CHARACTERISTICS OF THE PENDULUM TYPE INCLINOMETER AND ITS APPLICATION

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Introduction

Presented in this report is the description of the development and testing procedures and results of an originally designed inclination regulating system for field machinery use, especially for keeping a tractor-mounted sprayer boom constantly parallel to the field surface as the tractor on which the boom is mounted is caused to incline or roll by irregularities of the field surface.

The study for the development of the inclination regulator mentioned above was conducted with a final objective at the reduction of the chemical spray volume fluctuation through the optimization of the sprayer boom's inclination. The importance of this study is supported by the fact found by scientists that agricultural chemical application errors are costing farmers across the world over a billion dollars annually. Among these errors, such as incorrect spraying speed, mixing error, etc., more attention is being directed toward the fluctuation of spray volume caused by the constant change in the sprayer boom's height and inclination, as the significance of the spray volume fluctuation increases with the length of boom and the number of long booms in farm operation is practically increasing.

This project consists of two working steps as described below:

1) Sensitivity test and dynamic motion simulation of the pendulum type inclinometer originally constructed in the laboratory.

2) The sprayer boom control or inclination steering (hereinafter referred to as "steering") test of the inclination steering device constructed in the laboratory, employing the said inclinometer.

SENSITIVITY TEST OF THE INCLINOMETER

1: Test Device and Data Acquisition

1.1: Test Device

A sketch of the test device is shown in Fig. 1. According to the figure, the inclinometer to be tested was bolted on a swing board which could be swung ± 2.5 deg. above and beneath the horizontal line by a rotating eccentric cam which is directly driven by an electric motor with adjustable speed ranging from 10 to 50 rpm. The inclinometer constructed consists of a pendulum, two proximity switches, and a pendulum box. The pendulum itself was designed to have a natural vibration frequency of 1 Hz. The pendulum ball was made of lead to obtain the maximum weight within the size limit. In this case the weight of the pendulum ball was 300 grammes.

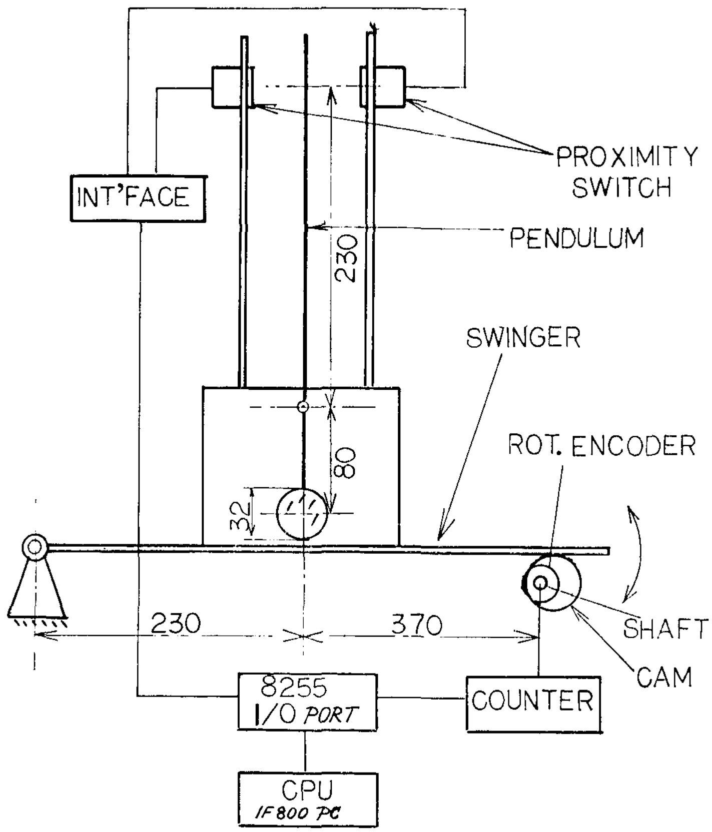


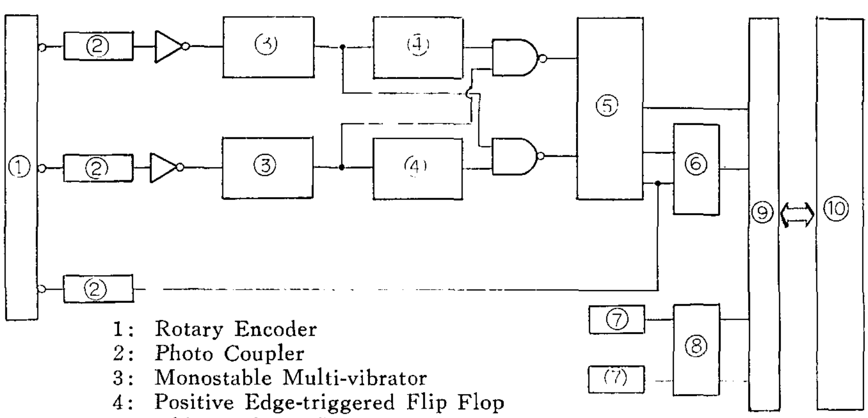
Fig. 1. Pendulum type inclinometer, sensitivity test stand and data acquisition system.

The pendulum box was constructed in reservation for the application of liquid dampers with different viscosities in case of excessive vibration.

The two proximity switches (sensitivity = 10 mm and output voltage = 10 volts) were set to detect any inclination greater than 0.5 degs. (See explanation in Section 1.3 below.) Therefore, according to Fig. 1, any counterclockwise inclination beyond the horizontal position that is greater than the sensitivity set (0.5 degs.) will be detected by the proximity switch on the right side of the pendulum tail (hereinafter referred to as the "upward-swing detector"); and any clockwise inclination beyond the horizontal position that is greater than the set sensitivity will be detected by the switch on the left (hereinafter referred to as the "downward-swing detector").

1.2: Data Acquisition

The inclination of the swing board was measured by a rotary encoder (360 pulses/rotation) mounted at the end of the cam shaft. With the help of the up-down counter on the I/F board shown in Fig. 2 and a specific interface program algorithm, the inclination could be measured with an accuracy as high as 0.01 deg., or one-fiftieth of the sensitivity of the inclinometer. The digital data from the inclinometer and the rotary encoder were recorded and processed by an 8-bit digital computer (If-800/30, Oki Electric Co., Ltd.). The soft-ware used in the data acquisition procedure was written



1: Rotary Encoder
2: Photo Coupler
3: Monostable Multi-vibrator
4: Positive Edge-triggered Flip Flop
5: 8-bit Up-down Counter
6: RS Flip Flop
7: Proximity Switch
8: EX-OR Gate
9: 8255 A I/O Port
10: If-800 PC

Fig. 2. Interface circuit used for the data acquisition in the sensitivity test of the inclinometer.

in Machine Language and executed on a 58 k CP/M operating system.

