variety of crops with little or no change in the automatic steering components.

2. To design a system which could be justified economically where labor is scarce and expensive or unskilled, or where the tractors are operated in hazardous conditions.

REVIEW OF LITERATURE

Feeler Systems

Even though the idea of automatically steering a tractor came about during the early days of the mechanization of Agriculture, most of the work has been accomplished during the past five to seven years. The earliest attempt was to lock the front wheels in a manner which enabled the tractor to travel in a circular path. Such an arrangement was used for circular plowing for example, or in routine specific tractor job arrangements.

Among the recent investigators the works of C. B. Richey (8) of the Ford Motor Company and Louis L. Liljedahl (3) of the United States Department of Agriculture have gained considerable popularity.

Liljedahl has developed an automatic pilot for farm tractors that mechanically senses the position of a crop row. The main objective of this work, which was done under a United States Department of Agriculture weed control machinery project, was to determine if some control equipment could be developed which would be sufficiently sensitive, so that the tractor could be steered or guided more accurately and consistently. The control units operate on the following principles:

A wish-bone shaped feeler arm rides on either side of the crop row, and pivots to a bracket mounted to the tractor. When the tractor gets off the crop row a predetermined amount, the feeler arm actuates miniature switches which are located on either side of the arm. The switch in turn operates an Electro-hydraulic valve which is located in the tractor power steering system. Thus when the switch is closed, flow of the hydraulic fluid guides the tractor back onto the row. In order to prevent the tractor from over guiding as it returns to the correct position on the crop row, the switches are fastened by means of a mechanical linkage to the steering arm on the front wheels. Thus as the tractor returns to the correct position with respect to the crop row, the tractor wheels are straightened out just before the tractor gets back to the correct position, thus preventing over-guiding.

Liljedahl has also indicated that such a system was best utilized when the plants were over six inches high. However, since weed control is most important when the plant is very young, more sensitive mechanical components are needed for more accurate performance.

A somewhat similar device has been developed by C. B. Richy (8) of the Ford Motor Company Farm Implement Division. This mechanism also employs a set of feelers to actuate sensitive micro switches. When the switches are on, the current from the battery is carried to a DC motor through a relay. The motor powers a screw mounted on a drag link. As shown in Figure I displacement of the feelers to the right rotates the switch actuating bar (a) to close micro switch (b). As the circuit is completed, the DC motor operates and changes the length of the drag link which is attached to the steering cylinder. Actuation of the steering cylinder steers the tractor to the right, and also rotates the micro switch box (c) in a counter clockwise direction through a push-pull cable (d), therefore canceling the signal by opening the switch. A picture of the tractor equipped with automatic steering as shown in Figure II.

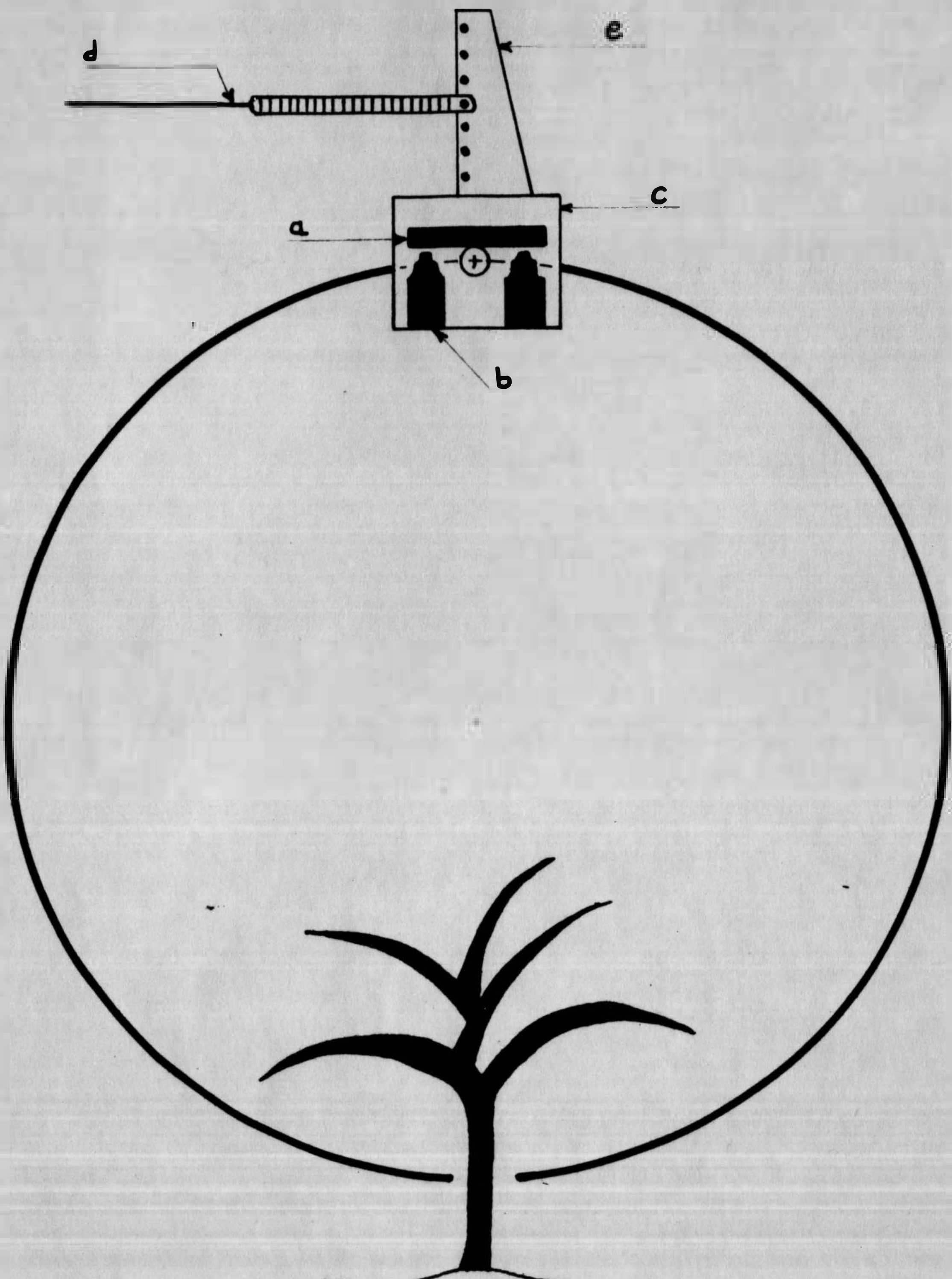

Figure I. Arrangement of the Feelers.

Figure II. Automatic-Steering Enables a Tractor to Follow a Circular Path.

Richy has reported that accuracy and high stability characteristics are a result of the interaction of the following factors:

1. Rate of angling.

2. Correction ratio, i.e., degree of wheel angle change per inch of feeler displacement.

3. Feeler lead.

4. Width of null band.

In order to prevent hunting, another feature is added to the steering device. This feature is the addition of a mechanical follow-up or servo-connection which controls the amount of front wheel angle in proportion to feeler displacement. Therefore if the feeler is displaced a given distance, the front wheels are angled a given amount and then held there. This steering device can be used when cultivating corn, provided the plants are at least ten inches high with pencil size stalks for sufficient stiffness to actuate the feelers. Weeds are not a problem as long as their height does not exceed that of half the height of the corn plant.

Radio Control

A radio control system is another solution to providing a tractor with automatic steering. Several attempts have been made, probably the most important of those are the investigations of James D. Pichon (6) of the University of Nebraska. The system is composed of a radio transmitter and a receiver which is mounted on the tractor. The radio component used in this system has eight channels. The transmitter has dual audio modulators, which allow two control signals to be transmitted simultaneously. The receiver output for the individual channels is a relay, which is used either to control and complete a circuit or to energize additional relays for control sequences. Aside from steering the tractor, other functions also may be performed. The main part of the system is an electrical reset stepping relay, which can be made to reset itself from any of its control points. Pulsing the proper channel on the transmitter the desired number of times turns on the primary ignition, starts the tractor, and finally when the stepping relay is returned to its original position the engine stops. Other controls are also used for engaging and disengaging the clutch. The tractor may be shifted to the reverse gear, a second forward gear, and a neutral position.

Steering is controlled by two separate radio channels, one for either direction. The front wheels are automatically returned to the central position when no turn signals are being transmitted. The steering mechanism consisted of a modified power steering unit, a hydraulic control unit, and a solenoid hydraulic valve. The solenoids are double wound to give two way action to the hydraulic valve. The self-centering portion of the steering system consists of cam actuated micro switches, mounted on the front spindle of the tractor. These micro switches complete the circuit and cause the front wheels to return to center after a turn is completed. The self-centering of the steering system is wired in series, through the normally closed contacts of the turn signal relays. Such a feature allows the operator to over ride the self-centering action at any time that a turn is desired.

Along the line of the radio control, a tractor which is operated by remote control has been developed and is being tested by the United States Army Research and Development Laboratories (7). It is believed that such a tractor may prove very valuable for construction purposes in radio active and combat zones. With the aid of a standard radio receiver and transmitter the operator can start, stop the machine, engage or disengage the gears, and change the direction of travel. Normal operations may be performed up to a distance of fifteen miles away. However, it is believed that by installation of a small television camera on the tractor the remote operator will be given additional knowledge of the performance of the machine.

A machine has been developed in Russia (1), which is capable of simultaneous tilling along the rows and between the hills while following the crop row. The cultivator is equipped with both fixed and rotary shovels. The fixed shovels till simultaneously along six rows, while the rotary hoes operate between the hills. As the cultivator moves along the rows the contact feeler touches the plant. The contact closes the circuit in the winding of a polarized relay. The polarized relay switches on the intermediate relay which in turn closes the circuit in the winding of the rotating electromagnetic clutch. As a result the clutch is engaged with the rotary hoes. While the rotary hoes are locked the rotating clutch makes one turn. This position of the hoes corresponds to the process of tilling between the hills. When the clutch has completed one turn, the mechanical circuit breaker will interrupt the circuit in the winding of the intermediate relay. As a result the circuit in the winding of the brake clutch is broken. This stage corresponds to the released position of the rotary hoes, and their passage by the plants. The power for the contact feeler circuit comes from a dry battery. The design of the feeler may vary according to the degree of the plant development. With weak plants, during the earliest cultivations the feeler should touch the upper part of the plants. Upon repeated cultivation and with more developed plants, the contact should be made with the stem.

Results of several tests indicated that an automated cultivator is practical for simultaneous tillage along the rows and between the hills. The cultivator is economical in fuel, lubricants, and increases the productivity of the tractor unit. It also reduces the deterioration of the soil structure in comparison with the cross row method of cultivation.

A field test has been conducted by Lovely and Hunt (2) to determine the efficiency of an automatically guided tractor when cultivating corn. It has been reported that during the first cultivation, when the plants were at three to four leaf stage, the operator had to assume the manual control very often. However, for the second cultivation when the corn plants were fifteen to eighteen inches high and the soil surface was considerably smoother, automatic steering functioned more satisfactorily. A count of the stands before and after cultivating with automatic steering gave the following data:

> "The plant population was reduced when automatic steering was used for both the first and second cultivation. Prior to the first cultivation stands averaged 14,922 stalks per acre. The automatic steering caused an average stand reduction of 1,890 stalks per acre, as compared to 140 stalks for manual steering. Stand counts made just prior to the second cultivation averaged 14,567 stalks per acre. The average stand reduction of 430 stalks per acre was observed with automatic steering as compared to 90 stalks for manual steering."

Lovely and Hunt also conducted other tests to determine the fatigue effect in the operator with manual steering as compared to the automatic steering. The following tests were conducted:

1. Critical Flicker - Fusian Test.
2. Arm Hand Steadiness Test.
3. Subjective Feeling Test.
4. The Visual Phoria Test.

The results of these tests gave the following conclusions:

"No strong or definite conclusions can be drawn from this study; however, the psychological means of fatigue used in this test could appear to be valid and to have value as practical indicators of operator condition during field work."

Also with respect to performance study, Lovely and Hunt concluded that:

"The automatic guidance device used in these studies is still in the experimental stages of development. Automatic steering resulted in greater stand reductions, lower yields and poorer weed control than manual steering. These studies show that the automatic guidance system tested under the conditions that existed during the experiment did not improve the effectiveness of corn cultivation."

