ADAPTIVE CONTROL FOR MILLING MACHINES

by

RAMESH MOHANLAL PARIKH

B. S., University of Utah, 1962

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1965

Approved by:

Major Professor

TABLE OF CONTENTS

INTRODUCTION

In the last 85 years metallurgists and engineers dealt with different aspects of machining. Engineers are involved in the metal cutting problem in two ways: (1) The manufacture of a machine tool for cutting metal, and (2) the use of a machine tool. Engineers are concerned with the cutting process primarily.

Taylor[6] began laboratory research on the metal cutting process in 1880. These experiments extended over a period of 26 years, and his findings were reported in 1906. Taylor observed that the following variables effect the power consumption and metal removal rate in a metal cutting process:

1. The hardness and other physical properties of the metal being cut.
2. The diameter of the work. (Taylor used an engine lathe in most of his metal cutting research.)
3. The depth of the cut.
4. The feed.
5. The rigidity of the work, cutting tool, and machine.
6. The shape of the tool.
7. The material of which the tool is made.
8. The cutting fluid used, if any.
9. The tool life desired.
10. The speed and feed changes available on the machine.
11. The pressure of the chip on the tool.

[ ] Shows reference number.

12. The power of the machine when working at various speed, feed and depth of cut combinations.

For this thesis a study was carried out to observe the effect of depth of cut, feed and power consumption for various combinations of speed, feed and depth of cut.

In order to study the above-mentioned variables in a metal cutting process, in this instance experiments were carried out on a milling machine. A study was made to determine time spent for an operation with conditions of no-load and load with a special controlling device, or adaptive control. Power consumption and metal removal were also measured.

MILLING

There are, of course, many different metal cutting processes, e.g., turning, drilling, boring, milling, etc. The majority of theoretical work has been concentrated upon turning, because the continuous contact of the tool and workpiece facilitates analysis. However, milling is more important economically, and the potential return from adaptive control is larger.

The milling machine used in this experiment was a Type G Keller of standard manufacturing type milling machine with some special features. The machine has special table and special lead screw in place of standard part. It is not feasible at this point to explain every part of this machine, but there are certain features which need clarification to understand the control designed for this machine.

The machine has an automatic electric tracer control for vertical and horizontal movements only. This is accomplished by a means of a gear box driving 4 magnetic clutches. The tracer head controls and guides the vertical and horizontal movements of the machine. All control switches are concentrated in the control box. There are also handwheels with graduated dials for all movements of the feed screws.

Power Limit Relay. In order to allow the cutter to operate at maximum capacity, an automatic feed control is utilized. This device automatically stops the feed when power consumed by the cutter reaches a predetermined maximum limit. As the cutter continues to rotate the load is reduced and the controller starts the feed again. The power limiting relay has a dial graduated in amperes, as shown in Fig. 5 (top of control box). The actual current for which the power limiting relay is set will be shown by the cutter motor ammeter to be the point at which the feed will stop. The current will fall a few devisions, and then go up again. This interruption takes place every time the power limiting relay opens the control circuit and stops the feed. The power limiting relay remains open when the power demand exceeds the setting of the relay.

Rheostat. A rheostat provides a means for adjusting the speed of feed, as shown in Fig. 5 (lower right hand side of control box). Basically, it can be defined as an easily adjustable resister. It is designed to operate manually.

Variable Speed Control. The motor driving the feeding motion of the machine is of the variable speed type, and has a speed range of about 2 to 1. The speed is adjusted by the manually operated rheostat. In connection with a three-speed gear box the total speed range is from $\frac{1}{4}$" to 3" per minute. Machine speed was labeled 1/8" to $1\frac{1}{2}$" but on checking was found to be $\frac{1}{4}$" to 3".

The machine is operated by three different motors:

1. Cutter coolant pump motor.
2. Cutter drive motor.
3. Feed drive motor.

First two motors are constant speed motors in the sense that at all load the speed remains constant when supplied from constant potential field.

The shaft of cutter motor drive is connected with eight speed spindle drive. The spindle drive is through V-belts by means of a pair of V-pulleys and back gears, giving a speed range from 140 to 3600 RPM.

The third motor is a variable-speed motor which includes those types in which the speed is inherently variable, changes as the load changes, with constant impressed voltage.

ADAPTIVE CONTROL

The term, "adaptive,"[7] is borrowed from biology where it describes the ability of an organism to adjust itself to its environment. It is here used in the same sense.

The term, "adaptive,"[8] will be applied to any control system which measures, continuously or intermittently, the impulse response or some other function which characterizes the system and which makes use of this system's characteristic function to determine and to generate the necessary forcing function to cause the system to behave in a desired manner.

An adaptive control device was designed to perform the following functions:

1. It should operate under various speed ranges.

2. It should adjust itself for small incremental speed changes.

3. The control should be operated so that smoothness, or a specific rate, or acceleration or deceleration can be achieved.

The device is a feedback control type in which actuation of the control mechanism is determined by the performance of the motor being controlled. The control device consisted mainly of an electronic amplifier.

The amplifier is used with negative feedback and is represented by a triangle with the base at the input end and apex at the output end, as shown in Fig. 1. The general requirements for a DC amplifier are high gain, high input impendence, low output impendence, good linearity and stability. The circuit of the amplifier used in this device is shown in Fig. 1. [The +300 volt power supply is a conventional electronically regulated unit which provides the +300 volts for operation of the amplifiers.]

DC amplifiers (sometimes also called operational amplifiers) capable of performing the operation of:

1. Integration.
2. Addition.
3. Multiplication by a constant.
4. Multiplication by -1 (inversion).

The amplifier in the control device was used as a multiplier, inverter and subtracter.

Amplifier as Multiplier and Inverter. In Fig. 2, e_1 represents the input voltage, e_g the grid voltage, e_o the output voltage, R_1 the input resistor and R_f the feedback resistor.

The gain of an amplifier is given by:

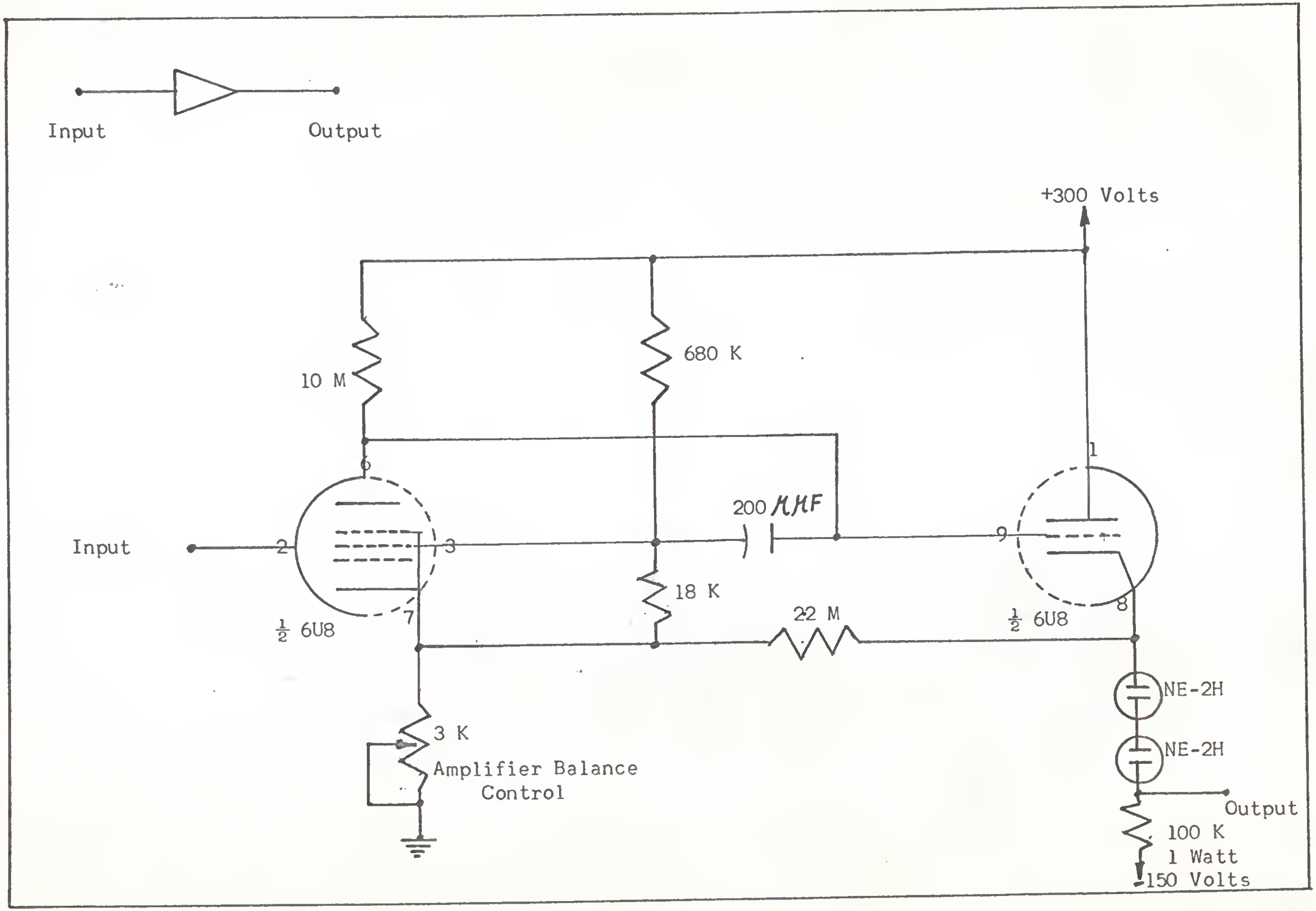


Fig. 1 D.C. OPERATIONAL AMPLIFIER

$$A = -\frac{e_o}{e_g}$$

On solving for e_g, the expression

$$e_g = -\frac{e_o}{A} \qquad (1)$$

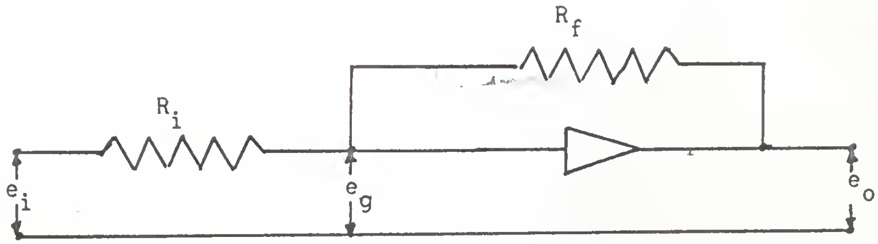


Fig. 2

is obtained. It can be seen that e_g approaches zero as A approaches infinity. So usually A is made large with respect to e_o.