1.3: Desired Sensitivity

With an assumption that if 20% of the fluctuation of the spray volume caused by the inclination of the sprayer boom is acceptable, in order to keep the fluctuation within this limit, the boom must be steered so that its inclination is within ± 2.5 degs. from the line parallel to the field surface. Therefore, it was assumed that an inclinometer sensitivity of at least 0.5 degs. would be necessary for the said steering degree of precision and the inclinometer was set to detect any inclination of 0.5 degs. or more from the horizontal line in the test.

2: Result and Discussion

2.1: Simulation of The Pendulum Motion

The motion of the pendulum was expressed by a non-linear differential equation of the second degree as follows:

$$\ddot{\theta} = \frac{k}{ml}\left(\dot{\theta} - \frac{ea}{Ll}\,\omega \sin \omega t \cdot \sin \theta\right) - \left(g + \frac{a}{L}\,e\omega^2 \cos \omega t\right) \sin \theta$$

where,

a = horizontal distance between the swinger shaft and the pendulum shaft (See Fig. 1)
e = eccentricity of the disc cam
g = gravitational acceleration
k = damping coefficient at the pendulum shaft
l = length of the pendulum arm
L = distance between the cam shaft and the swinger shaft
m = mass of the pendulum ball
θ = angular displacement of the pendulum
ω = rotation speed of the cam shaft

After the damping coefficient at the pendulum shaft bearing was computed from a logarithmic decrement equation, the formulated equation of motion of the pendulum was then analysed through a simulation by a digital computer in order to (1) estimate the period of time required for the oscillation amplitude to fall within the dead band of the inclinometer and (2) identify the highest periodic disturbance frequency at which the pendulum still reponds with accuracy.

Important facts that cam be extracted from the simulation are:

a: The pendulum stops oscillating, regardless of the continuous swinging of the swing board, after about 8 seconds of oscilation (See Fig. 3a). The maximum angular velocity of the cam shaft at which the pendulum motion behaves, this way is 1700 deg/s or about 283 rpm. The cam shaft angular velocity of 1700 deg/s is where the velocity curve begins to get distorted by the high frequency disturbance.

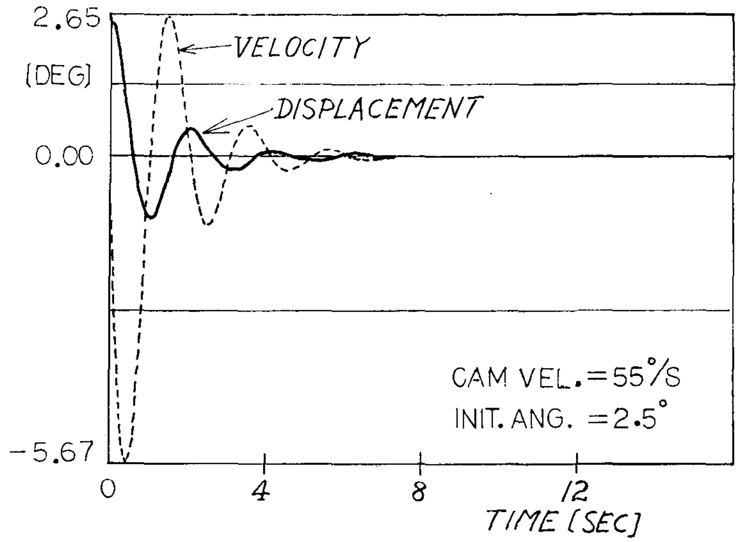


Fig. 3a

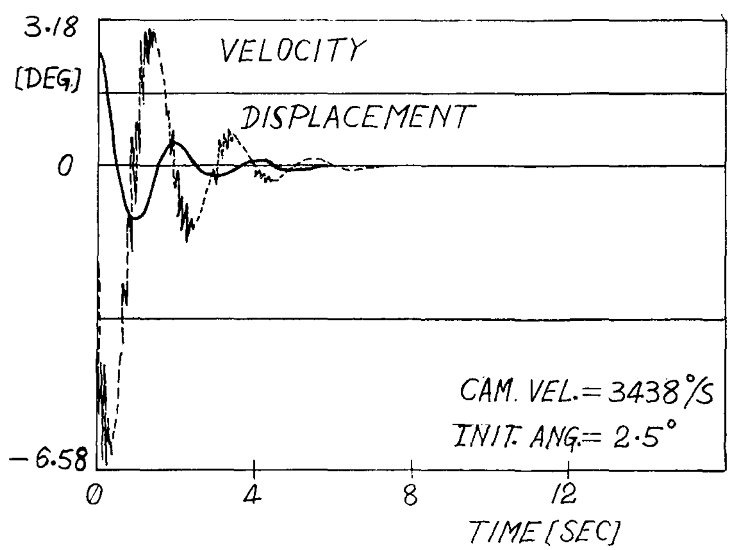


Fig. 3b

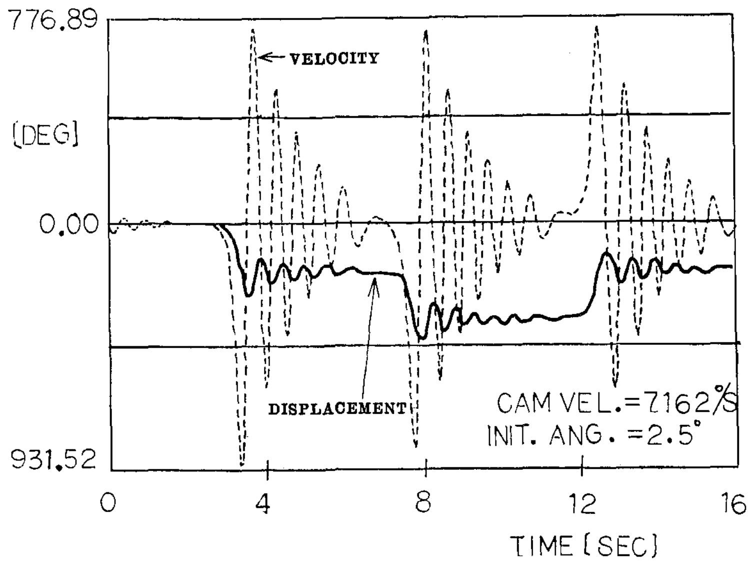


Fig. 3c

Fig. 3. Result of the simulation of the motion of the pendulum under a continuous disturbance and an initial angle of 2.5 degrees.

b : The real splitting of the velocity curve occurs at the cam shaft angular velocity of 3437 deg/s or 573 rpm. However, the oscillation of the pendulum still diminishes at this rotation speed. (See Fig. 3 b)

c : Mechanical resonance occurs at the shaft angular velocity of over 7000 deg/s or 1167 rpm. (See Fig. 3 c.)