Magnetic Cable

A different approach, similar to what was employed by Dr. Zworykin, has been used to design an automatic steering system in the Farm Mechanization Department at the University of Reading, England. With this system a wire is laid in or on the ground and is energized with a low voltage alternating current. Two search coils are mounted on the front of the tractor, and when the center of the tractor is above the wire the current induced in the coils are balanced. However if one coil is nearer the wire than the other, as happens if the tractor begins to veer to one side, the current induced in the coils becomes out of balance. The coils are in series with a balance relay, which controls solenoid operated hydraulic valves. The valve controls the oil supply to a double acting ram, and this ram operates a conventional hydraulic steering booster. Any tendency for the tractor to wander away from the wire is instantaneously corrected by the booster.

The system can be converted to conventional steering when the control switch is off. Therefore it is possible to provide automatic tractor operation where it is worth while laying down permanent or semi permanent wires.

In the automobile industry some work has been done to provide the cars with automatic steering. A model car has been built, and laboratory tested by the Radio Corporation of America (11). Certain electrical devices are used to assist the driver in such matters as bad weather steering, and collision prevention. The model car which is powered by a storage battery is designed to perform the following functions:

1. It is capable of steering itself along a prescribed route.
2. Stops itself when approaching a metal obstruction.
3. Turns out of its original lane to a second lane as if passing another car.

The car is equipped with two coils, which are capable of picking up the signals from a cable which is laid in the road bed. The cable carries a moderate frequency alternate current and as a result sets up a magnetic field of certain frequency around itself which is picked up by the coils. If one of the coils receives more signal than the other one, this indicates that the car is no longer centered on the wire. Therefore the electronic components controlling the steering wheel bring the car back on course. In this system the driver not only can control the car speed, but in addition can switch at will from automatic to manual control and vice versa.

Analysis of the Steering Forces

A wheel maintains its rolling motion in the longitudinal plane. However, if by the action of some external forces, the wheel is forced to deviate from true rolling motion the tire counteracts and resists the external force by a cornering force. The magnitude of such a force depends upon the area contact between the rubber tire and the ground, and the angle by which the wheel has deviated from the true rolling direction. There are several factors which influence the cornering force:

1. Slip angle, or the angle of deviation from true rolling direction. The cornering force increases with increase in slip angle. As the slip angle gets larger, the maximum cornering force results, after which the tire starts to skid. The cornering force is determined per degree of slip angle and is known as cornering power.

2. Radial load: the cornering force is proportional to the radial weight acting on the wheel. The cornering power per unit of vertical load is defined as cornering coefficient. As the radial load increases, the relative cornering capacity declines. Therefore, the more axial load a tire is carrying, the less effective it is in supporting the side forces.

3. Camber angle: Figure III. This is the angle by which the wheel is deviated from the perpendicular position. The direction of travel of a cambered wheel deviates from natural rolling path, and thus creates a slip angle, which results in cornering force. The magnitude of the force resulting from the camber angle, may be added or

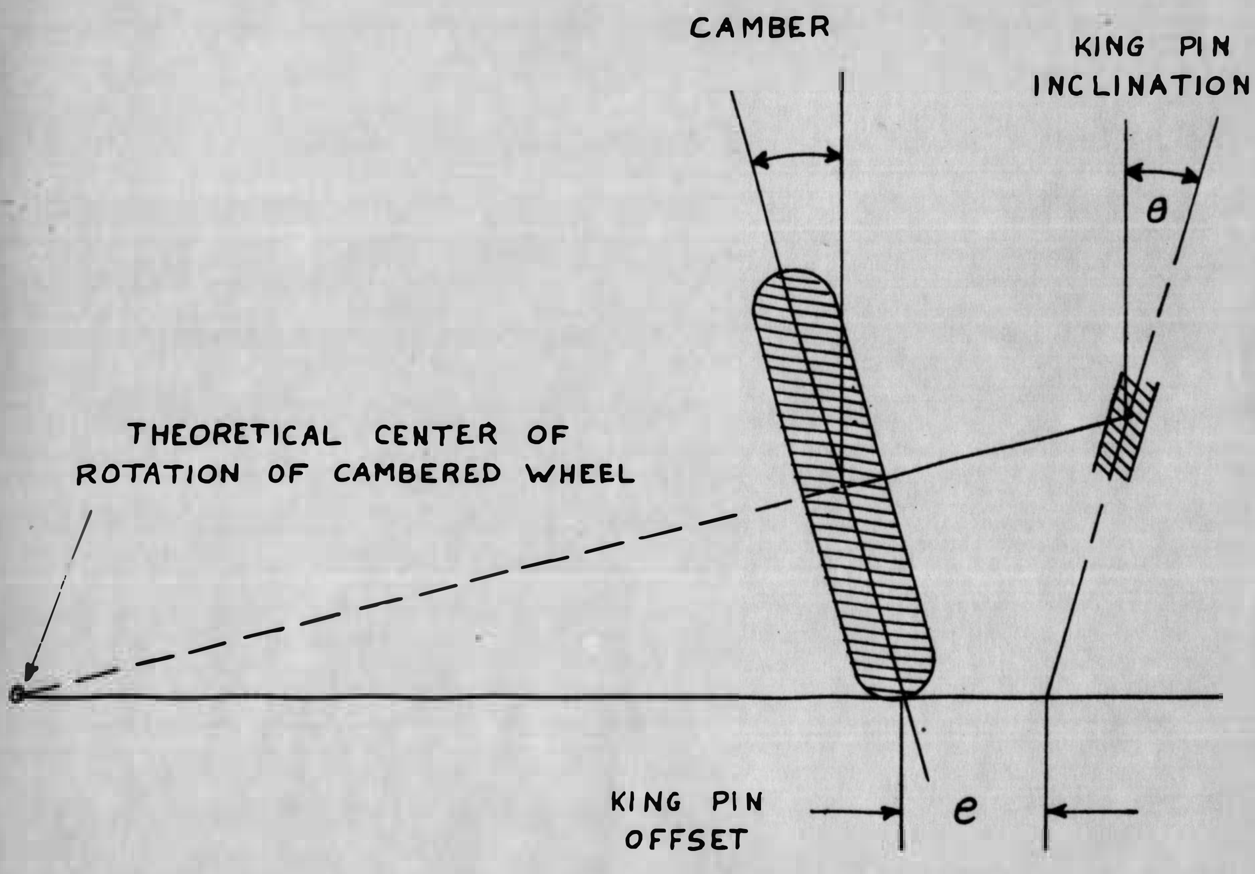

Figure III. Camber Angle and King-Pin Offset.

subtracted from cornering force, depending on whether the camber inclination is toward or away from the inside of the curve in which the wheel is traveling.

4. Inflation pressure. Higher inflation pressure results in an increase in the cornering power. Therefore, it is desirable to have higher inflation for better cornering.

The steering system is so designed that when the steering wheel is turned, forces are set up which tend to turn the front wheels to a straight line position. These forces are caused by caster and king pin inclination. On four wheel type tractors the king pin, Figure III, is usually inclined. The king pin is used to decrease the king pin offset (e), but it also produces a self-aligning moment.

In order to steer a tractor, the self-aligning moment which is caused by acceleration forces must be overcome. Because the tractor describes a circular path when it is steered, the radial acceleration must be considered. In order to arrive at an expression which may be used to calculate the total moment required for equilibrium at the steering angle, the following procedure is used:

When an object is in a circular path the radial acceleration is found from

$$a = \frac{v^2}{R}$$

Where a is the acceleration in ft./sec.^{2}, v is the velocity and R is the radius of the circular path. However, for small values of $\alpha = \frac{dy}{dx}$, from the geometry of Figure IV, the following expression holds true

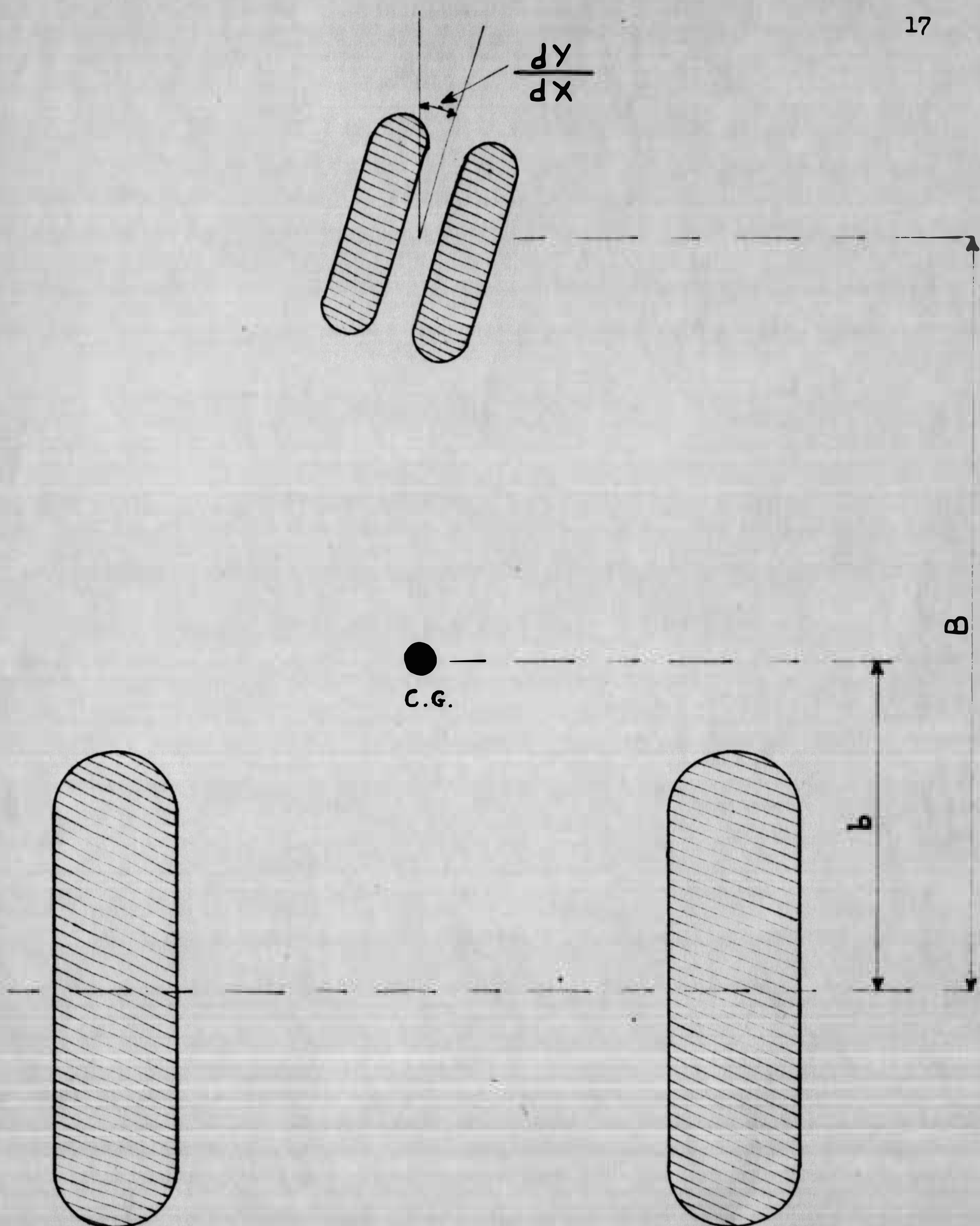

Figure IV. Tractor Travelling Through an Angle α .

$\frac{dy}{dx} = \frac{B}{R}$ in which B is the wheel base. Therefore $R = \frac{B}{\frac{dy}{dx}}$

Substituting back in equation for acceleration results

$$a = \frac{V^2}{R} = \frac{V^2}{\frac{B}{\frac{dy}{dx}}} = \frac{V^2 dy}{B\ dx}$$

On the other hand, the radial force is represented by equation $\frac{W}{g}$ a. The corresponding value of acceleration is substituted in this equation to obtain

$$\frac{W}{g}(a) = \frac{W}{g}\frac{(V^2)}{B}\frac{dy}{dx}$$

If the radial force on the front wheel is represented by (F) then its value can be calculated by taking the moment about the rear wheel axle

$$\Sigma M = o$$

$$\frac{W}{g}\frac{(V^2)}{B}\frac{dy}{dx} b - FB = o$$

$$F = \frac{WbV^2}{g\ B^2}\frac{(dy)}{dx}$$

The moment about the front wheel spindle due to the turning forces can be found if the caster offset (c) which is the distance ahead of the center of contact between the ground and the wheel is known.