Since the input to the amplifier is the grid of a tube, the current through the amplifier from the input can be considered to be zero, with the result that current e_i through the resistor R_i is, for all practical purposes, equal to the current i_f through the resistor R_f, with the result that

$$\frac{e_i}{R_i} = -\frac{e_o}{R_f} \qquad (\text{since } i = \frac{e}{R}) \qquad (2)$$

This equation also shows that the output voltage is of the opposite sign to the input voltage, so that the amplifier also acts as an inverter or sign changer.

<u>Amplifier as Subtraction</u> (negative addition).

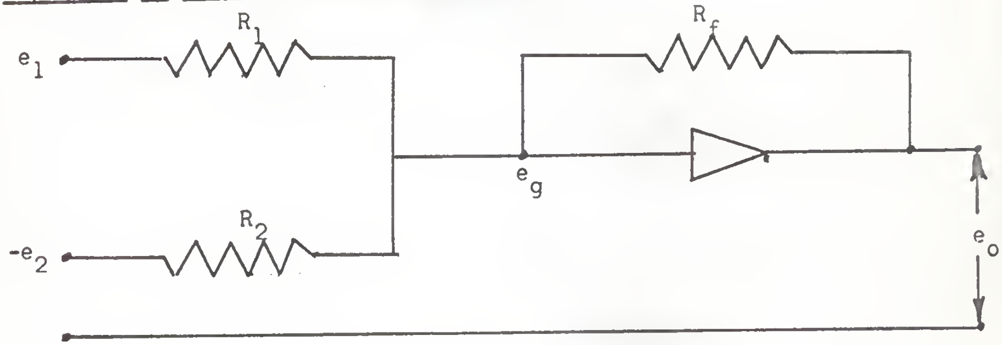


Fig. 3

If, instead of the one input resistor shown in Fig. 2, two or more resistors are used as shown in Fig. 3, the operational amplifier becomes an adder.

Again making use of $e_g = o$, the sum of the currents in the input resistors equals the current through the feedback resistor.

Thus,

$$i_1 - i_2 = -i_f \qquad \text{since } i = \frac{e}{R}$$

$$\frac{e_1}{R_1} - \frac{e_2}{R_2} = - \frac{e_o}{R_f}$$

$$e_o = - \left(\frac{R_f}{R_1} e_1 - \frac{R_f}{R_2} e_2\right) \qquad (3)$$

So, for the voltage amplification A of an amplifier has been defined as the ratio of the output voltage to the input voltage. The amplification produced by a single stage is often not enough to raise the output voltage to the required level. In such a case the output of the first stage is fed in to a second stage, and hence, if necessary, to a third stage, and so on, until the output level is satisfactory.

The circuit of the control device is shown in Fig. 4; which consists of three amplifiers. First amplifier acts as the subtractor, second as the inverter and third as the multiplier. The function of these amplifiers is illustrated as follows:

If voltage at pt. F is -2V and at V (voltage supplied by amp.) is +7V, then by using the equation 2 in this case $\frac{R_f}{R_1} = \frac{R_f}{R_2} = 1$ and using equation 3, output voltage of the first stage will be -5V. In the second stage also $\frac{R_f}{R_1} = 1$. So output voltage will be +5. But in the third stage, $\frac{R_f}{R_1} = 30$. Hence its output voltage will be -30x5 = -150 volts. But the amplifier was designed to operate between +50V to -120V. Hence total output voltage will be only -120V. But in practice, when this control is working, voltage at pt. F will be less than -2V, depending on the load. The tube shown at the end of the circuit acts as a variable resistor. The tube has the following characteristics:

Tube No. 6080 or Equivalent 6AS7-G.

Type Low-Mu Twin Triode.

Filament volts 6.3 volts.

Filament Amps 2.5 Amps.

Maximum Plate watts 13 watts.

Maximum Plate Volts 250 volts.

When voltage output at the end of third stage is +50V, agregate electrons, travel from cathode towards anode, are less in number, through grid (screen). While when output is -120V, electrons still travel but higher in number. Hence when electrons are more it has more resistance and

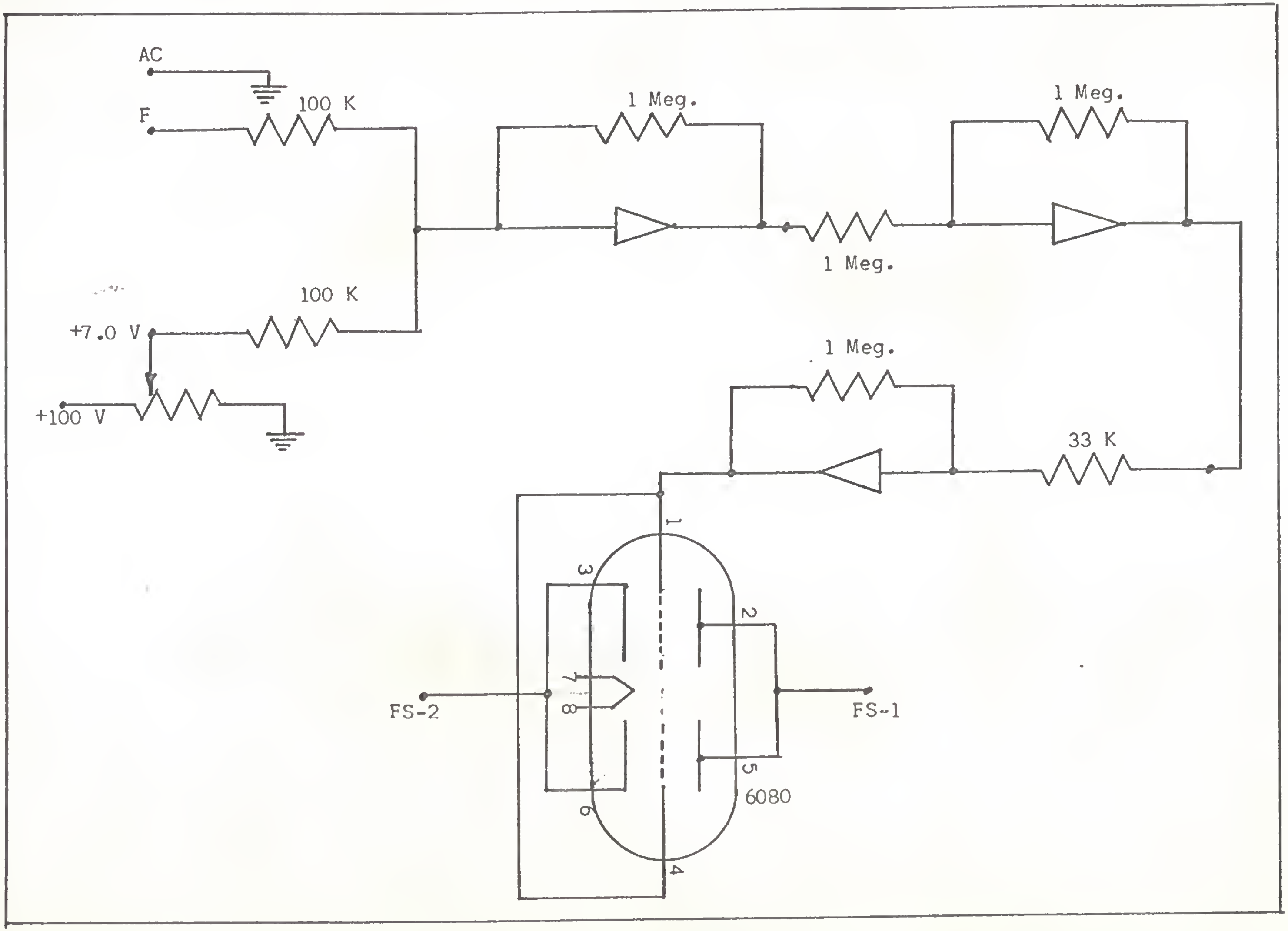


Fig. 4 ADAPTIVE CONTROL CIRCUIT

vice versa, depending on the load. So indirectly when load increases speed decreases and vice versa.