The facts above indicate that this pendulum will function as an inclinometer without irregularities when the frequency of a continuous input does not exceed 9.55 Hzs. or 3437 deg/s (at which the velocity curve begin splitting) in angular velocity.

2. 2: Measurement Result

The saw-tooth shape input on the graph in Fig. 4 a and 4 b is the disturbance curve obtained from the cam's motion. The hatched areas are the ranges of the angular displacement where the proximity switches are sensitive (ON).

In order to make the discussion of the results of the test easier to understand, it is necessary to explain the meaning of some technical terms below.

a : "on-to-off logic level transition" of a switch, is the transition of logic level from "high" to "low" that occurs at one switch, either left or right.

b: "off-to-on logic level transition" of two switches, is the transition that occurs after one switch, either left or right, turns off and the switch on the opposite side turns on.

2.2.1: Logic Level Transition Delay or Sensing Delay

When the cam shaft rotates slowly (from 9 rpm to approximately 12 rpm), the effect of the inertia force of the pendulum during the upward swing is fairly small and can be neglected, as can be seen in Fig. 4a where no switching occurs beyond the neutral position. However, when the pendulum box is swung downward by the swing board, a gravitational acceleration component adds itself to the pendulum's angular acceleration and the pen-

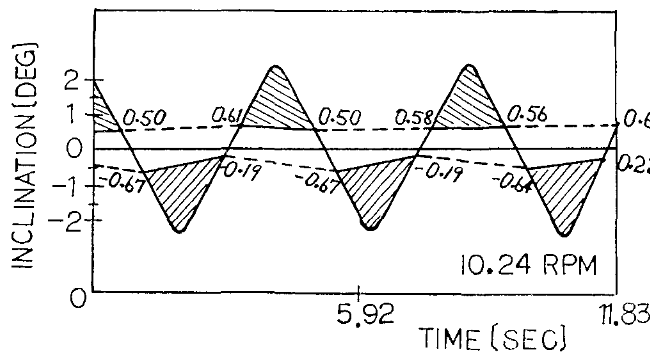


Fig. 4a

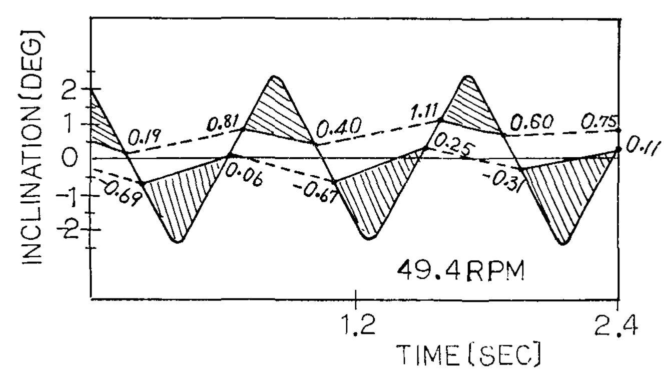


Fig. 4b

Fig. 4. Result of the measurement of the sensitivity of the inclinometer under a periodical disturbance generated by the rotation of the eccentric cam. Hatched areas are where the switches are sensitive; and the band between the broken line and these hatched areas is the dead band.

dulum swings clockwise (when the system is viewed in such a way that the cam shaft is on the left hand side of the pendulum shaft) with greater force than when the system swings upward and the pendulum swings counter-clockwise. This results in the delay of the turning off, or the on-to-off logic level transition of the downward swing detector (the switch that is responsible for the detection of the downward movement of the system). For example, for the 10 rpm graph in Fig. 4 a, the on-to-off logic level transition delay of the downward swing detector is $0.67-0.19=0.48$ degs.

For better understanding of the motion of the pendulum and the logic transition processes, please note that,

a) The on-to-off logic level transition of the upward swing detector occurs after the system starts to swing downward.

b) The on-to-off logic level transition of the downward swing dector occurs after the system starts to swing upward.

c) The off-to-on logic level transition *of two switches* are composed of the transition in a) and b). The angular measurement between these two transitions is the non-sensitive range (or dead band) of the inclinometer.

Logic level transition delay of the upward swing detector becomes more significant when the cam shaft rotates at speeds higher than 16 rpm. At 16 rpm the on-to-off transition level delay of the upward swing detector averages 0.15 degs. or about 21% of the off-to-on sensitivity of the switch (measured in degrees from the neutral vertical axis to the point where the switch's logic level transition from "low" to "high" occurs). At the same speed (16 rpm) the on-to-off transition level delay of the downward swing sensing switch is 0.33 degs. or about 48% of the off-to-on sensitivity of that switch.

The on-to-off logic level transition delay values at low rotation speed, from 10 rpm to 22 rpm, increases proportionately with the rotation speeds. This relation is shown in Fig. 5. At higher speeds the logic level transition delay of the upward swing sensing switch is more unpredictable. However, the logic level transition delay of the downward swing sensing switch still increases with the rotation speed and at the highest rotation speed tested the on-to-off logic level transition of the switch does not occur until after the swing board swings backward pass the neutral line (or horizontal line), as shown in Fig. 4 b. In this case the delay is over 100%.

The causes of the on-to-off logic level transition delay in high speed rotation, other than the gravitational and inertia force of the pendulum, can also be attributed to the following facts:

a: Damping effect at the pendulum shaft bearing increases when divided

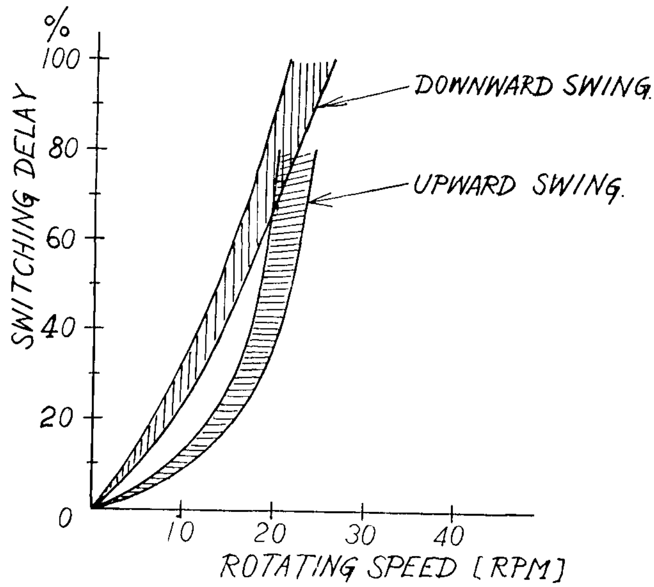


Fig. 5. Relationship between logic level transition delays of the proximity switches and the disturbance frequency.

by time, as the damping force at the pendulum shaft bearing increases with the angular velocity of the pendulum which depends on the disturbance frequency.

b: Time constant of the proximity switches and the data acquiring system becomes more significant as rotation speed increases.