Therefore:

$$M_a = \frac{WcbV^2}{g\ B^2}\frac{(dy)}{dx}$$

The above formula is correct for the tricycle type tractors. However, for the four wheel tractors the following procedure is used.

It is assumed that the wheel of a given diameter mounted on an axle of such length to provide a king pin offset of distance (e) can be replaced in geometric model by a wheel of infinitely small diameter at a distance from the king pin axis along the axle.

The principle of virtual work is used to derive an expression for the moment required to turn the axle about the king pin. The work required is given by $M_{kp}\alpha$

Where α is the angle through which wheel is turned. On the other hand when the tractor is steered it is raised slightly. Now the work required to raise the tractor is found by first determining the weight on front wheels.

$$\Sigma M = 0$$

$$W(b) - P(B) = 0$$

$$P = \frac{Wb}{B}$$

The weight on each wheel then is $\frac{WB}{2B}$

If the tractor is raised a distance Δz as shown in Figure V then

$$\text{Work} = \Delta z \left(\frac{Wb}{2B}\right)$$

and therefore:

$$M_{kp}\alpha = \frac{Wb}{2B}\Delta z$$

The value of Δz is found from the geometry of the Figure V-a

distance $X = \dfrac{\Delta z}{\sin\theta}$

Looking axially along the king pin and from the geometry of Figure V-b it may be written

$$\frac{\Delta z}{\sin\theta} = e - e \cos\alpha$$

or

$$\frac{\Delta z}{\sin\theta} = e(1 - \cos\alpha)$$

$$\Delta z = e(1 - \cos\alpha)\sin\theta$$

Substituting in equation for moment about king pin results

$$M_{kp} = \frac{W\, e \sin\theta\, (1 - \cos\alpha)\, b}{2B\alpha}$$

Steering of the stationary tractor:

As it is shown in the Figure VI, Torque Ms is required to turn the tractor tire around its projected center S. The magnitude of such a force depends upon frictional forces of the foot print area. Therefore $M_s = \mu_s WK$ in which μ_s is the coefficient of the sliding friction, W the radial load and K is the polar radius of gyration.

Center of rotation of the tire is located at a distance (e) from the foot print center; consequently the rotation of the wheel is not pure sliding, but a combination of sliding and rolling motions. Therefore, the effective torque arm becomes $h = \sqrt{e^2 + k^2}$, and the torque necessary to turn the wheel then is $M_{kp} = \mu Wh$. Friction coefficient μ is a function of distance (e) and the tire width. Value of K is calculated from the tire foot print which is a function of inflation pressure and radial load. The foot print area is assumed to be a circle of diameter (b), where b is the width of the tire. The value of K or

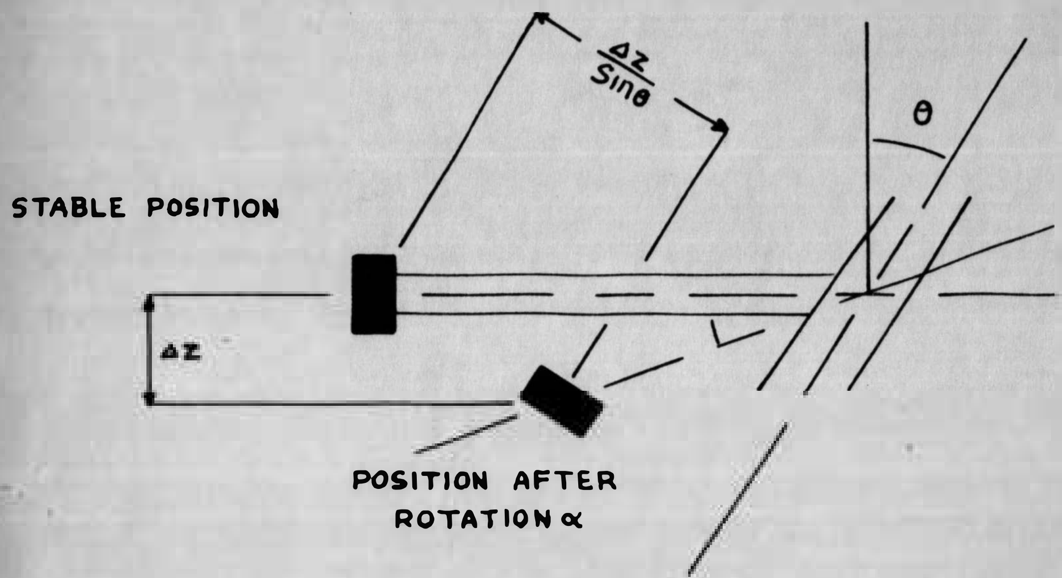

Figure V-a. Axle Rise in Turning.

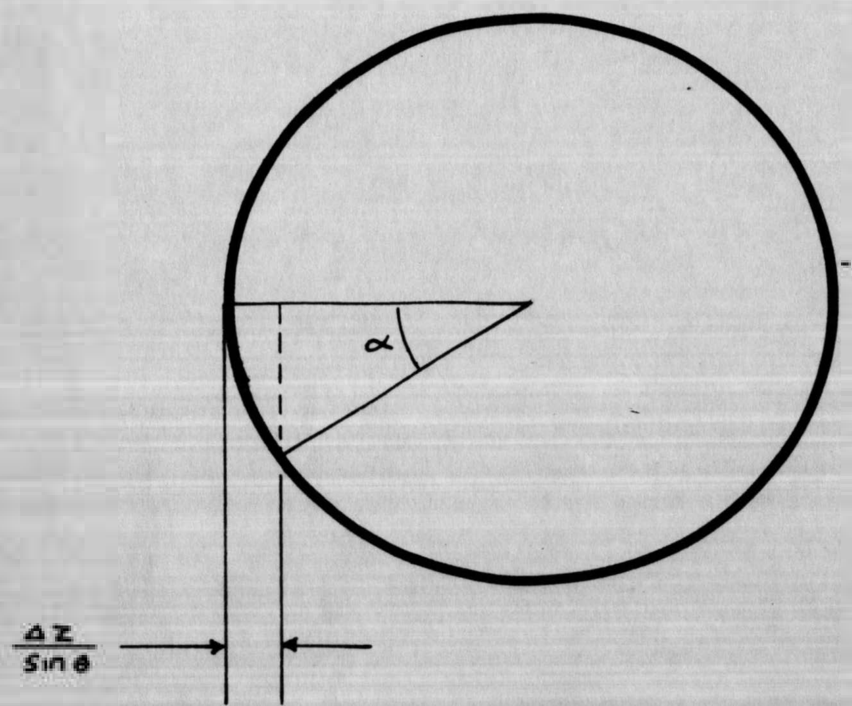

Figure V-b. Axle Rise in Turning.

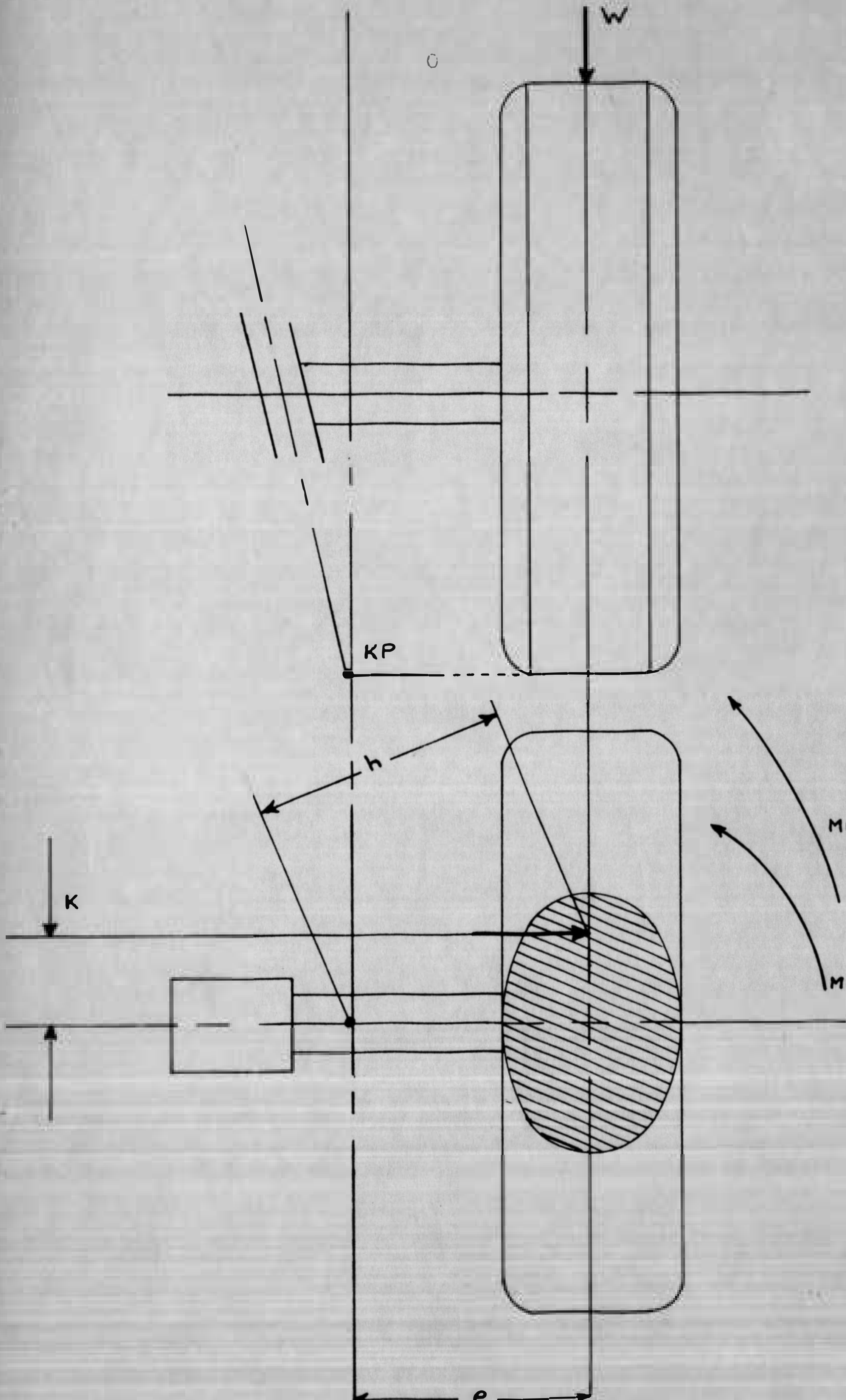

Figure VI. Actual Turning Center of a Steered Wheel is the Intersection of the King-Pin Axis with the Ground.

radius of gyration is found as

$$K = \sqrt{\frac{I_o}{A}}$$

in which I_o is the polar moment of inertia of the circle and A is the area.

Strain Gage Fundamentals

When a wire is stretched elastically its length and diameter both are altered, which results in a change in its electrical resistance. Any change in resistance of a strain gage is considered in terms of a change in strain. These changes are expressed as a ratio called strain sensitivity or gage factor:

$$\text{Gage factor} = G = \frac{\Delta R/R}{\Delta L/L}$$

where ΔR and ΔL are changes in resistance and length respectively. R = initial resistance of the gage and L is the initial length. In the above equation $\frac{\Delta L}{L}$ by definition is unit strain and is represented as micro inches/inch. According to Hooke's Law (9), strain is proportional to stress up to the elastic limit. On the other hand, strain and stress are related to each other through the equation: $e = \frac{\sigma}{E}$

where: e = strain in micro inch/inch

σ = stress in psi

E = Young's modulus of elasticity in psi

The strain gages may be used as a wheatstone bridge circuit to provide the desired unbalance. The bridge output voltage is determined using the principle of Thevenin's theorem:

"Any network with two accessible terminals may be replaced by an emf acting in series with an impedance; the emf is that between the terminals when they are unconnected externally, and the impedance is that represented by the network to the terminals when all sources of emf in the network are replaced by their internal impedances."