EXPERIMENT

This experiment started with the idea of removing constant amount of metal. To remove constant amount of material machine must have on-off system or speed regulating system with respect to load. As mentioned under "Milling," this requirement was satisfied. The following equipment was used for the experiment:

1. Heath-kit Electronic Analogue computer model EC-1. This computer had 9 amplifiers but only three of them were used (as shown in Fig. 5).
2. Tube 6080 (explained on page 8).
3. Voltmeter, to measure the voltage and to check that the equipment was working properly (Fig. 5).
4. Volt-Amp meter, to measure amp. of the cutter motor (Fig. 5).
5. 2 flute straight shank cutters HSS, 1 of 9/16", 1 of 11/16" and 3 of 3/4".
6. Stop watch, standard Meylan watch with 1/100 of a minute graduations.
7. Timer, to record the fraction of time machine was on and off.
8. Milling machine (pages 2 to 4).
9. Resistors, varying from 1 meg. to 10 k.
10. Aluminum ring, as a fixture to hold steel.

    Samples being machined:

11. ½" sq. hot rolled steel.
12. ½" to 2½" HRS (Fig. 6).

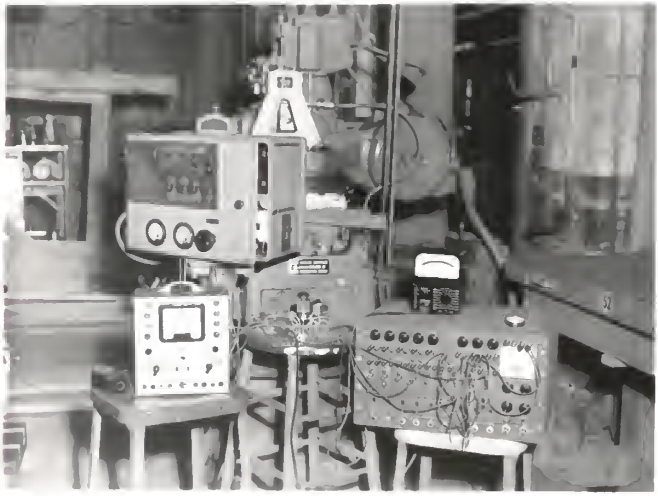


Fig. 5. ADAPTIVE CONTROL

Fig. 6. END MILLING

End milling process was used throughout the experiment (as shown in Fig. 6). To test the power relay control several runs were carried out while machining aluminum and steel. Under different conditions many trial experiments were carried out to help to formulate a specific problem for further investigation. Only some of the results are included in this report. Moreover, it was not feasible to carry out further tests on aluminum due to the fact that higher feed and speed were required. Several observations were taken while cutting steel at approximately 100 fpm. with the power relay setting at 3 and 4 amps. The results are shown in Tables 1 and 2. A $\frac{1}{2}$"x$\frac{1}{2}$" HRS was used for this purpose.

Some more observations were taken while machining $\frac{1}{2}$"x2$\frac{1}{2}$" hot rolled steel with the same set up mentioned above. The results are shown in Table 3. This time with the help of a timer it was possible to measure the fraction of total time machine was "on." The results are included in Table 3.

To observe the consistency in the experiment some more runs were carried out with 3 cutters all with same geometry. Five observations for each setup were taken and average results are shown in Table 4.

Then the same experiment was carried out using adaptive control device. The control circuit is shown in Fig. 4. The device was connected to rheostat wires FS-1 and FS-2. The tube (6080) then works in place of the rheostat. The connections were made between the controller and the field of the cutter motor at AC and F (as shown in Fig. 7). By controlling the resistance in the field of the feed motor it was possible to control the speed with the ratio 2:1. Amplifiers were connected to AC and F to control the voltage developed. This voltage varied from -2.8 Volt (with no load) to -7 Volt (with load), depending upon cutter load. The results are shown in Table 5.

RELAY SETTING = 3 AMPS.

Material = ½" x ½" HRS   Cutter = 9/16" 2 flute straight shank

RPM = 563   Ampere = 3.3

Control Volts = 12.5   Cutting Speed Appr. = 100 FPM

(A = Horizontal speed in inches per minute)

Reading	Amperes on the meter: Min. Amps.	Amperes on the meter: Max. Amps.	Depth of cut in inches	A inches/min.	Continuous or on-off	Time in min.
1	3.4	4.2	0.25	1/4	continuous	1.93
2	3.4	5.0	0.50	1/4	continuous	2.00
3	3.4	5.4	0.75	1/4	continuous	2.10
4	3.4	5.7	1.00	1/4	continuous	2.19
5	3.4	4.5	0.25	1/2	continuous	1.17
6	3.4	5.7	0.50	1/2	continuous	1.28
7	3.4	5.7	0.75	1/2	on-off	1.93
8	3.4	5.8	1.00	1/2	on-off	2.40
9	3.4	4.7	0.25	5/8	continuous	0.90
10	3.4	5.8	0.50	5/8	on-off	1.35
11	3.4	5.8	0.75	5/8	on-off	2.00
12	3.4	5.8	1.00	5/8	on-off	2.32
13	3.4	4.7	0.25	1-1/4	on-off	0.78
14	3.4	5.8	0.50	1-1/4	on-off	1.26
15	3.4	5.8	0.75	1-1/4	on-off	1.65
16	3.4	5.8	1.00	1-1/4	on-off	1.90
17	3.4	5.8	0.25	1-1/2	on-off	0.60
18	3.4	6.0	0.50	1-1/2	on-off	1.10
19	3.4	6.0	0.75	1-1/2	on-off	1.43
20	3.4	6.0	1.00	1-1/2	on-off	1.65
21	3.4	6.0	0.25	3	on-off	0.54
22	3.4	6.0	0.50	3	on-off	0.85
23	3.4	6.0	0.75	3	on-off	1.16
24	3.4	6.0	1.00	3	on-off	1.30

Table 1

RELAY SETTING = 4 AMPS.

Material = ½" x ½" HRS

Cutter = 9/16" 2 flute straight shank

RPM = 563

Ampere = 3.3

Volts = 12.5

Cutting Speed = Appr. 100 FPM

(A = Horizontal speed in inches per minute)

Reading	Amperes on the meter		Depth of cut in inches	A inches/min.	Continuous or on-off	Time in min.
	Min. Amps.	Max. Amps.				
1	3.4	4.0	0.25	1/4	continuous	2.15
2	3.4	4.3	0.50	1/4	continuous	2.22
3	3.4	4.9	0.75	1/4	continuous	2.51
4	3.4	5.4	1.00	1/4	continuous	2.83
5	3.4	4.4	0.25	1/2	continuous	1.20
6	3.4	5.3	0.50	1/2	continuous	1.48
7	3.4	6.2	0.75	1/2	continuous	1.57
8	3.4	6.3	1.00	1/2	on-off	1.76
9	3.4	4.5	0.25	5/8	continuous	1.00
10	3.4	4.8	0.50	5/8	continuous	1.15
11	3.4	6.3	0.75	5/8	on-off	1.33
12	3.4	6.3	1.00	5/8	on-off	1.66
13	3.4	4.4	0.25	1-1/4	continuous	0.59
14	3.4	6.3	0.50	1-1/4	on-off	0.80
15	3.4	6.3	0.75	1-1/4	on-off	1.14
16	3.4	6.6	1.00	1-1/4	on-off	1.29
17	3.4	6.2	0.25	1-1/2	continuous	0.40
18	3.4	6.4	0.50	1-1/2	on-off	0.66
19	3.4	6.4	0.75	1-1/2	on-off	0.98
20	3.4	6.4	1.00	1-1/2	on-off	1.13
21	3.4	6.4	0.25	3	on-off	0.32
22	3.4	6.6	0.50	3	on-off	0.52
23	3.4	6.7	0.75	3	on-off	0.75
24	3.4	6.8	1.00	3	on-off	0.92

Table 2

MATERIAL = $\frac{1}{2}$" x $2\frac{1}{2}$" HRS

RPM = 563

Volts = 12.5

Cutter = 11/16" 2 flute straight shank

Ampere = 3.3

Relay setting = 3 Amps.

Cutting Speed Appr. = 100 FPM

(A = Horizontal speed in inches per minute)

Reading	Amperes on the meter: Min. Amps.	Amperes on the meter: Max. Amps.	Depth of cut in inches	A inches /min.	Continuous or on-off	Time in min.	Fraction of time machine is on
1	3.4	4.0	0.25	1/4	continuous	10.10	1.0
2	3.4	4.4	0.50	1/4	continuous	10.20	1.0
3	3.4	5.0	0.75	1/4	continuous	10.10	1.0
4	3.4	5.4	1.00	1/4	continuous	10.10	1.0
5	3.4	4.2	0.25	1/2	continuous	5.72	1.0
6	3.4	5.1	0.50	1/2	continuous	5.71	1.0
7	3.4	5.8	0.75	1/2	continuous	5.78	1.0
8	3.4	6.0	1.00	1/2	on-off	9.80	0.423
9	3.4	4.8	0.25	5/8	continuous	4.10	1.0
10	3.4	5.1	0.50	5/8	continuous	4.10	1.0
11	3.4	5.7	0.75	5/8	on-off	5.91	0.788
12	3.4	5.9	1.00	5/8	on-off	8.63	0.447
13	3.4	5.0	0.25	1-1/4	continuous	2.13	1.0
14	3.4	5.9	0.50	1-1/4	on-off	4.33	0.553
15	3.4	5.9	0.75	1-1/4	on-off	5.60	0.432
16	3.4	6.3	1.00	1-1/4	on-off	6.91	0.346
17	3.4	5.3	0.25	1-1/2	continuous	1.58	1.0
18	3.4	5.9	0.50	1-1/2	on-off	4.17	0.528
19	3.4	6.3	0.75	1-1/2	on-off	5.91	0.357
20	3.4	6.4	1.00	1-1/2	on-off	6.70	0.279
21	3.4	5.8	0.25	3	on-off	1.52	0.60
22	3.4	6.3	0.50	3	on-off	3.70	0.284
23	3.4	6.6	0.75	3	on-off	4.75	0.242
24	3.4	7.2	1.00	3	on-off	5.93	0.167

Table 3

HORIZONTAL SPEED NOT CONTROLLED BY ADAPTIVE CONTROL

Material = ½" x 2½" HRS

RPM = 563

Volts = 12.5

3 cutters = 3/4", 2 flute straight shank

Ampere = 3.3

Relay Setting = 3 Amps.