2.2.3: Non-Sensitive Band (Dead Band/Zone)

A non-sensitive range or blind area of the inclinometer is the sum of the maximum inclination angles measured from the horizontal line or neutral line to the points where logic level transitions of the two switches occur. In the same swinging direction, it may be defined as the angular displacement between an off-to-on logic level transition of the two switches.

A non-sensitive range that occurs during the downward swing is generally greater than the one that exists in the upward swing. The greatest discrepancy occurs at the lowest rotation speed— 10.24 rpm— (32% of the non-sensitive range in the downward swing). This discrepancy is the result of the gravitational and inertia force acting on the pendulum ball, as these forces have a stronger effect on the delaying of the switchings in the downward swing than in the upward swing.

2.3: Application of the Result

For an average sensitivity of 0.50 degs. and a continuous disturbance that generates an input wave-form such as shown in Fig. 4 a and 4 b, the maximum input frequency that this inclinometer can be used at accurately is 7.32 deg/s. This value can be calculated from the slope of the input wave of the graph of the highest cam shaft rotation speed at which the accuracy of the inclination sensing is still acceptable (approximately 36 rpm).

For a tractor with a rear tire diameter of 200 cm and rear axle span of 150 cm, with one of its rear tires climbing a 20 cm high step (rectangular cross-section), the maximum traveling speed this inclinometer will respond accurately and stabilize within 1 second is 0.6 m/s.

STEERING TEST

In this section the steering system constructed is described and the result of the testing of this device in presented.

1: Description of the Steering System

1.1: Hardware

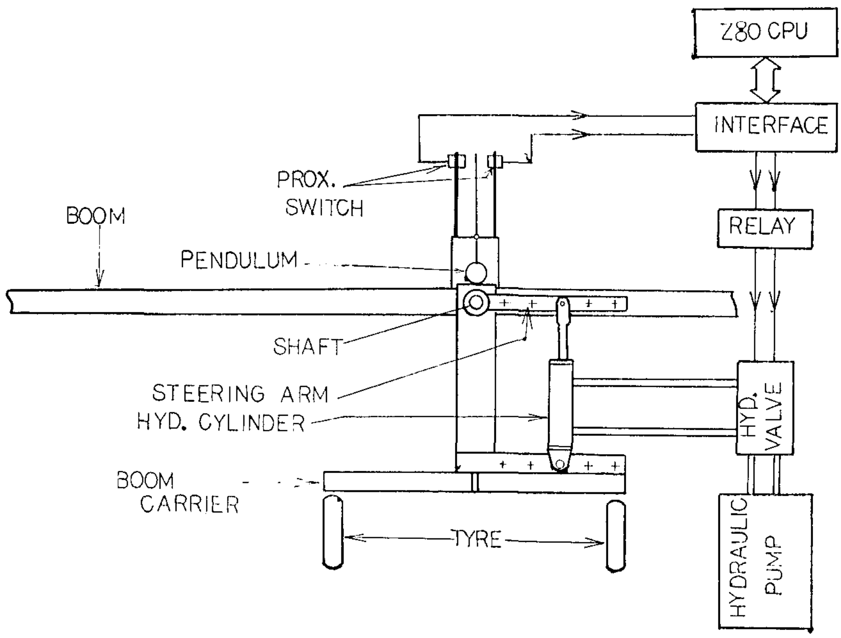


Fig. 6. Steering system. This steering system consists of a pendulum type inclinometer, a hydraulic actuator, and a computer-controlled control box.

As can be seen from Fig. 6, a sprayer boom is supported at the mid-point of the span in such a way that it can rotate clockwise and counter-clockwise when the hydraulic cylinder pushes or pulls the steering arm that is locked to the boom shaft. Steering speed can be adjusted by changing the length of this steering arm at which the hydraulic cylinder is attached, and the hydraulic pressure. The inclinometer is installed on the boom. When inclination is detected, the hydraulic cylinder will steer the boom in such a way that the boom will always be in the horizontal position regardless of the inclination of the boom carrier.

Boom: The boom used in the experiment was six meters long and weighed 26 Kgs. This boom is capable of supporting a high-pressure spray pipe and 10 spray nozzles. The boom carrier had two tires that were 150 centimeters apart or just wide enough to cover two rows of corn or potato plantings.

1.2: Test Field

A test road with a sinusoidal surface on one side and a flat surface on the other side was constructed. The boom was towed along this test field in such a way that, in the traveling direction, the left tire of the boom carrier traveled along the sinusoidal surface and the right tire traveled along the flat surface of the test field. The wave length and amplitude of the sinusoidal surface were approximately 200 cm and 35 cm respectively and the maximum inclination of the test boom when towed along this field was approximately 6 degs.

1.3: Control Circuitry and Data Acquision

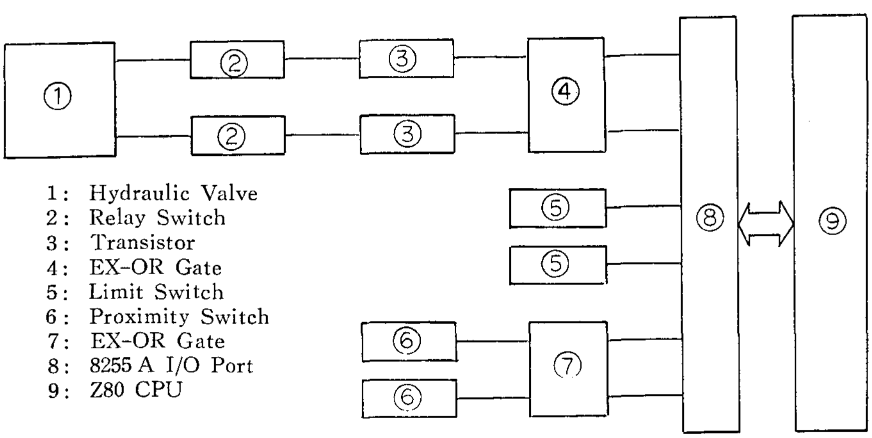


Fig. 7. Interface circuit used in the steering system.