When this theorem is applied to the bridge circuit, the corresponding equivalent circuits are obtained as shown in Figure VII. E_o is the open circuit voltage across the two accessible points N and P. The impedance R_o is that seen by the galvanometer or the amplifying instrument.

At balance, the following relationship holds true for the bridge circuit:

$$I_1R_1 = I_2R_3 \text{ and } I_1R_2 = I_2R_4$$

However, if the circuit is unbalanced due to any change in the resistance of the strain gages, which is brought about by any increase or decrease in strain, then the bridge circuit is no longer balanced. The deflection of the galvanometer needle may be calibrated in terms of the strain of the member on which the strain gage is bonded.

The value of the E_o or the open circuit voltage may be calculated from the following formula (5).

$$E_o = E\ G\ e\ n/4$$

in which E is the bridge input voltage and n is the number of active arms.

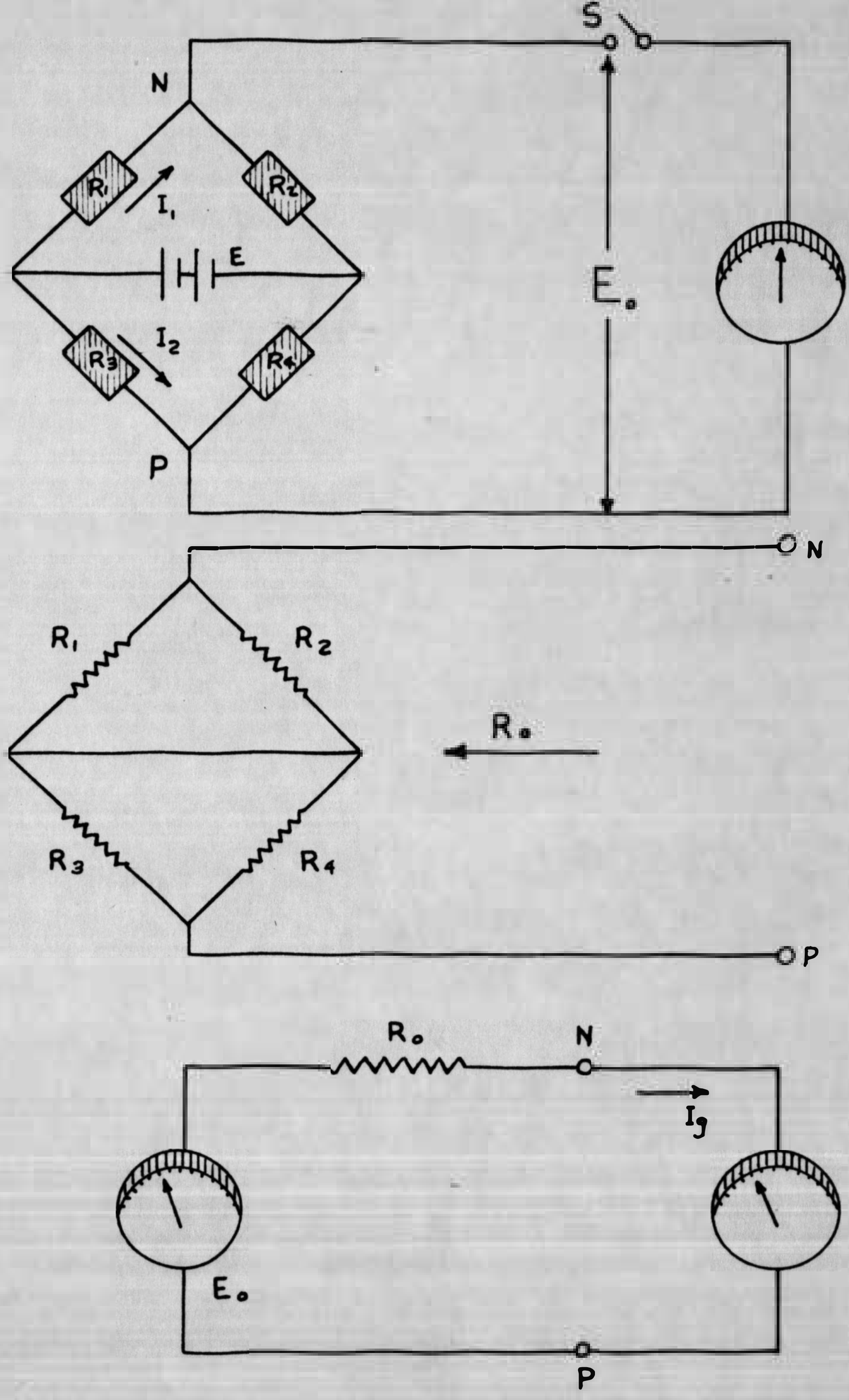

Figure VII. Basic Unbalance Wheatstone Bridge Circuit and Equivalent Circuits.

REQUIREMENTS OF THE SYSTEM

There are several approaches which could be used in the design and construction of an automatic guiding system. However, regardless of what method is employed, the system should have several important features for proper functioning. Some of the more important characteristics are mentioned below:

1. Compatibility with regular power steering. There should not be any interference of the automatic steering with manual steering. The components of the automatic steering may be separately located on the tractor. However, in case some of the components are used interchangeably, it is very important to see that both systems work properly and accurately.

2. Easy change over from automatic to manual control for turning and centering on the row. This is also an important feature because at the present time it is unprobable to eliminate the operator completely. Aside from positioning or centering the tractor on the row, it is also necessary to turn the tractor around at the end of each row. A feature such as a switch or a valve should be provided to make it possible to change from manual to automatic steering or vice versa with very little effort and in a short time.

3. No reduction in field speed as compared to manual steering, as most of the field operations require a certain speed for maximum efficiency.

4. Adaptable to a majority of field operations. It is not practical if the automatic steering cannot be applied to various field

operations. Also, it is highly desirable that no change be required in the component of the system when changing from one field operation to another. The steering components should be in a compact form and should be located on the tractor in such a way that it does not interfere with the cultivator or other attachments.

In addition to the above mentioned, provision should be made for operation under abnormal field conditions. The presence of weeds is a factor which could prevent the proper operation of the steering system. When the tractor is used for cultivation of young plants, the presence of weeds could hinder the operation and result in inefficient performance. However, as the plants grow taller and weed problem probably can be eliminated with a slight modification in the design of the system.

Another difficulty which might be encountered is slippage due to hillside operation. When using manual steering, the operator has to constantly steer to the opposite direction of slope to compensate for slippage. Therefore, any tractor with automatic steering should be capable of performing in the same manner if it is to be used for hill-side operation.

Some other factors which could also influence the design of the steering system are the presence of ice, snow, and draft due to a loaded wagon.

One should not overlook the economic aspects of the automatic steering system. While automatic steering could result in the reduction of total labor involved, the initial cost should not be too high to offset any saving obtained from less labor involved.

DESIGN AND DEVELOPMENT

Preliminary Concept of the System

There are several approaches to design an automatic steering for a tractor. Each method was given considerable thought, and the advantages of each approach were investigated thoroughly. It was finally decided to employ the principle of servomechanism, as it seemed that such a system could provide the best solution. The main factors which led to the selection of the servo system were:

1. Accuracy.
2. Sensitivity.
3. Reliability - continuous operation.
4. Stability - not affected by environmental changes.

In a servo system the output is mechanically driven by the difference between the output and the input. However, the output tends to agree with the input; therefore, the difference between the output and the input approaches zero. A servo system is made up of a series of elements, each performing a particular function. In a system where the output is constantly fed back to the input for comparison, a feed-back control or closed loop system is formed.

The basic equation for the closed loop servo system can be derived from Newton's third law of motion which states: "For every force or action there is an equal and opposite force or reaction."

Since the forces in a servo system are usually rotational, they can be expressed as torque. Therefore: Applied torque = reaction torque.

Vigorous mathematical derivations have been developed to explain the theoretical fundamentals of the servo system, but because one objective of this project was to deal with only one aspect of the application of the servomechanism, no attempt was made to establish any mathematical solution to the problem.

The automatic steering system which was designed for the purpose of this study, was to work on the following principles.

The sensing element of the system was made up of a set of feelers. These feelers were designed to follow the crop rows. Depending upon how far the tractor was from the centered position, the feelers were to be deflected a proportional amount. Two feelers were to be used to provide steering in both directions. The feelers were equipped with SR-4 strain gages. Therefore, any deflection of the member on which the gages were mounted could cause a corresponding change in the electrical resistance of the strain gages. As a result of the circuit unbalance, a signal in the form of the low voltage was to be transmitted to an amplifier. The degree of unbalance was dependent upon how far the feelers were deflected. Therefore, when the tractor was deviated from its correct path a short distance, only low signals were sent to the amplifier; but, as the tractor moved further away from the crop row, the output signal voltage was to increase proportionally.

The purpose of the amplifier was to activate an electro-hydraulic servo valve. The servo valve was to be located between the hydraulic pump and the hydraulic motor. The function of the valve was to control the oil flow rate. When the feeler was deflected, voltage signals as amplified by the amplifier were able to activate the servo valve. As a result, the valve could control the oil flow in such a manner that it would cause the tractor to steer in the opposite direction of the feeler deflection. The steering action was possible through a hydraulic motor which was connected to the servo valve by means of high pressure hoses. Faster steering action was possible as the feeler's deflection increased. As the front wheels were brought back to the centered position with respect to the crop row, the magnitude of the input signals from the sensing elements was decreased accordingly. Therefore, no oil could flow through the system at centered position. This was believed to be an important advantage of the system over on-off switch.

This system was to perform in a manner similar to that of the operator's reaction in steering. The steering would be quite fast when the tractor is way off position with respect to the crop row, while little steering action would be necessary if the tractor is deviated a slight amount.

Installation of the Power Steering

After the preliminary studies, a Case tractor model 400 which was readily available was used in conjunction with this research project. However, since the tractor was not equipped with power steering, it was felt desirable to convert the regular steering to power steering. The new system which was installed on the tractor used a separate hydraulic pump and a completely integrated fluid steering control system which resulted in elimination of all mechanical linkages between the steering wheel and steering mechanism on the axle.

The steering wheel was connected to a four-way valve and pump combination known as orbitrol which provides remote rotary servo control. The orbitrol was mounted on the tractor by means of 3/8" angle irons which were used as a bracket. The orbitrol is composed of a fixed displacement rotary motor, commutator feed valve sleeve, and a selector valve spool. The rotary meter is an orbiting gearotor in which the outer element is fixed in position as part of the housing. The inner gear moves in a small circular orbit within the outer element to displace the fluid. The moving element of the meter is coupled to the commutator valve sleeve, so that the orientation of the valve sleeve always indicates relative positioning of the displacement element of the meter. The control spool contains some parts which are matched to the commutator sleeve. The control spool moves within the valve sleeve and serves to provide the directional control and selection of fluid delivery rate. A cross section of the orbitrol in neutral position is shown in Figure VIII.