Cutting Speed = 100 FPM

(A = Horizontal speed in inches per minute)

Reading	Amperes on the meter		Depth of cut in inches	A inches /min.	Continuous or on-off	Time in minute	Material Removed in ^{3}/min.
	Min. Amps.	Max. Amps.					
1	3.4	4.4	0.25	1/2	continuous	4.84	0.067
2	3.4	5.2	0.50	1/2	continuous	4.82	0.1346
3	3.4	5.6	0.625	1/2	on-off	5.60	0.126
4	3.4	5.7	0.750	1/2	on-off	7.47	0.1263
5	3.4	5.8	0.875	1/2	on-off	8.95	0.120
6	3.4	5.8	1.000	1/2	on-off	10.20	0.1233
7	3.4	5.3	0.25	1-1/4	on-off	2.02	0.155
8	3.4	5.6	0.375	1-1/4	on-off	3.89	0.134
9	3.4	5.8	0.500	1-1/4	on-off	4.17	0.1517
10	3.4	5.9	0.625	1-1/4	on-off	5.45	0.1394
11	3.4	6.0	0.750	1-1/4	on-off	5.56	0.1690
12	3.4	6.1	0.875	1-1/4	on-off	6.99	0.162
13	3.4	6.1	1.000	1-1/4	on-off	7.57	0.1713
14	3.4	5.8	0.250	3	on-off	1.70	0.2017
15	3.4	6.2	0.375	3	on-off	2.60	0.168
16	3.4	6.1	0.500	3	on-off	2.78	0.231
17	3.4	6.6	0.625	3	on-off	3.83	0.220
18	3.4	6.2	0.750	3	on-off	3.69	0.2285
19	3.4	6.8	0.875	3	on-off	5.15	0.208
20	3.4	6.3	1.000	3	on-off	5.97	0.2098

Table 4

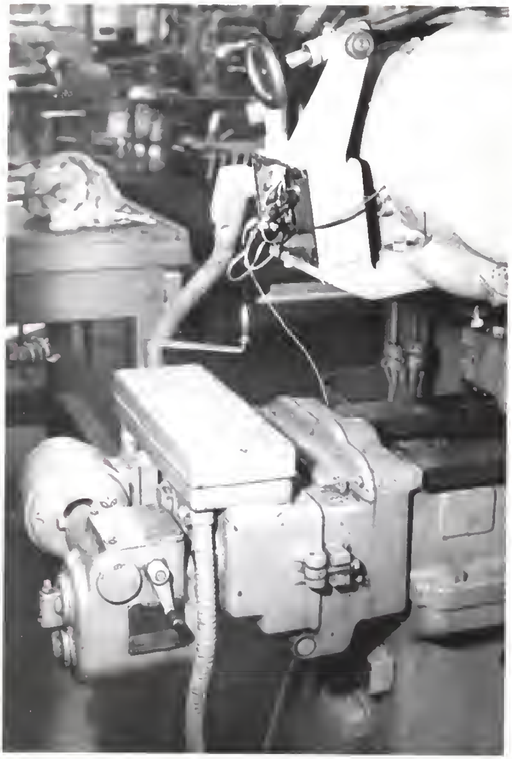


Fig. 7. FEED MECHANISM AND CUTTER MOTOR

HORIZONTAL SPEED CONTROLLED BY ADAPTIVE CONTROL

Material = ½" x 2½" HRS
RPM = 563
Volts = 12.5

3 Cutters = 3/4", 2 flute straight shank
Ampere = 2.8
Relay Setting = 3.5 Amps.
Cutting Speed = 100 FPM

(A = Horizontal speed in inches per minute)

Reading	Amperes on the meter		Depth of cut in inches	A inches /min.	Continuous or on-off	Time in minutes	Material Removed in ^{3}/min.
	Min. Amps.	Max. Amps.					
1	2.8	4.2	0.50	1/2	continuous	5.60	.112
2	2.8	5.8	0.75	1/2	on-off	9.15	.103
3	2.8	6.1	1.00	1/2	on-off	11.42	.109
4	2.8	5.2	0.25	1-1/4	continuous	2.14	.146
5	2.8	5.8	0.50	1-1/4	on-off	4.49	.139
6	2.8	6.1	0.75	1-1/4	on-off	7.30	.128
7	2.8	7.0	1.00	1-1/4	on-off	9.30	.134
8	2.8	5.8	0.25	3	on-off	1.70	.184
9	2.8	6.4	0.50	3	on-off	3.44	.182
10	2.8	7.0	0.75	3	on-off	5.48	.171
11	2.8	7.6	1.00	3	on-off	7.00	.179

Table 5

In order to test the control device for different cutting conditions more experiments were carried out at different depths of cut and feeds. The results are shown in Table 6. Table 7 shows the effect of different resistances in the third stage.

During the experiment it was observed that the amount of metal removed did not remain constant. To investigate this further some more observations were made without the adaptive control at different depth of cuts and feed so as to remove constant amount of metal during a specified time. The results are shown in Table 8.

DISCUSSION

Tables 1 and 2 show that for power relay setting 3 and 4 amps the maximum current to open the relay was 6 and 7 amps. respectively. This showed that the relay was functioning properly. Graphs shown in Fig. 8 and 9 show the relation between depth of cut and the time spent for machining. From this it is seen clearly that the machining time taken for relay setting 3 was more than for 4. This again verified a functioning power relay system.

Table 3 and the graph shown in Fig. 10 indicate the relation between depth of cut and time spent for machining a $\frac{1}{2}$"x$2\frac{1}{2}$" cross-section for relay setting 3. This showed clearly the consistency in the results. Column 7 in Table 3 shows what fraction of time the machine is "on."

Tables 4 and 5 show the amount of material removed without and with the adaptive control system respectively. Graphs shown in Fig. 11 and 12 show the relation between amount of material removed and depth of cut. This clearly shows the advantage of the adaptive control system over the rheostat

Material = $\frac{1}{2}$" x $2\frac{1}{2}$" HRS
RPM = 563
Volts = 12.5
1 Rev. = .250"
Cutter = 3/4", 2 flute straight shank
Ampere = 2.8
Relay Setting = 3.5 Amps.
Cutting Speed = 100 FPM
(A = Horizontal speed in inches per minutes feed rate)

Reading	Depth of cut in inches	Revolution	Time in min.	Rev./Min.	Inches/Min. or A	With or Without Control Device
1	.25	4.12	2.0	2.06	.515	with
2	.30	4.12	2.0	2.06	.515	with
3	.35	4.00	2.0	2.00	.500	with
4	.40	3.84	2.0	1.92	.480	with
5	.45	3.28	2.0	1.64	.410	with
6	.50	3.24	2.0	1.62	.405	with
7	.55	2.84	2.0	1.42	.355	with
8	.60	2.80	2.0	1.40	.350	with
9	.70	2.52	2.0	1.26	.315	with
10	.80	2.48	2.0	1.24	.310	with
11	.60	4.12	2.0	2.06	.515	without
12	.65	4.08	2.0	2.04	.501	without
13	.70	3.24	2.0	1.62	.405	without
14	.75	3.48	2.0	1.74	.4350	without
15	.80	3.00	2.0	1.50	.375	without
16	.85	3.00	2.0	1.50	.375	without
17	.90	2.76	2.0	1.38	.3250	without

Table 6

THE EFFECT OF VARIABLE RESISTANCE ON ADAPTIVE CONTROL

Material = ½" x 2½" HRS Cutter = 3/4", 2 flute straight shank

RPM = 563 Ampere = 2.8

Volts = 12.5 Relay Setting = 3.5 Amps.