TABLE 1. SYSTEM COMPONENTS

Component	General Name	Description
Sensor	Inclinometer	Pendulum-Switches/digital
Interface	1) I/O port 2) Relay 3) Solenoid	8255 A/8 bits×3 two 12-volt relay sw. two 100-volt solenoids
CPU	One-board Micro-computer	SBZ80 Hokuto Elec. Co. Ltd. Z80 CPU, 8 bits/4 MHz. Clk
Actuator	Hydraulic cylinder	Stroke 25 cm. Rod dia. 18 mm.
Safety devices	1) Limit switch 2) EX-OR gate	Two 5-volt micro-switches Prevent opposite direction control elements from turning on at the same time.
Data Acquisition	X-T pen-recorder	8 channels plus a potential divider

TABLE 2. PROXIMITY SWITCHES AND SOLENOID SWITCHES' LOGICAL RELATION

INPUT		OUTPUT	
R-SWITCH	L-SWITCH	UP-SOL.	DOWN-SOL.
L	L	L	L
L	H	L	H
H	L	H	L
H	H	L	L

R-SWITCH: right inclination (counter-clockwise) sensing proximity switch.
L-SWITCH: left inclination (clockwise) sensing proximity switch.
UP-SOL : solenoid that is responsible for pushing the boom up (clockwile).
DOWN-SOL: solenoid that is responsible for pulling the boom down (counter-clockwise).
Direction viewing: forward.

The control box consists of a one-board microcomputer and the interface circuitry shown in Fig. 7. The steering result was recorded by a multi-channel X-T recorder. To simplify the description of the system, a list of the components of the system is shown in Table 1.

The logical representation of the extremity control elements— the two proximity switches and the two solenoid switches, can be summarized as shown in Table 2.

The functional facts deciphered from Table 2 are:

1) The actuator (hydraulic cylinder) reacts only when one proximity is

turned on. If the counter-clockwise inclination sensing switch is turned on, the solenoid that is responsible for the clockwise steering will react. If the clockwise inclination sensing switch is turned on, then the counter-clockwise steering solenoid will do its work.

2) If the both proximity switches are turned on at the same time, either by mutual induction or electrical noises, the two solenoids are turned off. This is a very important safety measure since if the two solenoids are turned on at the same time the electric circuit and the hydraulic line will overheat and burn.

In fact, the solenoids are prevented from being turned on simultaneously by the EX-OR gate that is placed between the two relays and the I/O port.

1.4: Software

Although the steering was done in on-off method according to the logical relation in Table 2, which could be executed by a combination of logic gates, checking or clearing the chattering of the inclinometer with logic gates without a microprocessor will be very difficult and may require very sophisticated electronic circuit. Therefore, to facilitate this chattering clearing procedure, a microprocessor with a programmed EP-ROM was used to execute the steering logic and other complementary functions. The software used in the test was written in machine language. The flow chart of this program is shown in Fig. 8.

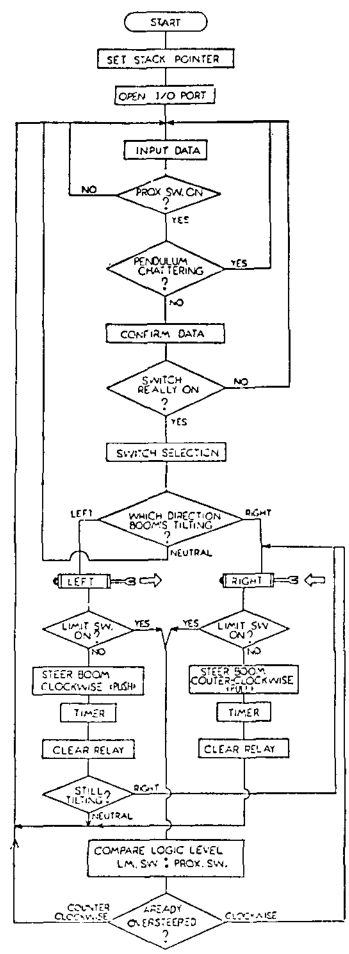


Fig. 8. Flow-chart of the control program used in the steering test. This program required about 1 kB of memory in machine language.

1.5: Test Conditions

Test conditions used are,

a: Traveling speed or disturbance frequency. The relationship between the inclination speed and traveling speed of the boom is as shown in Fig. 9a. The traveling speeds used are 0.1, 0.4, 0.7, and 1.0 m/s.

b: Steering arm length: 120, 240, 360, 480 and 600 mm from the center of the rotating boom shaft.

c: Actuator pressure: 2.0, 3.0 and 4.0 Kgf/cm². The relationship the steering speed and the steering arm legnth for each pressure used is shown in Fig. 9 b.

d: Pendulum damper: water, engine oil, and gear oil. The liquid dampers listed above were used to reduce the chattering of the pendulum.
In addition, an air cylinder was also used as a damper to reduce the shock from the hydraulic cylinder. This air damper was placed between the hydraulic cylinder and the steering arm.

Combinations of the conditions listed above were tested to identify the optimum steering condition for the system constructed.