A hydraulic orbit motor was mounted on the tractor to actuate the steering mechanism. The motor has an outer ring which is stationary and internal gear-like teeth. These teeth mesh with corresponding teeth on smaller gear which rolls inside the ring, and turns about an eccentric axis in an orbit as shown in Figure IX. The two ports of the motor were connected to the orbitrol by means of high pressure hydraulic hoses. Also the inlet and outlet ports of the orbitrol were connected to the pump by means of hydraulic hoses. When the installation of all the necessary components was completed, the tractor was started to

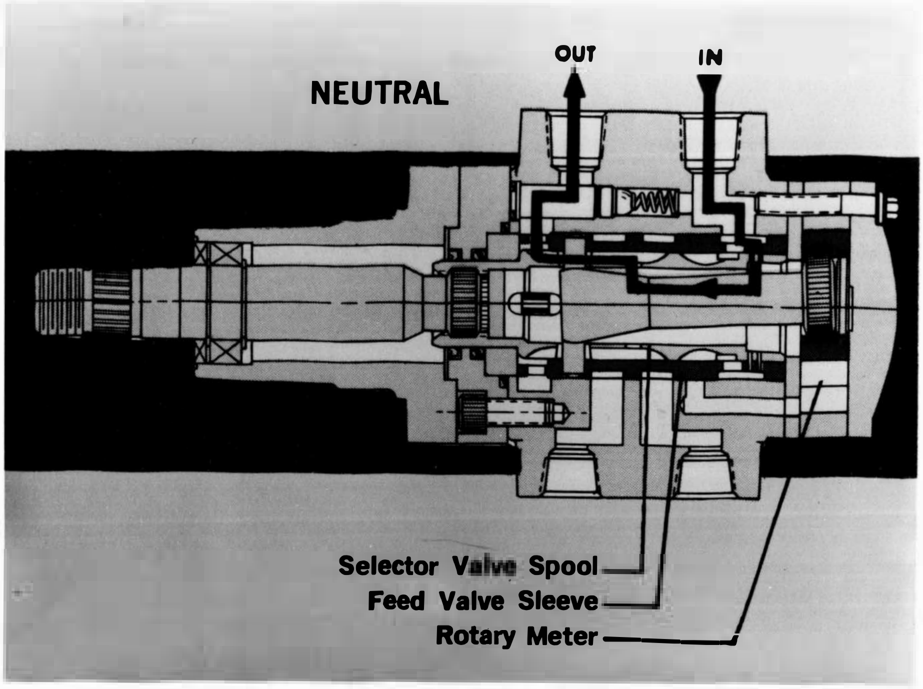

Figure VIII. Orbitrol in Neutral Position.

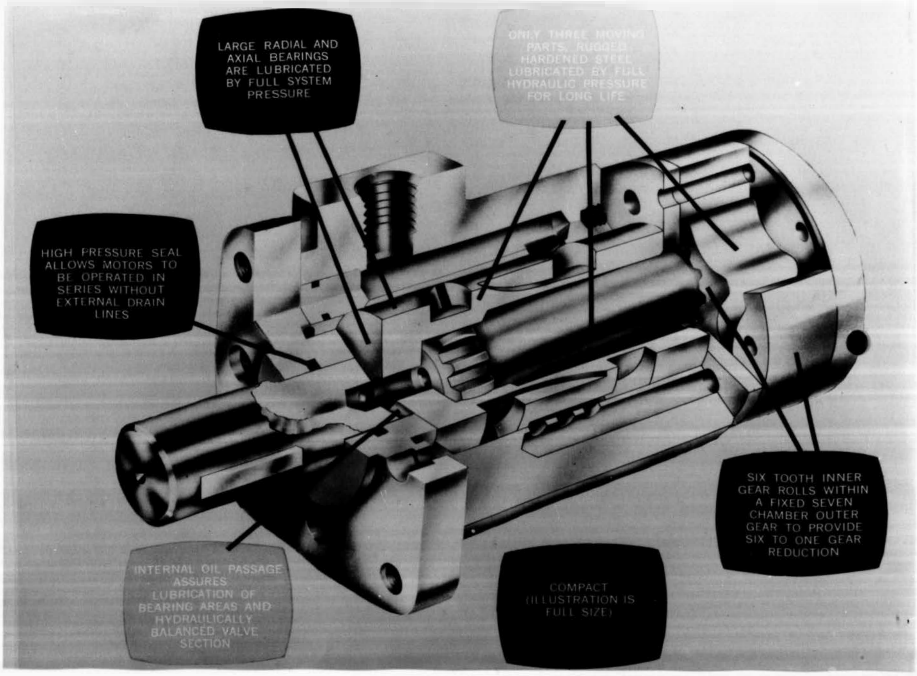

Figure IX. Hydraulic Motor.

check the operation of the steering system. Initial trials indicated that the system was completely satisfactory. The ease of operation and quick response of the steering mechanism resulted in a very dependable power steering system.

Torquemeter Data

The theoretical calculations could be used as a guide in selection of the components of the servo system. At the same time, however, it was felt desirable to obtain some experimental values regarding the Torque requirements, and other forces involved.

The main objective of this section, therefore, was to determine the variation in Torque requirement under different field conditions. To accomplish this purpose a torquemeter, Figure X, which had been constructed in the Agricultural Engineering Department was used. The torquemeter was equipped with SR-4 strain gages which were mounted on a circular shaft of a uniform cross section. Four gages had been used, and were located on the shaft in 90° angle with respect to each other. In order to provide electrical contact between the gages which were rotating, and the instruments which were stationary, collector or slip rings were used. The gage leads were soldered to the slip rings. Conducting brushes had been used to complete the electrical connections between the gages and recording instrument.

The torquemeter was installed between the hydraulic motor and the steering mechanism. A flexible coupling also was used to compensate for any misalignment. The gage leads were connected to an amplifier and

Figure X. Arrangement of the Torquemeter on Tractor.

Figure XI. Steering Torque Measurement in the Field.

a recording instrument. The set up allowed determination of the torque requirements dynamically.

The torquemeter was calibrated prior to field tests. To obtain the calibration factor, the torquemeter was held in position by securing it in a vise. An eighteen inch long pipe was used as the lever arm, and was positioned perpendicular to one end of the torquemeter shaft, while the other end of the shaft was kept stationary. A small scale was connected to the end of the lever arm in such a manner that it could be pulled in a perpendicular direction, with respect to the lever arm. The magnitude of the applied forces and the deflection of the indicating instrument to which the torquemeter leads had been connected were used to arrive at a calibration factor.

Several tests were performed to determine the variation in torque requirement for steering action. The most torque was required to steer, when the tractor was stationary on the concrete floor. On the other hand the least amount of torque was required when driving on plowed land. For comparison several charts showing the torque requirements under different conditions are shown in Figures XII, XIII, and XIV. Figure XI shows the steering torque measurement in the field.

The torque values as obtained with the above procedures are the required torque at the knuckle. However, due to the steering gear ratio, it was also desirable to obtain some values regarding the torque requirement at the spindle.

The following theoretical calculations were used to arrive at the moment around the king pin:

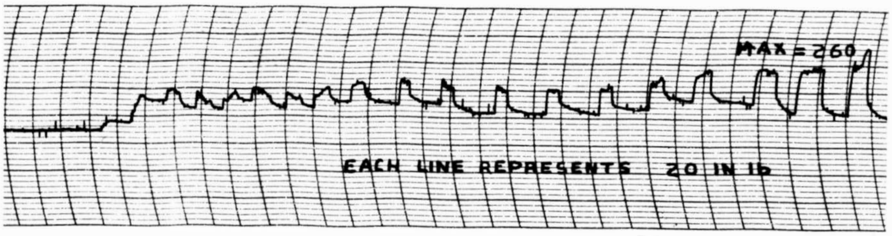

Figure XII. Torque Values for Steering of the Stationary Tractor on Concrete.

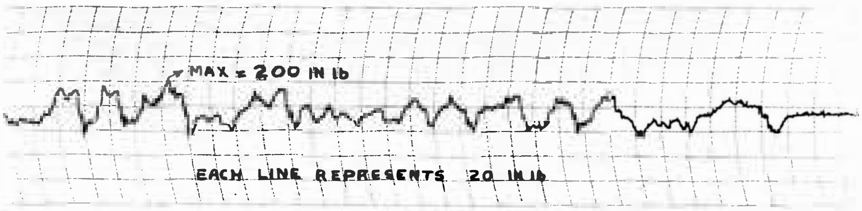

Figure XIII. Torque Values for Steering of the Moving Tractor on Loose Gravel.

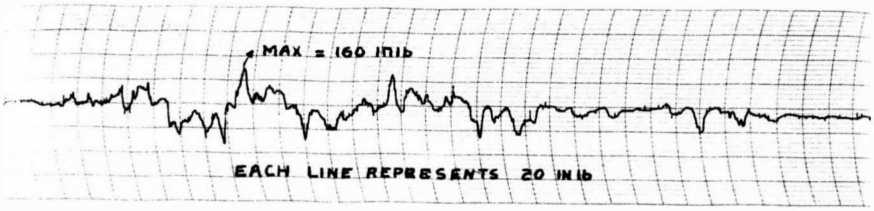

Figure XIV. Torque Values for Steering of the Moving Tractor on Plowed Land.

$$M_{kp} = \mu Wh$$

W is the axial load on each front wheel. Then using the total weight of the tractor, W was found to be:

weight of the tractor --- 4174 pounds.

$$w = \frac{4174\ (30.875)}{84.5} = 1324 \text{ pounds.}$$

30.875 = distance from the center of gravity of the tractor to the rear axle.

84.5 = the wheel base.

Therefore, the weight on one wheel was found to be:

1324/2 = 662 lbs.

The coefficient of friction μ was determined from the Figure XV.

The value of (e) on the king pin offset and the width of the tire was measured, and e was found to be:

$$\frac{e}{b} = \frac{1.45}{5} = .29$$

from the Figure XV, μ = .39

The value of h or the effective torque arm was calculated as:

$$h = \sqrt{e^2 + k^2}$$

K is the radius of gyration of the footprint area and its numerical value was found as:

$$k^2 = \frac{I_o}{A}$$

$$k^2 = \frac{\frac{1}{2}\pi \frac{b^4}{16}}{\pi \frac{b^2}{4}} = \frac{b^2}{8}$$

$$k^2 = \frac{(5)^2}{(8)} = 3.125$$

Substituting the corresponding values in equation for h resulted:

$$h = \sqrt{(1.45)^2 + (3.125)^2} = 2.28^4$$

$$M_{kp} = (.39)(662)(2.28) = 590 \text{ in.lb.}$$

The moment around the king pin was also determined experimentally using the following procedure:

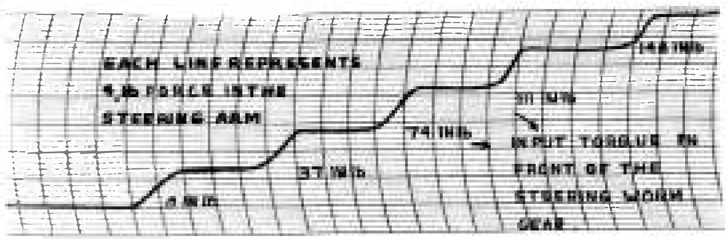

Figure XV. Steering Arm Forces for the Corresponding Torque at Steering Shaft.

A transducer equipped with SR-4 strain gages was calibrated and placed in the steering arm. The leads were connected to an amplifier and a recording instrument. Known torques were applied at knuckle in front of the worm gear while the corresponding forces in the steering arm were recorded by the instrument, Figure XV. Several tests were conducted and a curve such as shown in Figure XVI was obtained:

For example: One torque applied at the knuckle was:

18.5" (10) = 185 in.lb.