1 Rev. = .250" Cutting Speed = 100 FPM

(A = Horizontal speed in inches per minute, feed rate)

ADAPTIVE CONTROL CONNECTED

Reading	Resistor in ohms	Depth of cut in inches	Revolution	Time in min.	Rev./Min.	Inches/Min. or A
1	33 k	.3	4.12	2.0	2.06	0.515
2	33 k	.4	3.84	2.0	1.92	0.480
3	33 k	.5	3.24	2.0	1.62	0.405
4	33 k	.6	2.80	2.0	1.40	0.350
5	27 k	.3	3.56	2.0	1.78	0.4450
6	27 k	.4	3.56	2.0	1.78	0.4450
7	27 k	.5	3.04	2.0	1.52	0.3770
8	27 k	.6	2.60	2.0	1.30	0.3250
9	22 k	.3	4.04	2.0	2.02	0.501
10	22 k	.4	3.56	2.0	1.78	0.445
11	22 k	.5	3.00	2.0	1.50	0.375
12	22 k	.6	2.72	2.0	1.36	0.340
13	18 k	.3	3.64	2.0	1.82	0.4550
14	18 k	.4	3.48	2.0	1.74	0.4350
15	18 k	.5	2.92	2.0	1.46	0.3650
16	18 k	.6	2.60	2.0	1.30	0.3250
17	10 k	.3	4.12	2.0	2.06	0.515
18	10 k	.4	3.56	2.0	1.78	0.4550
19	10 k	.5	3.24	2.0	1.62	0.4050
20	10 k	.6	2.72	2.0	1.36	0.3400

Table 7

CONSTANT METAL REMOVAL RATE

Material = ½" x 2½" HRS
RPM = 563
Volts = 12.5

Cutter = 3/4", 2 flute straight shank
Ampere = 2.8
Relay Setting = 3.0 Amps.
Cutting Speed = 100 FPM

WITHOUT ADAPTIVE CONTROL

Reading	Depth of cut	Feed in /Min.	Time in Min.	in ^{3}/Min.	Voltage
1	0.0	Variable			2.8
2	0.125	2.0	1 min.	1/8	4.6
3	0.250	1.0	1 min.	1/8	5.0
4	0.500	0.50	1 min.	1/8	5.6

Table 8

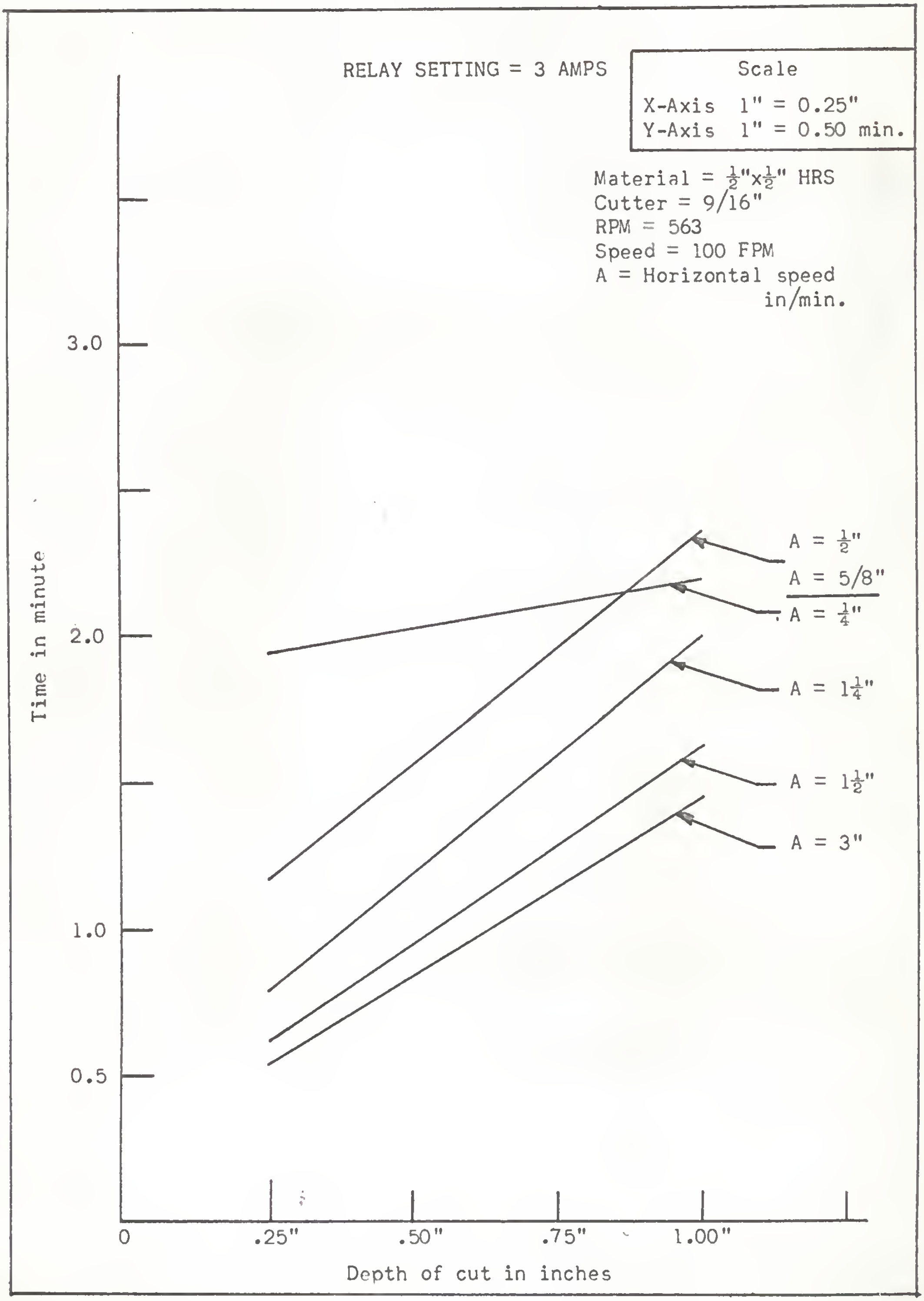

RELAY SETTING = 3 AMPS
Scale
X-Axis 1" = 0.25"
Y-Axis 1" = 0.50 min.
Material = ½"x½" HRS
Cutter = 9/16"
RPM = 563
Speed = 100 FPM
A = Horizontal speed in/min.
A = ½"
A = 5/8"
A = ¼"
A = 1¼"
A = 1½"
A = 3"
3.0
2.0
1.0
0.5
Time in minute
0
.25"
.50"
.75"
1.00"
Depth of cut in inches

Fig. 8

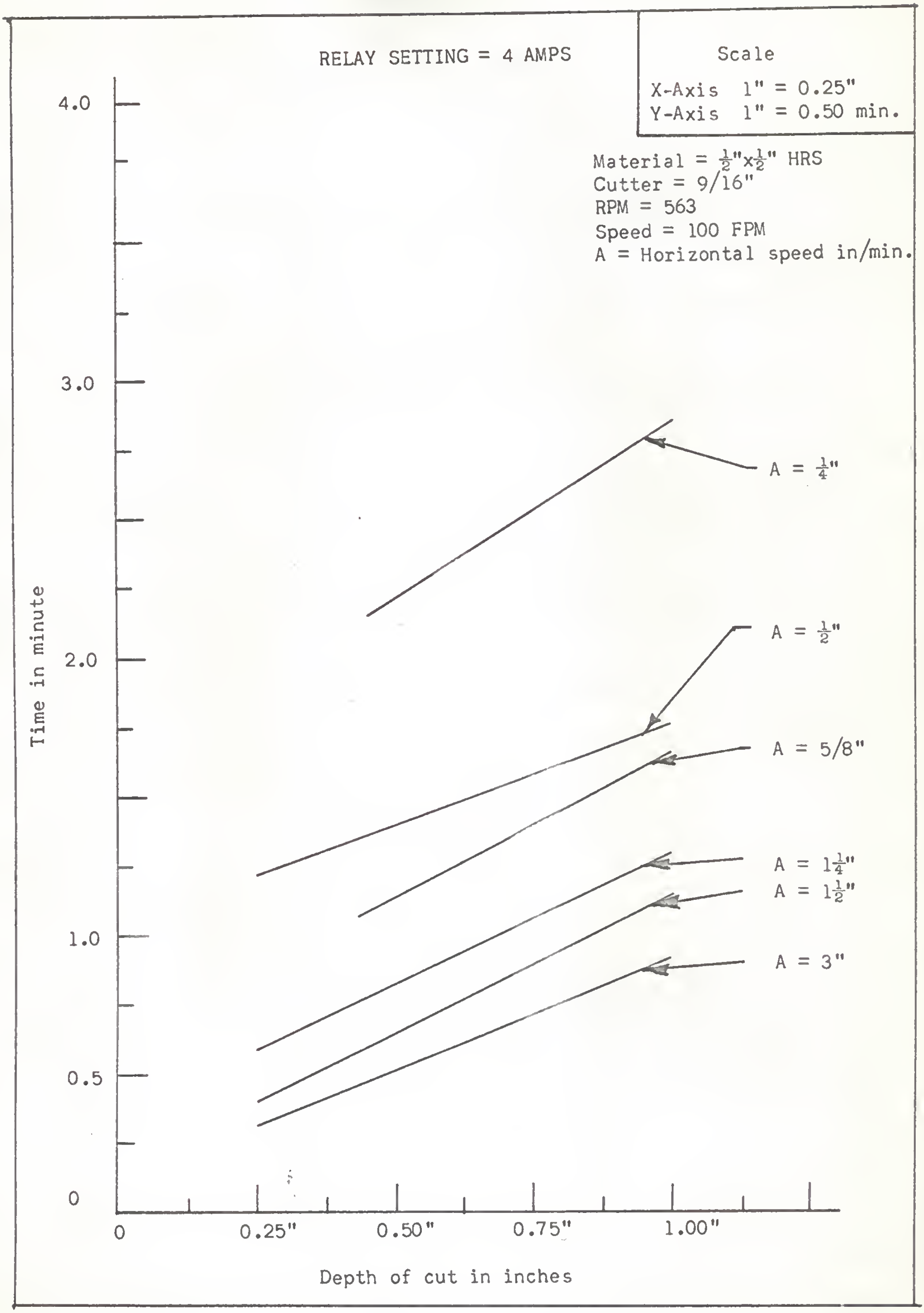

RELAY SETTING = 4 AMPS
Scale
X-Axis 1" = 0.25"
Y-Axis 1" = 0.50 min.
Material = ½"x½" HRS
Cutter = 9/16"
RPM = 563
Speed = 100 FPM
A = Horizontal speed in/min.
A = ¼"
A = ½"
A = 5/8"
A = 1¼"
A = 1½"
A = 3"
4.0
3.0
2.0
1.0
0.5
0
Time in minute
0
0.25"
0.50"
0.75"
1.00"
Depth of cut in inches