Regarding the data processing procedure, the data recorded by the X-T

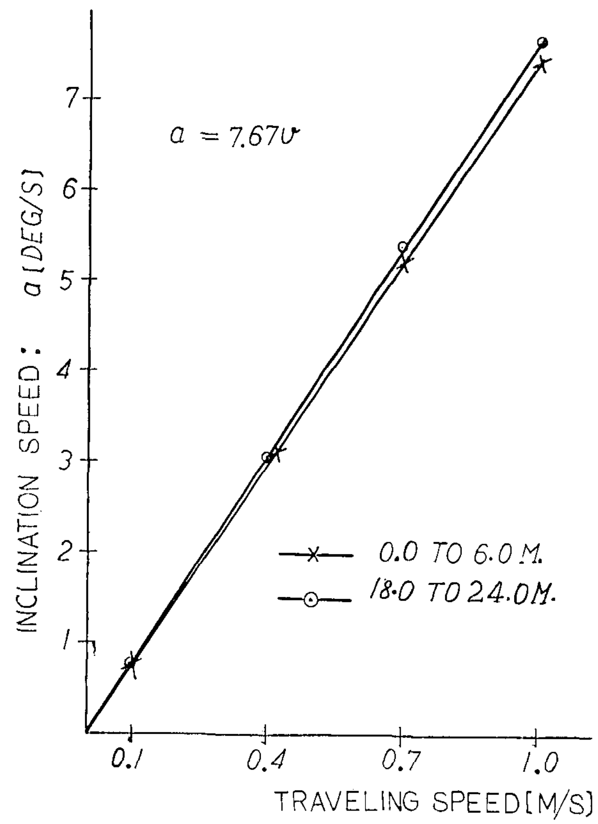


Fig. 9 a

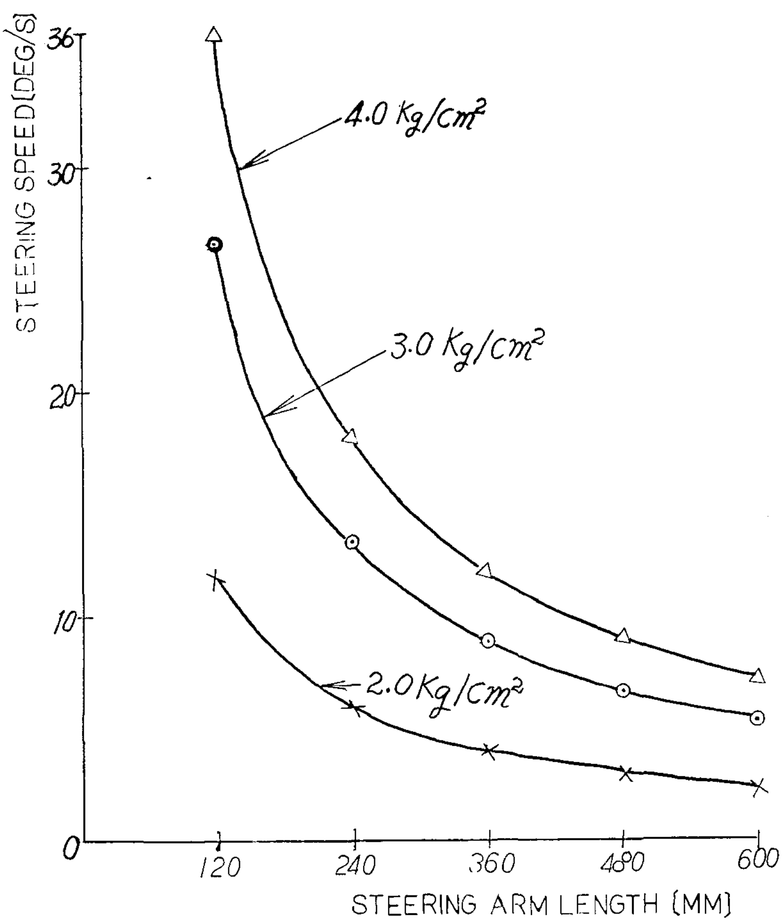


Fig. 9 b

Fig. 9. (a): Relationship between the traveling speed and inclination speed of the boom. (b): Relationship between the length of the steering arm and the steering speed under different hydraulic pressures.

recorder was read or numeralized by a digitizer and later processed and output through an X-Y plotter.

2: Result and Discussion

The resultant steering output (inclination of the sprayer boom) was plotted on the same coordinate as the disturbance (inclination of the boom carrier). Theoretically, ignoring the initial phase of the disturbance, if the steering speed and the disturbance frequency are well calibrated under ideal conditions where irregularities of the disturbance and steering overshoot do not occure, the steering output can be visualized as step-trace such as shown in Fig. 10 a. However, in real test conditions, there are always such irregularities as roughness of the test field and vibration of the steering arm and boom and overshoot which reduce the steering quality and cause irregularities in the output, such as shown in Fig. 10 b. In a case where the disturbance