The force in the steering arm from the chart = 136 lbs. Therefore, the moment around the king pin was found as:

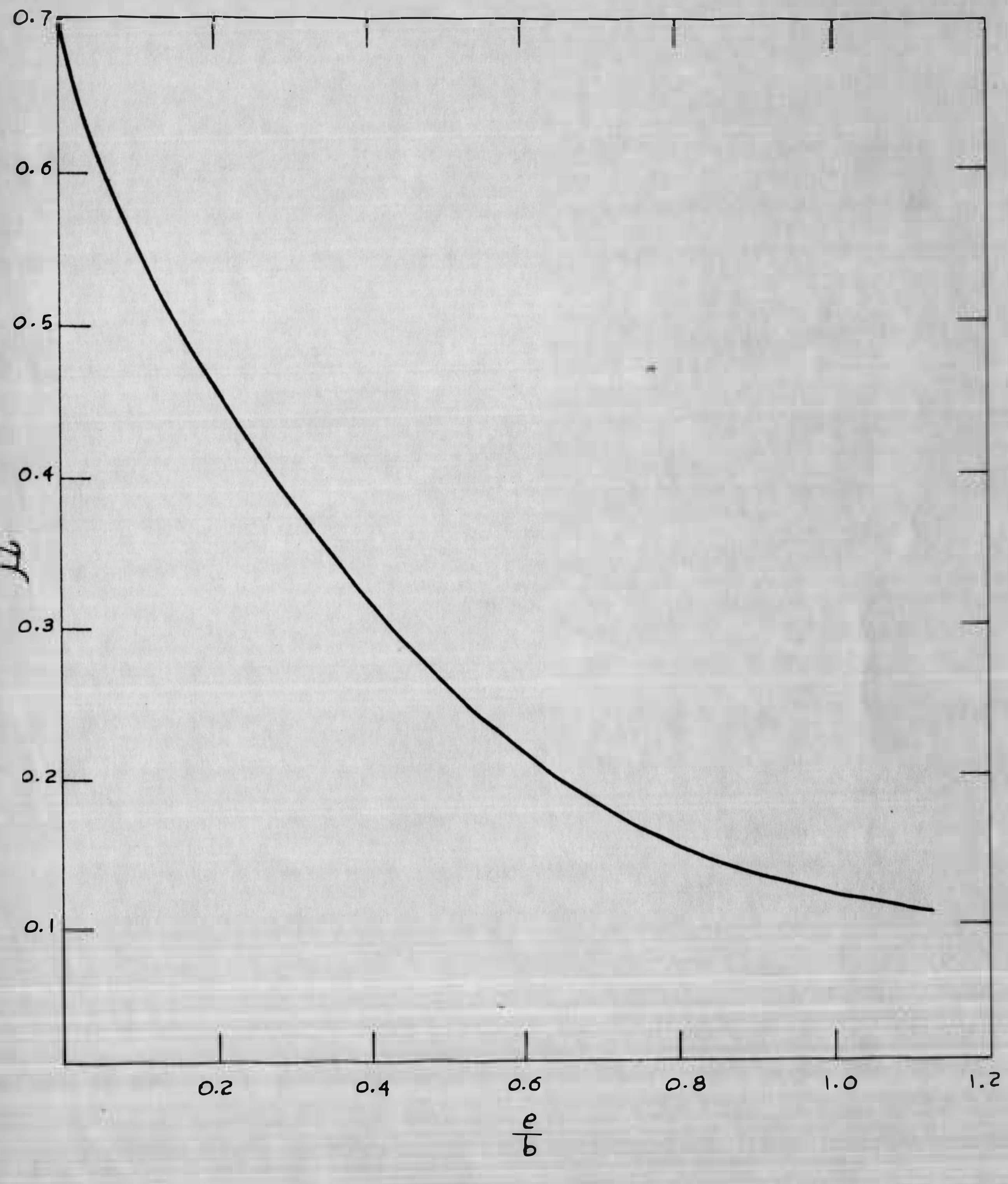

Figure XVI. Static Steering Friction Coefficient as a Function of Ratio of King Pin Offset to Normal Tire Width.

$$M_{kp} = 136(5.43) = 740 \text{ in.lb.}$$

Where 5.43 is the perpendicular distance from the steering arm to the king pin.

Investigation and data on determination of the steering torque requirements resulted in several conclusions:

1. A linear relationship exists between the input torque at the knuckle in front of the steering worm gear and the moment around the king pin. Input torques as plotted against the king pin moment are shown in Figure XVII. Also, the data in Table 1 indicated that the ratio of the input torque to the king pin moment was approximately 4.

2. The study of the experimental torque values indicated that a maximum of 260 in.lb. was required for steering of the stationary tractor on the concrete floor. This input torque, when converted to the moment around the king pin, resulted: 260(4) = 1040 in.lb.

On the other hand, the theoretical calculations show that the moment around the king pin was 590 in.lb. Keeping in mind that 1040 in.lb. is the moment around both king pins, then half of this value or 520 in.lb. is the required king pin moment, which approximately checks with the theoretical results.

3. When the tractor was tested in the field while moving, a maximum of 160 in.lb. at the knuckle or 640 in.lb. at the king pin was required to steer the tractor. Therefore, the king pin moment for each wheel would be: 640/2 = 320 in.lb.

The theoretical calculations, on the other hand, gave a completely different result as indicated below:

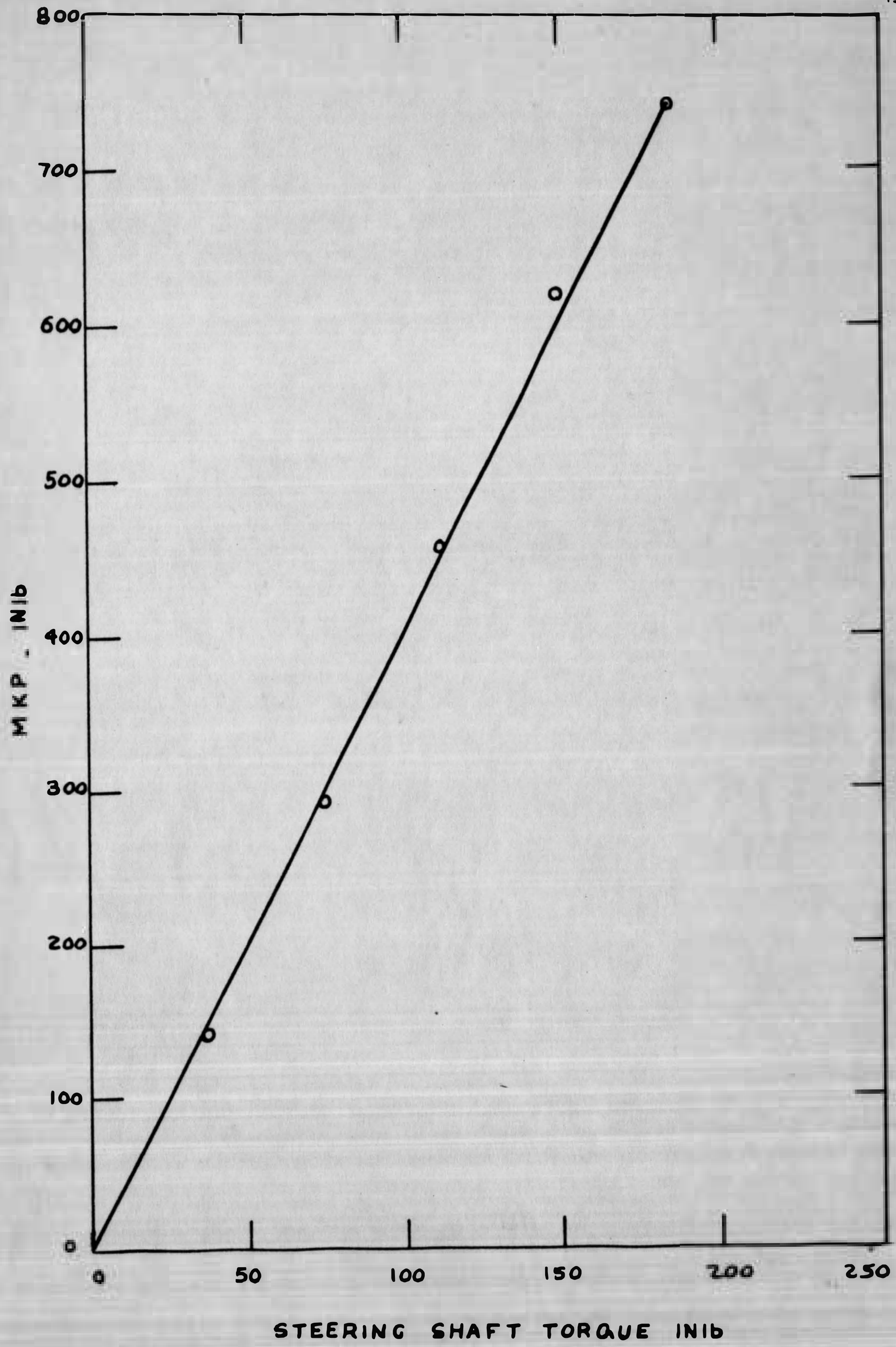

Figure XVII. Input Torque at the Knuckle Versus the Moment Around the King Pin.

Table 1. Experimental Value of Torque Requirement for Steering of Stationary Tractor.

Sleeving Shaft Torque, in.lb.	Steering Arm Forces, lb.	King Pin Moment, in.lb.	Ratio of Steering Shaft Torque to King Pin Moment
37.0	26.0	141.0	3.81
74.0	54.0	293.0	3.96
111.0	84.0	456.0	4.11
148.0	112.0	620.0	4.19
185.0	136.0	740.0	4.00

$$M_{kp} = \frac{W\ e\ \sin\theta\ (1 - \cos\alpha)\ b}{2B\alpha}$$

From the condition of the tractor, the numerical value of each term was found as follows:

W = 4174 lb.

e = 1.45 inch

θ = 7°

α = 90° for maximum king pin moment

B = 84.5"

b = 30.875"

Substituting these values in the formula and carrying through resulted:

$$M_{kp} = \frac{4174(1.45)(.122)(1-0)\ 30.875}{2(1.57)(84.5)} = 86 \text{ in.lb.}$$

Comparison of the theoretical to the experimental, results indicated a considerable amount of variation. Theoretically, only 86 in.lb.

of torque was required as compared to 240 in.lb. with the experimental results. Such a discrepancy could be explained and justified as follows:

Formula (1), which was used to determine the torque requirement of the moving tractor, is primarily designed for fast moving vehicles such as automobiles. On the other hand, under many field conditions the tractor has to travel less than five miles an hour. Therefore, it is entirely possible that at very low speeds, even though some of the static friction between the tire and the ground has been overcome, additional torque is required to compensate for both static friction and slow motion.

Selection of Automatic Steering Components

The first step in selection of automatic steering components was to choose a motor which would be capable of actuating the steering mechanism. A Char-Lynn motor model (g) was selected, and the oil flow rate through it was calculated. It was assumed that the motor would rotate at a maximum speed of 60 RPM. The torque output of the motor as was specified by the company was 2,250 in.lb. Therefore, the volume of oil flow through the motor was found to be:

60 RPM (.05 gal/rpm) = 3.0 gpm

2,250 in.lb. (.16 gpm/100 in.lb.) = 3.6 gpm

3.0 + 3.6 = 6.6 gpm

Thus, at a speed of 60 RPM up to 6.2 gallons could flow through the motor. But the torquemeter data indicated that only 1,040 in.lb. of torque was necessary for full steering action. As a result, the actual volume of the oil through the motor was found to be:

60 RPM (.052) = 3.0 gpm

1,040 in.lb. (.16 gpm/100 in.lb.) = 1.68 gpm

3.0 + 1.68 = 4.68 gpm

The next step was to select an electro hydraulic servo valve capable of discharging at least 4.68 gallons of oil per minute.

A Pegasus servo valve model 120-F was selected, Figure XVIII. The valve had a flow capacity of 5 gpm at 1,000 psi, as shown in Figure XIX.

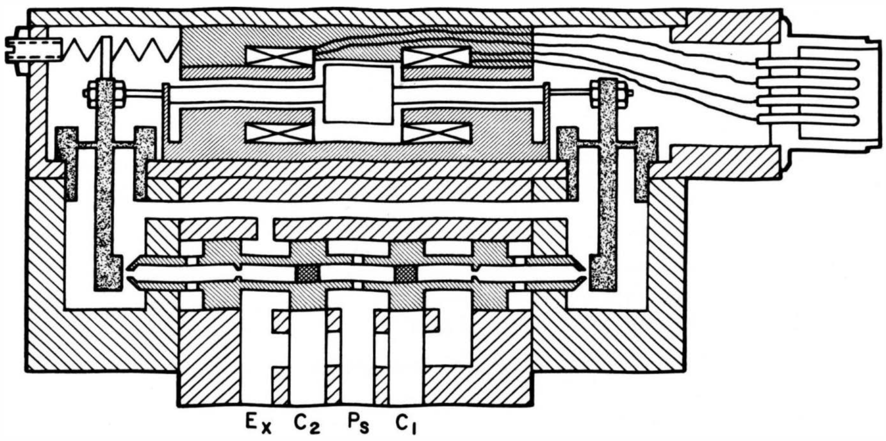

Figure XVIII. Servo Valve.