Fig. 9

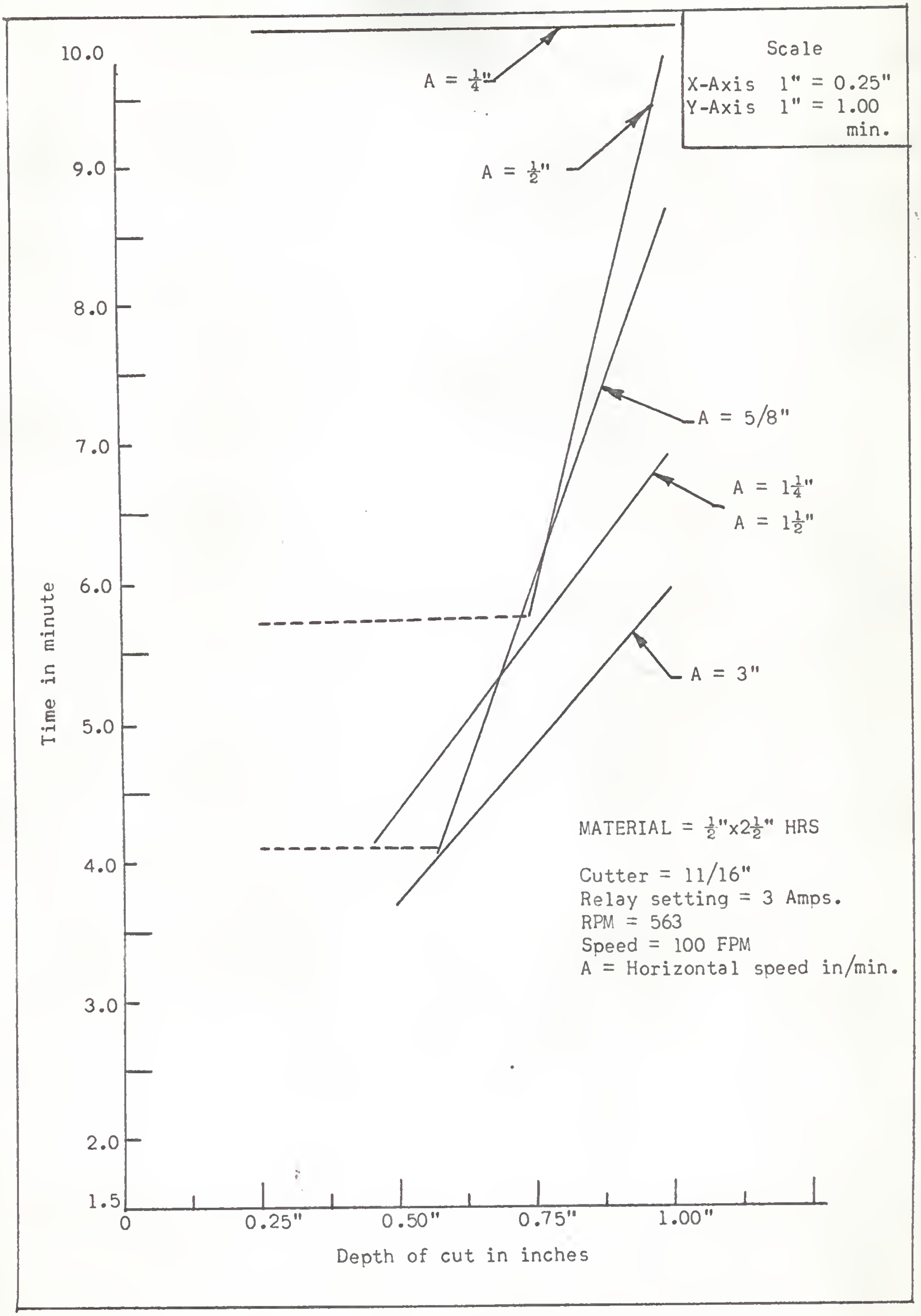

Scale
X-Axis 1" = 0.25"
Y-Axis 1" = 1.00 min.
A = ¼"
A = ½"
A = 5/8"
A = 1¼"
A = 1½"
A = 3"
MATERIAL = ½"x2½" HRS
Cutter = 11/16"
Relay setting = 3 Amps.
RPM = 563
Speed = 100 FPM
A = Horizontal speed in/min.
Time in minute
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.5
0
0.25"
0.50"
0.75"
1.00"
Depth of cut in inches

Fig. 10

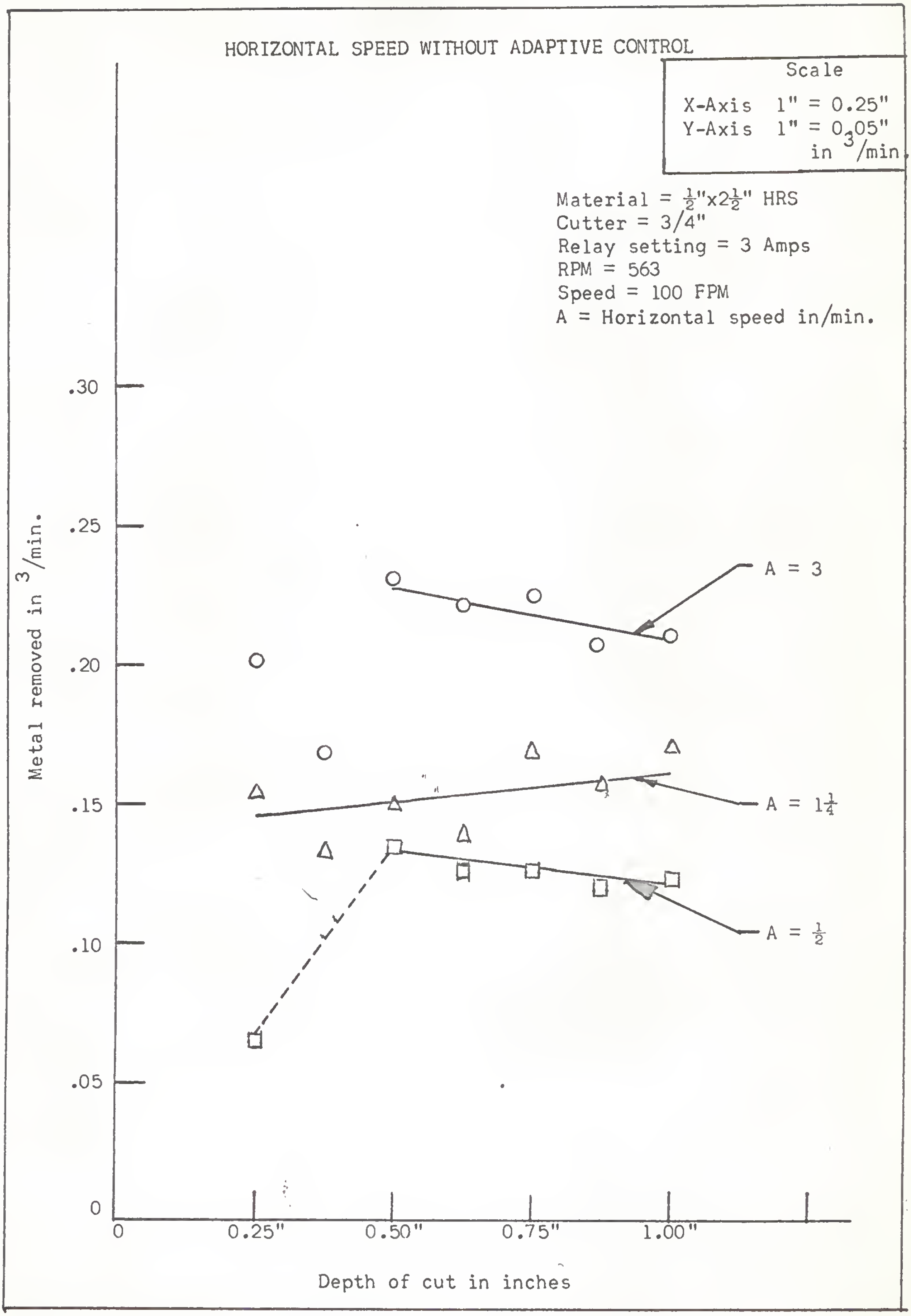
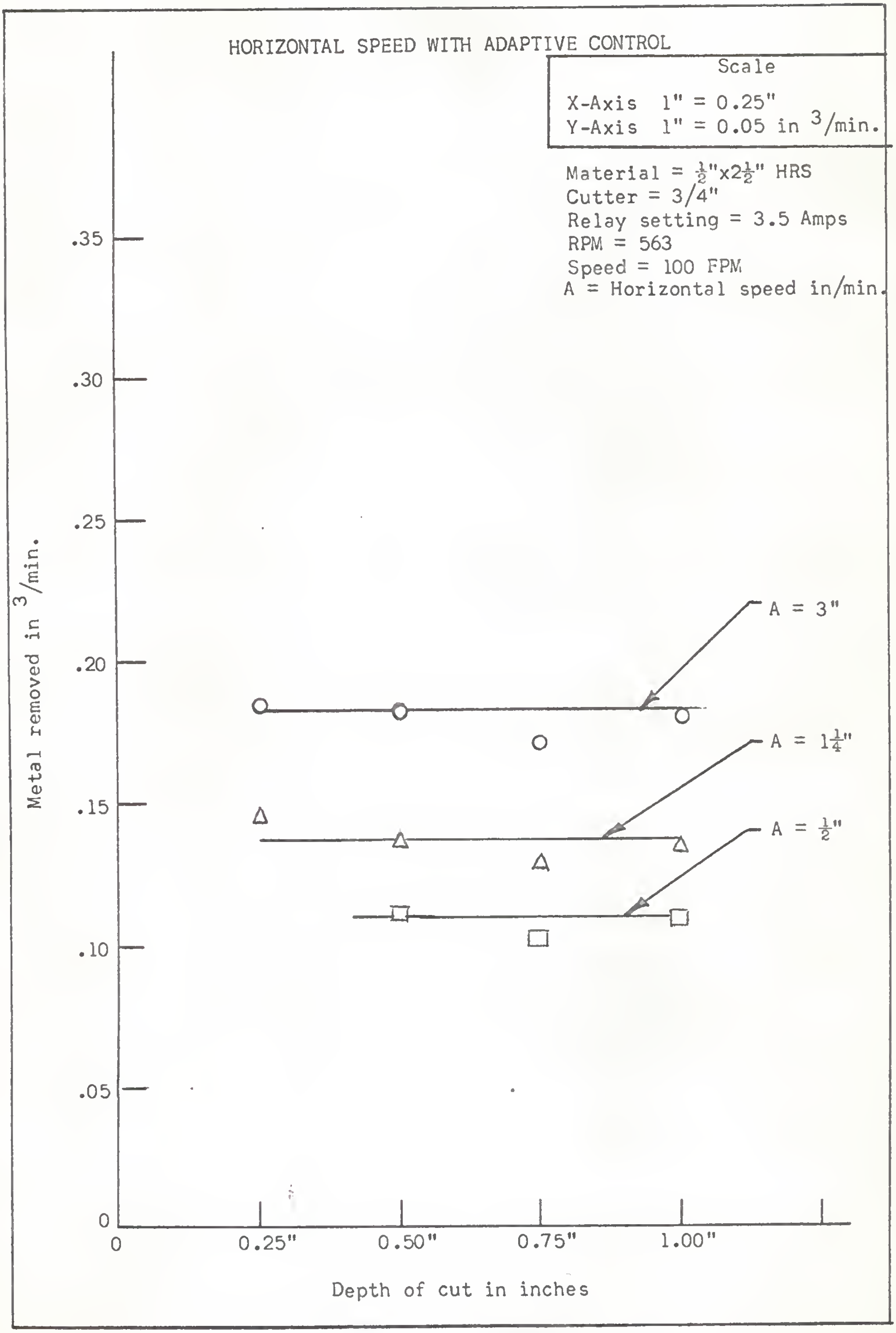