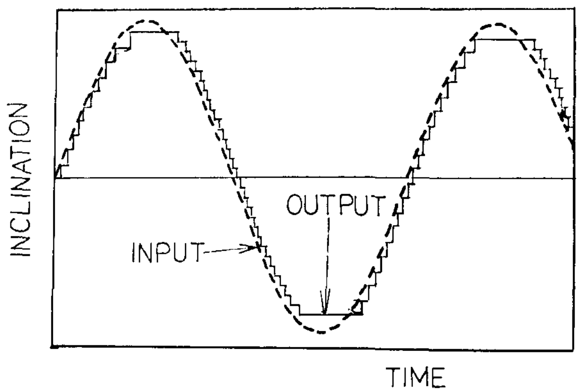


Fig. 10 a

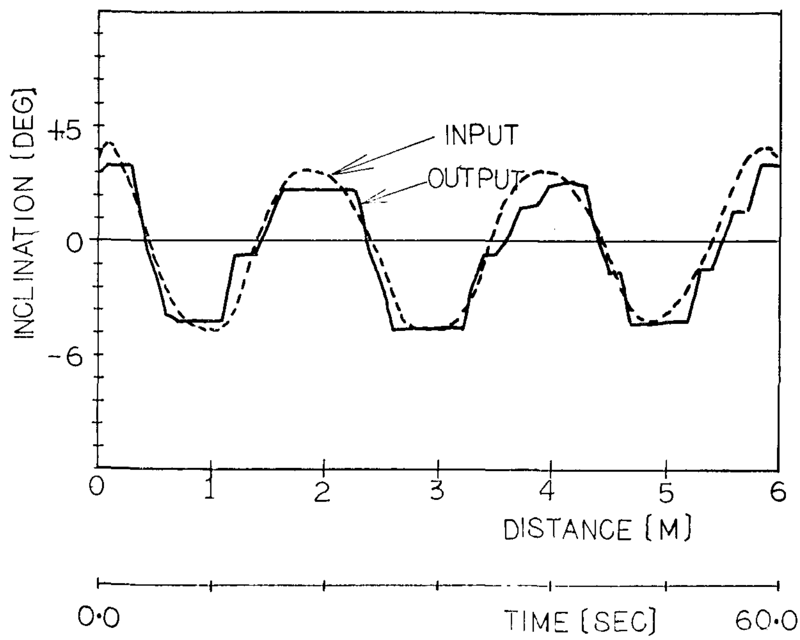


Fig. 10 b

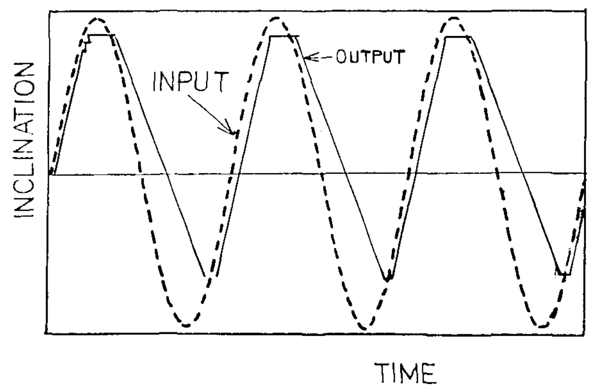


Fig. 10 c

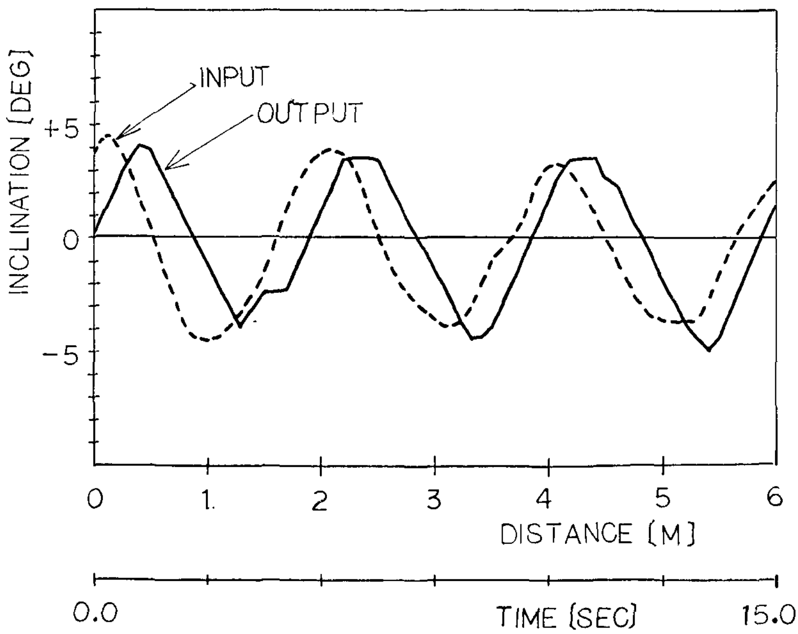


Fig. 10 d

Fig. 10. (a) and (c) are the results of the graphic simulation of the integration of the steering force and the functional steering logic of the device. (a) is obtained when the steering force and the disturbance are well calibrated ; (c) is obtained when the disturbance speed is higher than the steering speed. (b) is the result of the steering test under low pressure at a traveling speed of 0.1 m/s. (d) occurred when the traveling speed was 0.4 m/s at a pressure of 2 kg/cm^2.

frequency is higher than the steering speed the output can be visualized as shown in Fig. 10 c, where the reality of this case is shown in Fig. 10 d for comparison. (Figs. 10 a and 10 c were obtained from a graphic simulation of an integration of the steering force and the logical relation of the function of the device. They do not represent the real input and output state of the device but only illustrate some irregularity-free state. In order to make the results of the simulation perfectly represent the real input and

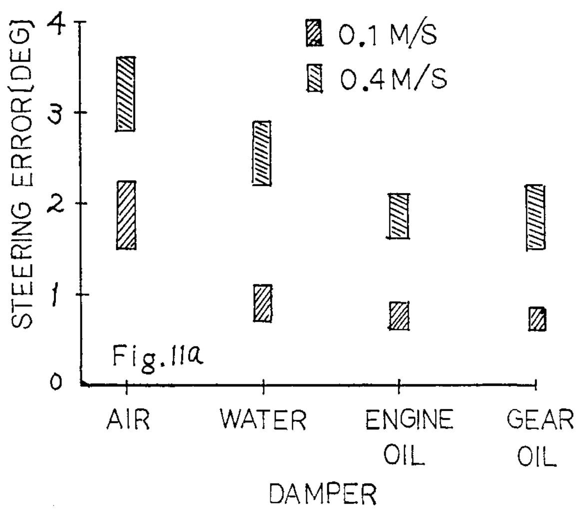


Fig. 11 a

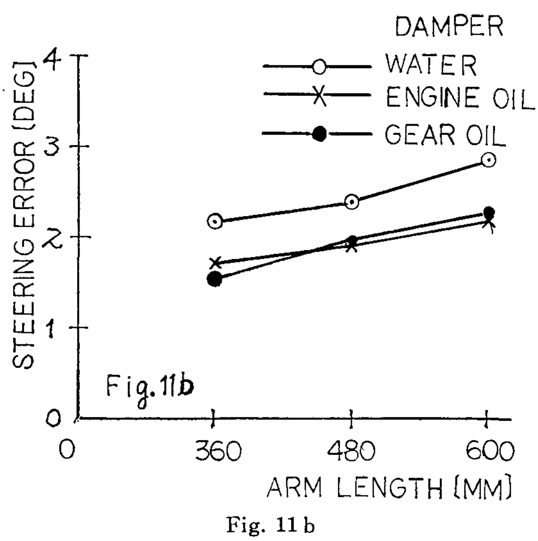


Fig. 11 b

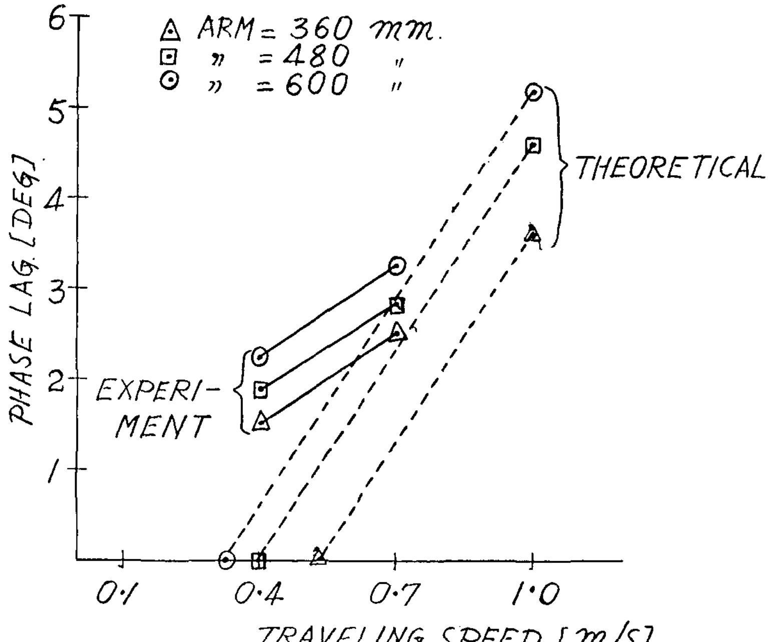


Fig. 11 c

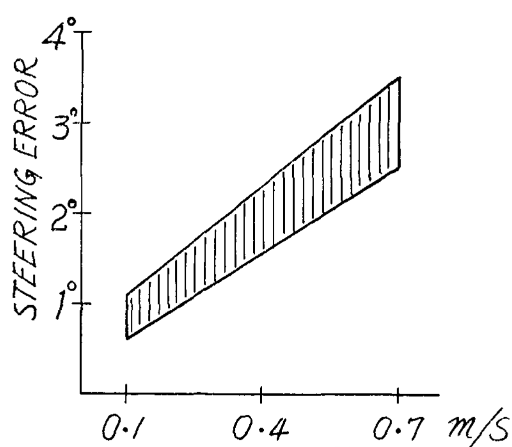


Fig. 11 d

Fig. 11. (a) shows the effect of the pendulum damper upon the magnitude of the steering error. The height of each bar represents the fluctuation of the steering error. (b) shows the effect of the steering arm length upon the magnitude of the steering error. (c) shows the effect of the disturbance frequency upon the phase lag. (d) shows the effect of the disturbance frequency upon the magnitude of the steering error. The breadth of the curve represent the fluctuation of the magnitude of the steering error.

output state of the device, it will be necessary to use the real disturbance frequency and steering speed obtained from the measurement in the simulation which will require some modification of the software.)