The valve is capable of controlling the oil flow rate to the hydraulic motor in proportion to a differential current input signal

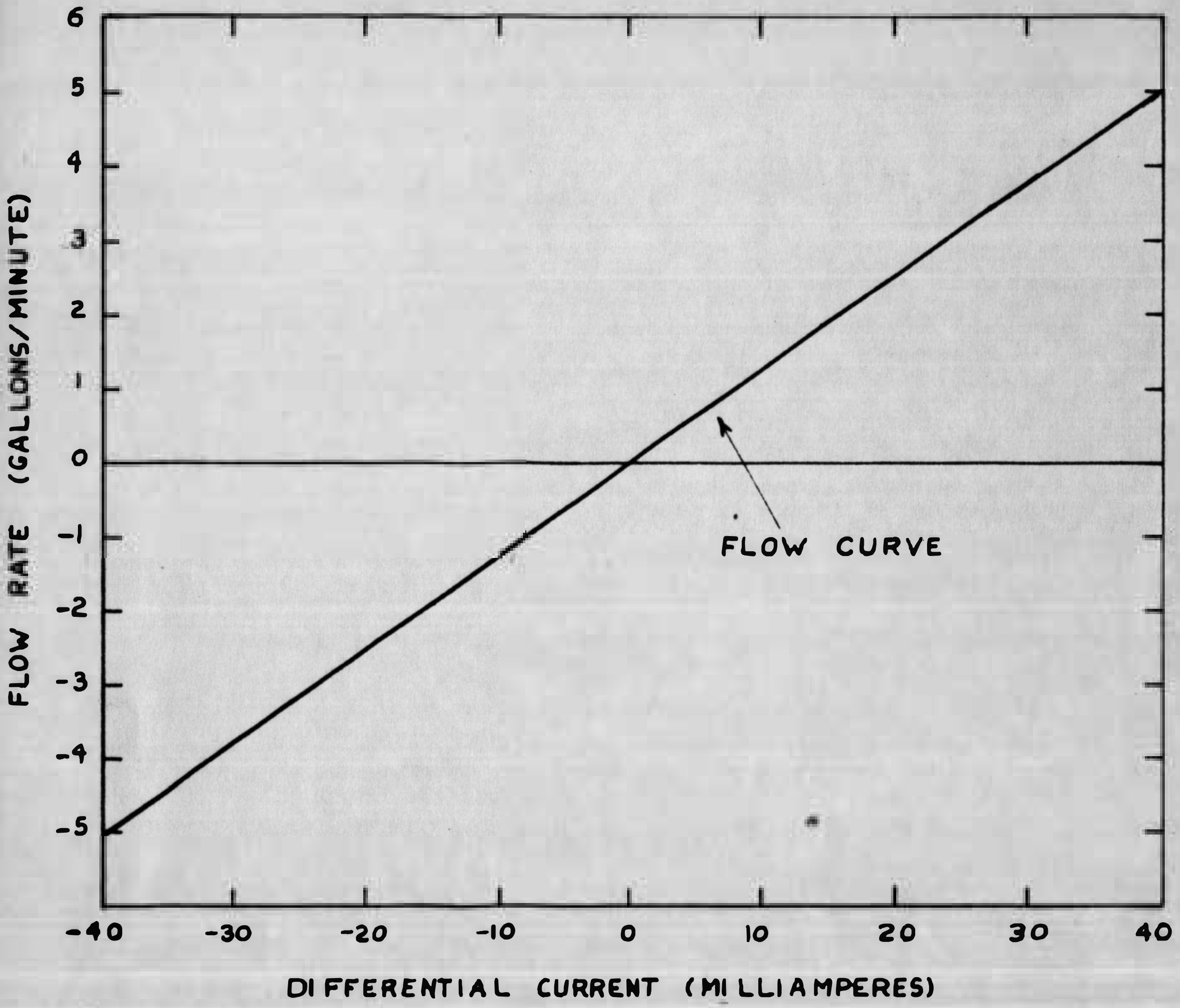

Figure XIX. Servo Valve Oil Flow Curve.

from an amplifier. The valve is made up of an electro mechanical actuator and a zero lapped four-way valve. The servo valve is also equipped with a double flapper boost system which drives the spool at elevated force and stiffness levels. The spool is driven by the fixed rods which are located at each end of the servo valve. These pivot rods are sealed in place and actuate the variable nozzles which are located at the end of the spool. Oil under pressure enters the boost system through the center of the spool and is filtered before it reaches the fixed up stream nozzles.

To match the servo valve, a Pegasus model 402 amplifier was selected. The amplifier is so designed to provide a differential current to a two-load coil in response to a low voltage input. The amplifier is a three-stage push-pull direct coupled amplifier, the output of which is 0 to $\pm$ 40 milliampers. The amplifier is designed to operate with 110 V AC. Thus it was necessary to provide an inverter capable of converting the 12 V DC power supply of the tractor to 110 volts alternate current. The selected inverter had an output capacity of 80 watts and was quite adequate to operate the amplifier which required 40 watts.

Preliminary Tests

According to the specification of the servo amplifier, an input of 200 millivolts provides an output of 40 milliampers. The 40 milliampers differential current from the amplifier enables the servo valve to allow a flow rate of 5 gallons per minute at 1000 psi. To temporarily obtain the required 200 millivolts for test purposes, a simple potentiometer circuit was constructed.

Using a variable resistor of 10k, the required current to secure 200 millivolts voltage across the resistor was calculated as:

200 millivolts = .2 volts

$V = RI$

$.2 = 1000\ (I)$

$I = .2/1000 = 2(10)^{-5}$ amperes

To obtain the calculated current of $2(10)^{-5}$ amperes a small storage battery of 1.35 volts was used. Then using Ohm's law, the correct size of a resistor was determined, which, when put in series with the battery, allowed only a current of $2(10)^{-5}$ amperes or 20 microamperes through the circuit.

$V = RI$

$1.35 = R(2)(10)^{-5}$

$$R = \frac{1.35}{2(10)^{-5}} = 67500 \text{ Ohms}$$

Therefore, a circuit such as shown in Figure XX was developed to provide the necessary input voltage to the amplifier. With this setup it was possible to change the value of input voltage between zero and 200 millivolts. The purpose of the two-way switch was to provide a means by which the input voltage could be reversed both in the positive and negative directions. Therefore, it was possible to obtain a maximum differential current of + 40 milliamperes from the amplifier.

The output leads of the potentiameter were connected to the input terminals of the amplifier. The variable resistor was adjusted so that no signal was being transferred to the amplifier. Next, the tractor was

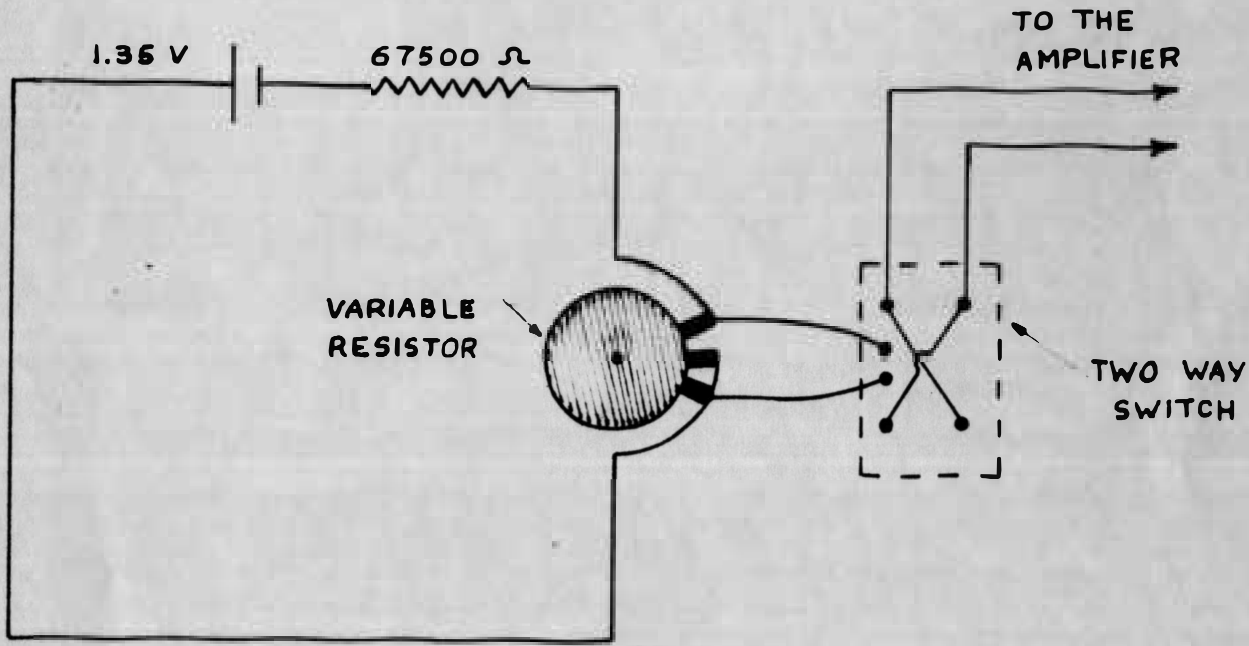

Figure XX. Potentiometer Circuit.

started and the amplifier turned on. The meter indicating the input milliamps to the servo valve was balanced to read zero when there was no input signal. When the variable resistor was turned clockwise to allow the signals to enter the amplifier, the servo valve was not actuated and the tractor's front wheels stayed stationary. The signals were intensified up to 200 millivolts but the servo valve did not respond. The same situation was noticed when the direction of the differential current was reversed.

The system was checked thoroughly. Every component was functioning except the servo valve. Therefore it was concluded that the hydraulic hoses between the pump, servo valve, and hydraulic motor were not connected properly. The hose connections were switched around, and secured in position in a pattern which seemed most reasonable and logical.

When the system was ready, the signals were sent to the amplifier again and it was noticed that the servo valve was responding and the front wheels started to steer to the left. However, when the direction of differential current was reversed, there was no steering action to the right.

Attention was focused again on the servo valve. The valve was dismounted and taken apart. It was found that the valve spool had been stuck in position, so that it could not be moved by sealed pivot rods. The components of the valve were washed with cleaning fluid and were flushed with compressed air. Even though the valve was equipped with a screen filter in the supply port, nevertheless, pieces of iron filings and other foreign materials were found around every port. The valve was put back again in the system, but it did not function properly despite considerable effort and repeated attempts.

One conclusion was reached after the valve was taken apart several times. Operation was not possible while there was any trace of iron filings and other materials in the oil.

The situation was explained in a correspondence with the company. In a reply from the company, installation of a full flow filter in the hydraulic pressure line preceding the servo valve had been highly emphasized. According to the manufacturer's recommendation, a filter with 10 micron cartridge was purchased and installed in the pressure line. Then, in order to flush the system, the pressure line to the valve was by-passed around the valve to exhaust. With the system connected as such, the tractor was started and allowed to run for two hours. At the end of two hours, the servo valve was also placed in the system. When the input signals from potentiometer were sent to the amplifier, the steering of the tractor to the left indicated that the valve was functioning properly. The switch in the potentiometer circuit was placed in reverse position. Therefore, as a result of change in the direction of the differential current, steering action started in the opposite direction. At this point it was concluded that a fine full flow filter must be an integral part of the system, without which the operation of the servo valve would be impaired.

The addition of the filter resulted in a workable system; however, new problems were encountered at the same time. The filter could not withstand the high oil pressure as the engine RPM increased.

Heavy leakage was noticed which made the automatic steering impractical at very high engine speeds. To overcome this problem, a relief valve was installed in the system in parallel with the oil filter. Addition of such a valve made it possible to by-pass some of the oil flow around the filter. The relief valve had to be kept half open to allow enough oil to pass through it, and thus prevent filter leakage.

When satisfactory operation of the automatic steering was assured, the next step was to determine whether it could also be used interchangeably with power and manual steering. When all the connections were secured, an attempt was made to steer the tractor manually with the automatic components in the off position. Even though the steering was possible, it seemed that a continuous resisting force was opposing the rotation of the hydraulic motor in the direction that was intended by the steering wheel. The automatic steering also did not function very well with the power steering in the system. To improve the situation, several gate valves were installed in the hydraulic system. Two valves were installed in the pressure and return lines joining the hydraulic pump to the servo valve. Also, four additional valves were installed in the lines joining the pump to the orbitrol, and the orbitrol to the hydraulic motor.

A thorough check was made of the overall performance of the system, and the results indicated the reliability of both automatic and power steering. However, it was noted that only two valves in the supply lines to the orbitrol and servo valve were sufficient for satisfactory operation; while the other four gate valves did not affect the operation of the system. It was also concluded that in order to speed the change over from manual to automatic steering, the present gate valves should be replaced with a different type to provide a quicker on and off operation. Figure XXI shows the instrument involved in automatic steering and Figure XXII shows the location of gate valves and the oil filter.