HORIZONTAL SPEED WITHOUT ADAPTIVE CONTROL
Scale
X-Axis 1" = 0.25"
Y-Axis 1" = 0.05" in 3/min
Material = ½"x2½" HRS
Cutter = 3/4"
Relay setting = 3 Amps
RPM = 563
Speed = 100 FPM
A = Horizontal speed in/min.
A = 3
A = 1¼
A = ½
Metal removed in 3/min.
.30
.25
.20
.15
.10
.05
0
0
0.25"
0.50"
0.75"
1.00"
Depth of cut in inches

Fig. 11



HORIZONTAL SPEED WITH ADAPTIVE CONTROL
Scale
X-Axis 1" = 0.25"
Y-Axis 1" = 0.05 in 3/min.
Material = ½"x2½" HRS
Cutter = 3/4"
Relay setting = 3.5 Amps
RPM = 563
Speed = 100 FPM
A = Horizontal speed in/min.
A = 3"
A = 1¼"
A = ½"
Metal removed in 3/min.
.35
.30
.25
.20
.15
.10
.05
0
0
0.25"
0.50"
0.75"
1.00"
Depth of cut in inches

Fig. 12

system.

Table 6 and graph shown in Fig. 13 show the relation between depth of cut and the voltage (and thus feed in/min as shown in Fig. 13), with and without adaptive control. This clearly shows that the tool in case of adaptive control runs at a lighter load, thus minimizing the tool wear.

The graph shown in Fig. 13 also shows that the amount of material removed was not constant because the slope of the line between the depth of cut and feed was not unity.

To study the effect of gain at various resistances the graph in Fig. 14 was plotted from Table 7. According to theory the gain should increase and the slope of the line would therefore approach unity as the resistance decreases. But from the graph it is seen clearly that the slope of the line was always in neighborhood of 0.6. This could be due to two main reasons:

1. The electronic tube reaches a saturation point.

2. The voltage at the field of the cutter motor does not remain constant.

In the first case the amplifiers were designed to operate between +50 volts and -120 volts since the gain was more than -120 V the amplifier output did not increase.

Then the only possibility was to check the voltage at the field of the cutter motor. Table 8 shows that the voltage at the field of cutter motor was not constant. This in effect indicated the variation in the tool force at the different depth of cuts. This is clearly seen from the graph in Fig. 15.

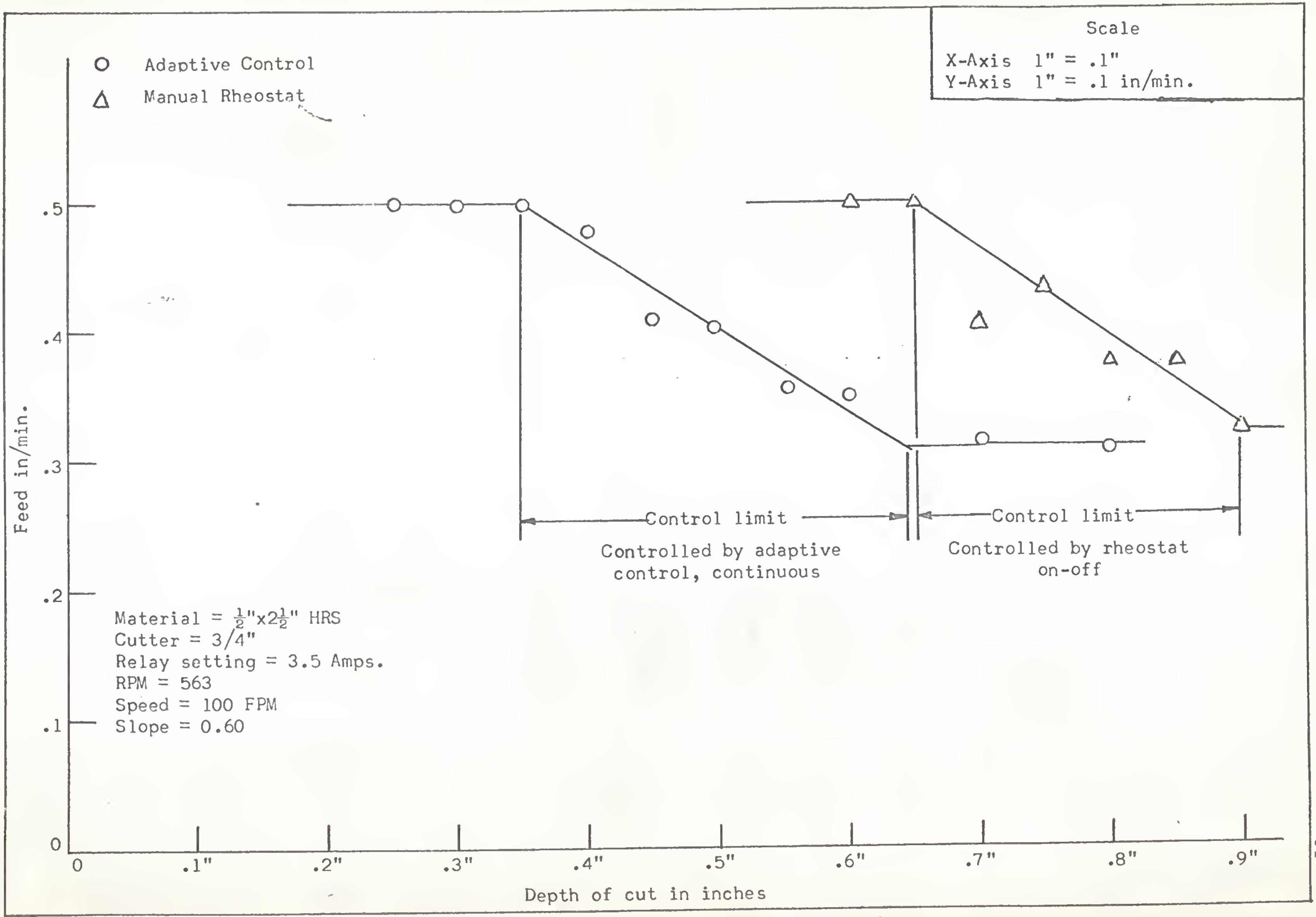

Scale
X-Axis 1" = .1"
Y-Axis 1" = .1 in/min.
Adaptive Control
Manual Rheostat
Control limit
Controlled by adaptive control, continuous
Control limit
Controlled by rheostat on-off
Material = ½"x2½" HRS
Cutter = 3/4"
Relay setting = 3.5 Amps.
RPM = 563
Speed = 100 FPM
Slope = 0.60
Feed in/min.
Depth of cut in inches
0
.1
.2
.3
.4
.5
0
.1"
.2"
.3"
.4"
.5"
.6"
.7"
.8"
.9"