In this report, the result of the test is discussed in terms of steering error and phase-lag. Steering error is any deviation in the inclination of the boom from the horizontal position immediately after a steering stroke is completed. A phase-lag occurs when the disturbance frequency is faster than the steering speed and is visualized as the vertical displacement between the imput curve and output trace in Fig. 10 c. Both steering error and phase-lag are considered as indexes of steering quality and are discussed with respect to each variable in the test conditions.

2.1: Effect of the Pendulum Damper

As shown in Fig. 11 a, the quality of the steering is generally better when there is a damper in the pendulum box. Each bar in the figure represents the range of steering error in degrees. From this figure it can be seen that the steering error does decrease with the increasing viscosity of the damper. However, there is no significant discrepancy in the steering quality when engine oil and gear oil are used as a damper (the viscosity of engine oil and gear oil used were 0.0007 and 0.0008 mm^2/s respectively.). Therefore, at this stage, it can be concluded that either engine oil or gear oil may be used as a damper. (See also Fig. 11 b)

2.2: Effect of the Steering Arm Length

Theoretically, the steering speed increases when the steering arm becomes shorter (see Fig. 9 b). However, permanent steering oscillation was observed when the steering arm length was 240 mm or shorter; therefore the arm lengths of 240 and 120 mm were excluded from the test conditions. Test with arm lengths of 360, 480, and 600 mm show that an arm length of 360 mm produced the least steering error and phase lag. This conclusion is supported by Fig. 11 b.

2.3: Effect of the Hydraulic Pressure

Steering oscillation was observed regardless of the steering arm length and the magnitude of the traveling speed when the pressure was 4 kg/cm^2. At a pressure of 3 kg/cm^2 steering oscillation was observed at traveling speed of 0.4 m/s or above, regardless of the steering arm length. It is assumed that the steering oscillation caused by high pressure is the result of the excessive steering force exerted on the steering arm which may (1) oversteer the steering arm and cause the pendulum to oscillate or (2) cause vibration in the steering arm that is powerful enough to make the pendulum oscillate.

Therefore, steering pressures of 3 kg/cm^2 or more were excluded from the test and only a steering pressure of 2 kg/cm^2 was used.

2.4: The Effect of the Disturbance Frequency or Traveling Speed

Disturbance frequency directly affects the phase lag of the system—the higher the disturbance frequency is, the greater the phase lag becomes. The magnitude of the phase lag also increases with the length of the steering arm. According to the test results, phase lag could be observed at traveling speed of 0.4 m/s or more; however, the there is a singificant discrepancy between the magnitudes of the experimental and theoretical phase lag, such as shown in Fig. 11 c. In terms of steering error, the range of the steering error at the pressure of 2 kg/cm^2 for all arm lengths is characterised as shown in Fig. 11 d.

2.5: Effect of the Air Shock Absorber

The air shock absorber improved the steering quality at an arm length of 600 mm, with a pressure of 4.0 kgf/cm^2 and a traveling speed of 0.7 m/s. Tests with shorter steering arms showed sharp increases in the magnitude of the overshoots, especially at a traveling speed of 0.4 m/s.

It is possible to improve the steering precision at higher disturbance frequencies by using the steering shock absorber used in the tests. In this case, the length of the steering arm should be 600 mm and the optimum value of the hydraulic pressure should be investigated. A pressure lower than 3,0 kgf/cm^2 will not produce a positive effect on the steering guality.

3: Conclusion

According to the test results described above, the present steering device has the highest reliability and accuracy when it is used with a steering arm length and steering pressure of 360 mm and 2 kg/cm^2 and a pendulum damper's viscosity of 0.007 to 0.0008 mm^2/s. For the type of the disturbance used in the test, the system is most reliable when the traveling speed is not more than 0.4 m/s. More detailed study is required for the employment of the air shock absorber.

4: Possibility for Practical Employment

If the boom carrier climbs up a 20-cm high step with the standard spraying operation speed (1.2 m/s), with the most stable steering speed (arm = 360 mm and pressure = 2.0 kg/cm^2), it will take 2 seconds until the boom is steered parallel ($\pm$0.5 deg. from the line parallel to the field surface) to the field surface, or after the boom has traveled 2.4 meters.

SUMMARY

In this study an inclinometer for sprayer boom inclination detecting was constructed and tested. This inclinometer consisted of two proximity switches and a pendulum. The motion of the pendulum was analysed through a simulation. This simulation indicated that the pendulum could be used as an inclinometer without disorderly behaviors at disturbance angular velocities lower than 1700 deg/s and that the mechanical resonance of the motion of the pendulum occurred at disturbance angular velocities higher than 7000 deg/s. The results of the measurement of the sensitivity of the inclinometer showed that this inclinometer could accurately detect an inclination as small as 0.5 degs. when the angular velocity of the disturbance was 7 deg/s or less, or approximately 0.6 m/s in terms of traveling speed of a tractor on a rough field surface.

Later this inclinometer was employed in combination with an inclination steering device constructed in the laboratory. This steering device consisted of a boom, and actuator unit, a controlling interface and a microprocessor. The actuator unit used was a hydraulic cylinder and the microprocessor used was a one-board microcomputer. The steering test was conducted by towing the boom along the test field with the left tire of the boom-carrier on a sinusoidal surface and the right tire on the flat surface of the test field. Different pendulum dampers, steering arm length, and hydraulic pressure were tested at a traveling speed of 0.1 m/s to 1.0 m/s. At the lowest traveling speed (0.1 m/s), the steering error was found to be within a range of 0.6 to 1.1 deg.; at a traveling speed of 0.4 m/s this error range was 1.5 to 2.3 deg.; at a traveling speed of 0.7 m/s the sterring error range was 2.5 to 3.5 degs. Regarding the effects of the steering arm length and the hydraulic pressure, it was observed that steering arm lengths shorter than 360 mm and pressures higher than 3 kg/cm^2 caused undesirable overshoots and oscillations of the boom and the pendulum. At the highest traveling speed tested (1.0 m/s) constant violent oscillation (chattering) of the pendulum was observed and no steering occurred. The steering device was found most reliable and accurate when liquid with viscosity from 0.0007 to 0.0008 mm^2/s was used as a damper together with a steering arm length of 360 mm and pressure of 2 kg/cm^2. Under these conditions, the steering speed of the device was about 3.5 deg/s.

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