Design of the Strain Gage Transducer

It has been mentioned before that a maximum of 200 millivolts was required to best actuate the servo components of the automatic steering. To supply the necessary voltage it was decided to use strain gages in a wheatstone bridge circuit.

Two feeler arms were located on the tractor to form a cantilever beam anytime the tractor would turn away from the crop row. Selection of the material for the feelers required laboratory testing of several readily available materials. There were several desired characteristics which were looked for in the feeler arm material, such as:

1. Low modulus of elasticity.
2. High stress.
3. High yield point and elastic limit.
4. Flexibility.

Spring steel provided a highly flexible arm, however, since its modulus of elasticity was quite high, not much strain resulted when it was bent. Next, attention was focused on plexiglass. Plexiglass showed a very high degree of flexibility; however, when the properties

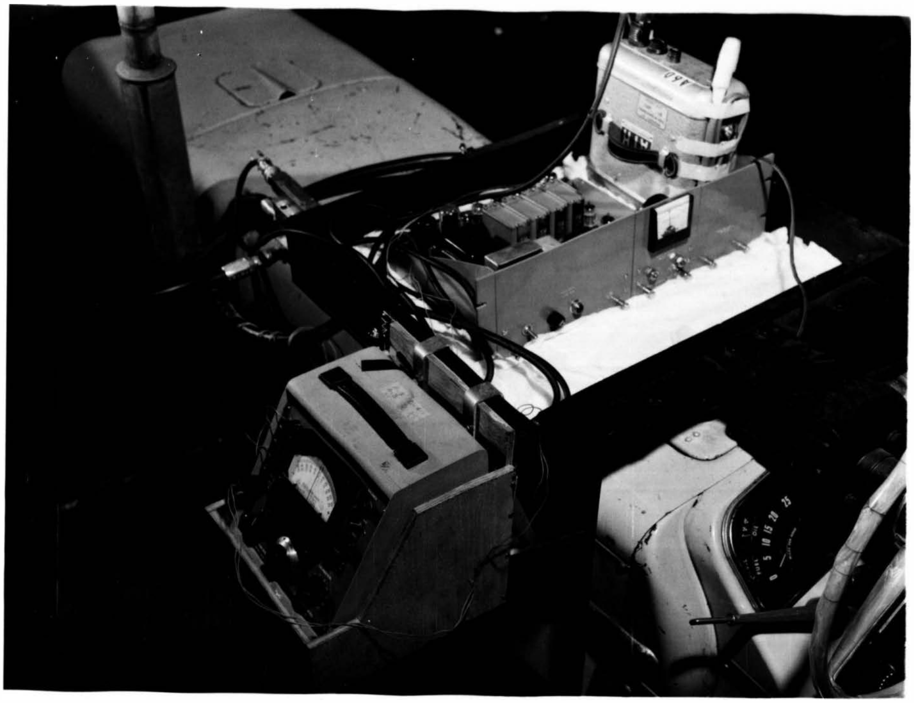

Figure XXI. Automatic Steering Components.

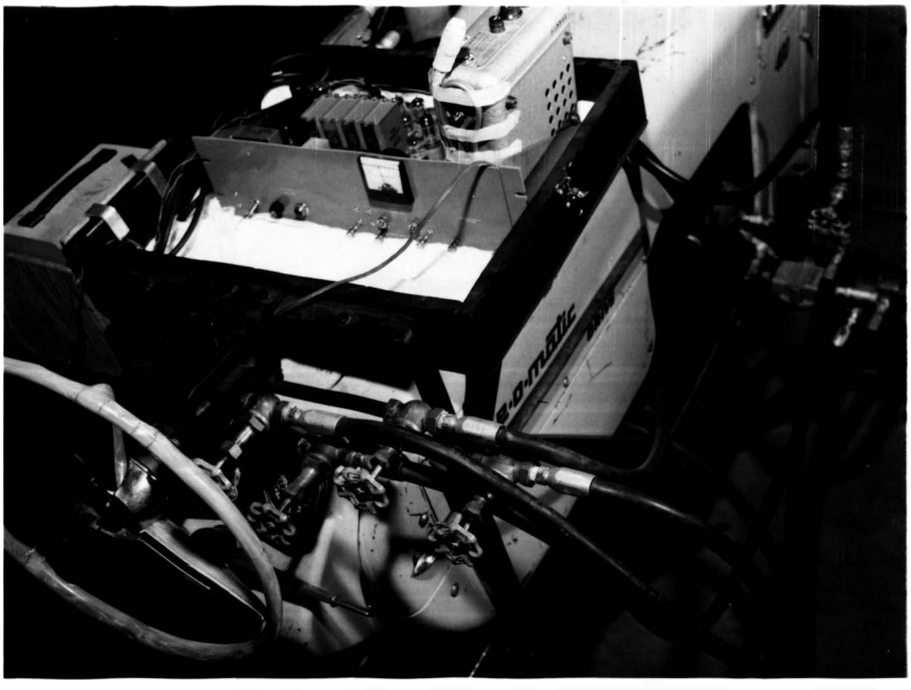

Figure XXII. Gate Valves and Hydraulic Oil Filter.

of the material were studied, it was found that plexiglass had a very low stress capacity. But because the modulus of elasticity of the plexiglass was also low, it was believed that it could develop the necessary voltage in the bridge circuit.

Four strain gages were mounted on a piece of 2 inch wide and 2 feet long plexiglass. The gages were mounted in a manner so that any deflection of the arm could result in tension in two gages while the other two gages would be in compression. The terminals of the circuit were connected to an indicating instrument. But the result of the test indicated that the maximum output voltage could not exceed 50 millivolts, which was not quite enough to actuate the servo system. Another disadvantage of the plexiglass was the fact that it had a very low heat dissipation property which resulted in self heating of the gages.

As a compromise between spring steel and plexiglass, aluminum seemed to provide the best answer. Aluminum has a relatively high stress while its modulus of elasticity is low. The only objection in using aluminum was its rather poor flexibility which resulted in residual bending. The value of strain for aluminum was calculated using Hooke's law.

$$e = \frac{?}{E}$$

$$e = \frac{27000}{10000000} = 2700 \text{ micro inch/inch}$$

The following calculations pertain to the aluminum for the sensing device.

Several assumptions were made in the design of the strain gage transducer as follows:

1. The full output of the bridge circuit was based on a six inch deflection of the feeler arms.

2. The feeler arms were to be deflected six inches when a maximum 2 pounds of force was applied.

To determine the correct width of the feeler, the following calculations were used:

$$y = \frac{p\ ^3}{3EI}$$

where y = maximum deflection = 6"

p = maximum applied force = 2 lb.

= the length of the arm = 24 inches

E = modulus of elasticity of aluminum = $10(10)^6$

I = moment of inertia of the cross section in in^4

Substituting the corresponding values in the formula and solving for (I) resulted:

$$6 = \frac{2(24)^3}{3(10)(10)^6 I}$$

$$I = \frac{2(24)^3}{18(10)^7} = \frac{1536}{(10)^7}$$

For a rectangular cross section the moment of inertia (I) is given by the equation:

$$I = \frac{1}{12} bh^3$$

Where b is the width of the cross section and h is the height. Therefore, for h = 1/8" b was calculated as:

$$I = \frac{1536}{(10)^7} = \frac{1}{12} b (1/8)^3$$

$$b = \frac{1536 \quad (12)}{(10)^7 \; (.125)^3} = .95''$$

Figure XXIII shows the location of the feeler on the tractor.

An important factor in the design of the strain gage transducer is to prevent any self heating effect in the gages. The heating effect is caused by the input voltage to the circuit. Therefore, selection of the storage battery for the bridge circuit requires careful consideration. Usually a maximum self heating effect of .5 watts is allowed per arm of bridge. Using this value the correct size of the battery was calculated as:

$$W = RI^2$$

W = dissipated power in the form of heat

R = resistance of strain gage = 120 Ohms

I = the current through the bridge arm in amperes

$$.5 = (120)\, I^2$$

$$I^2 = \frac{.5}{120} = .00417$$

$$I = .0645 \text{ amperes}$$

Therefore only a current of .0645 amperes through each arm of the bridge could not cause any self heating effect:

$$V = IR$$

$$V = .0645\,(120 \times 120)$$

$$V = .0645(240) = 16 \text{ volts}$$

A 16 volt storage battery was selected and placed in the circuit. Then the maximum output voltage of the transducer for six inches

Figure XXIII. Location of Feeler on the Tractor.

Figure XXIV. General View of the Tractor with Automatic Steering Components.

deflection of the feelers was calculated as:

$$E_o = E\,G\,e\,\frac{n}{4}$$

$$E_o = 16(2)(2700)\,\frac{4}{4}$$

$$E_o = 86500 \text{ microvolts}$$

$$86500/1000 = 86.5 \text{ millivolts}$$

As it is observed from the calculations, the output voltage of the bridge was not quite adequate to best actuate the servo valve. As a result, the steering action was not quick enough. To overcome this problem, one alternative was to add another wheatstone bridge circuit to the feeler and place it in series with the original circuit. With this method it was possible to increase the output voltage to 173 = 2(86.5).

However, a second alternative was to place a preamplifier device between the bridge circuit and the servo amplifier. Because the latter method was more practical, it was decided to try it out. The result was very satisfactory as the output voltage could be amplified up to 200 millivolts. In the future it may be possible to provide a transistor preamplifier to replace the present amplifier and indicating instrument.

SUMMARY

An automatic guiding system which enables a tractor to guide itself in the field by sensing the position of the crop rows was designed, constructed, and laboratory tested. The design criterion for the system was obtained from previous investigations, present trends, and the need for more automation of the agricultural processes.

The system described in this study applies the principle and fundamentals of servomechanisms. The primary criterion for selection of the servo components was the torque requirement for steering action. The required torque for steering under various field conditions was calculated theoretically, and also determined experimentally, using a torquemeter in front of the worm gear. The relationship between the torque at the steering shaft and the torque around the king pin was determined, using a strain gage transducer in the steering arm and calculating the force for the corresponding input torque at the steering shaft.

A completely hydraulic power steering system which resulted in removal of all the mechanical linkages between steering wheel and steering axle was installed on the tractor. This new power steering not only facilitated the installation of the automatic guiding components, but also resulted in a quicker and more positive manual steering.

The sensing element of the system consisted of two feeler arms, and was located on the tractor in a manner to deflect as a cantilever beam whenever the tractor was off the center with respect to the crop row. The feeler arms were equipped with SR-4 strain gages to form a

wheatstone bridge circuit. The bridge circuit provided the necessary voltage for actuation of the servo components of the guiding system. The output voltage of the transducer depended upon the amount of deflection in the feeler arms.

Several materials were laboratory tested to arrive at a suitable material for the feeler arms. Aluminum appeared to provide the best answer at the present time. The plexiglass materials were also promising due to a high degree of flexibility.

Several problems were encountered while constructing and testing the guiding system as follows:

1. The output voltage from the feeler's bridge circuit was not adequate for best performance of the servo valve. A preamplifier unit was used to overcome this problem.

2. High precision parts of the servo valve were very sensitive to any foreign materials in the fluid which resulted in the addition of a filter with 10 micron cartridge in the pressure line of the servo valve.

CONCLUSIONS

1. The automatic guiding system developed in this study has been laboratory tested successfully. The results of the tests indicated the following advantages over the previous guiding methods: (a) The steering action is proportional to the feeler's deflection, and (b) Full steering action is possible in both directions, the quickness of which depends on the input signals.

2. A full flow filter equipped with a 10 micron cartridge and installed in the supply line of the servo valve must be an integral component of the system, without which the operation is impaired.

3. Strain gages can be used to provide the source of input signals. However, since the maximum voltage cannot be obtained from one bridge circuit, a preamplifier device should be placed between the transducer and the servo amplifier.

4. The theoretical formula for determination of moment around the king pin of a stationary tractor agrees with the experimental values, but the same is not true when the tractor is moving.

5. A linear relationship exists between the input torque at the steering shaft and the moment around the king pin.

6. The numerical values of the torque requirement for steering of the stationary and moving tractor as determined theoretically and experimentally are:

	Stationary Tractor	Moving Tractor
Theoretical	590 in.lb.	86 in.lb.
Experimental	520 in.lb.	320 in.lb.

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