Fig. 13

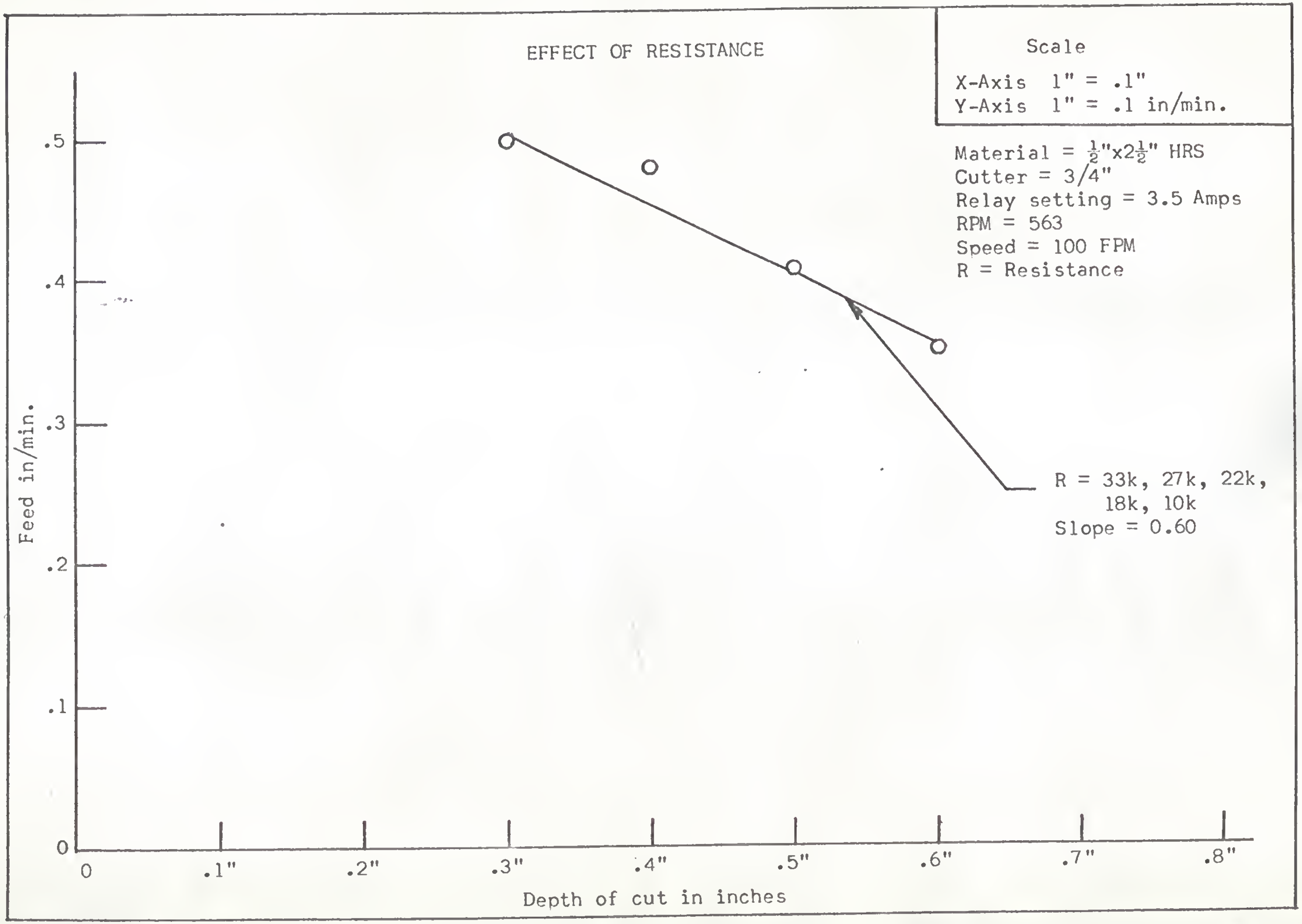

EFFECT OF RESISTANCE
Scale
X-Axis 1" = .1"
Y-Axis 1" = .1 in/min.
Material = ½"x2½" HRS
Cutter = 3/4"
Relay setting = 3.5 Amps
RPM = 563
Speed = 100 FPM
R = Resistance
R = 33k, 27k, 22k, 18k, 10k
Slope = 0.60
Feed in/min.
.5
.4
.3
.2
.1
0
0
.1"
.2"
.3"
.4"
.5"
.6"
.7"
.8"
Depth of cut in inches

Fig. 14

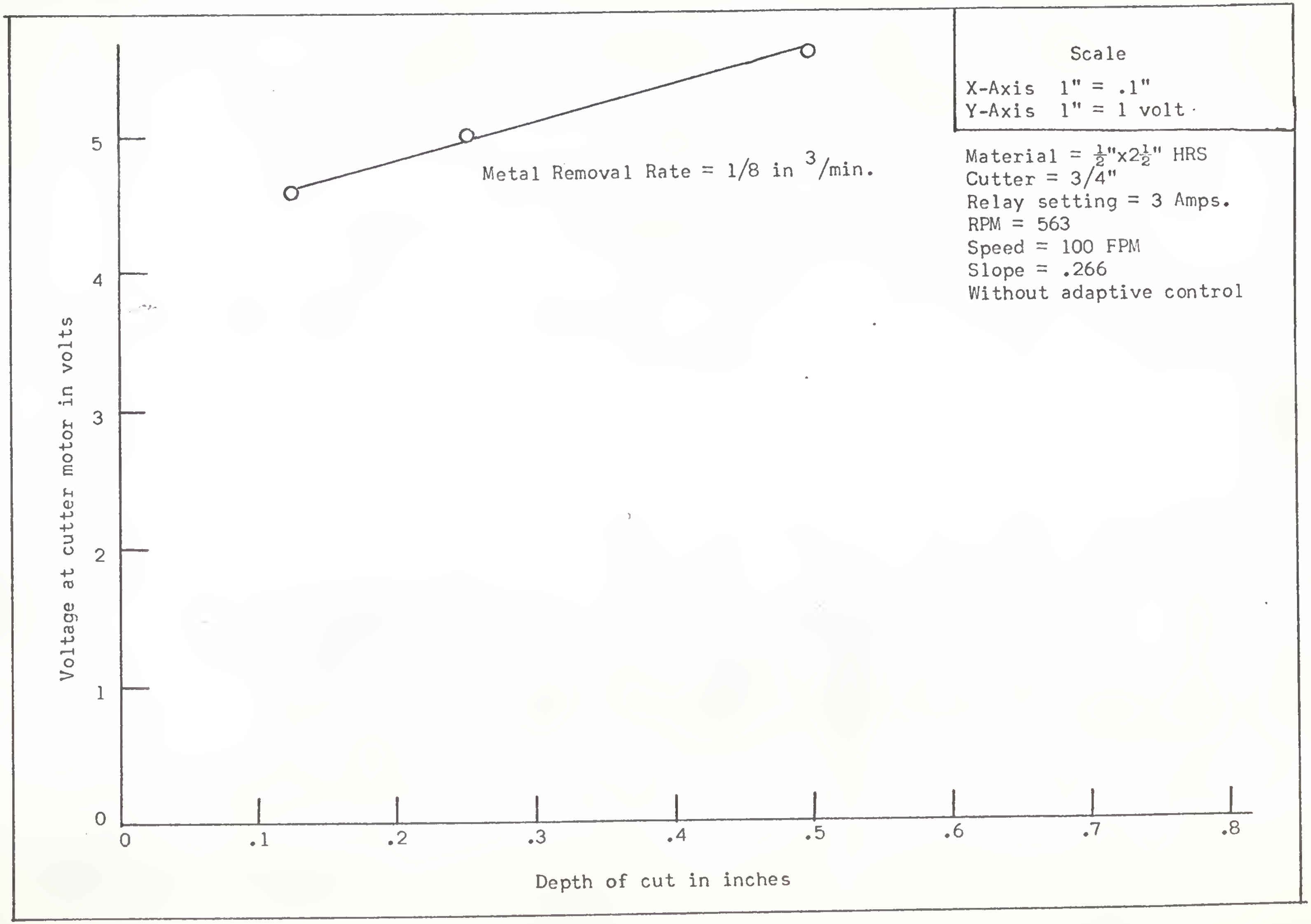

Scale
X-Axis 1" = .1"
Y-Axis 1" = 1 volt
Material = ½"x2½" HRS
Cutter = 3/4"
Relay setting = 3 Amps.
RPM = 563
Speed = 100 FPM
Slope = .266
Without adaptive control
Metal Removal Rate = 1/8 in 3/min.
Voltage at cutter motor in volts
0
1
2
3
4
5
0
.1
.2
.3
.4
.5
.6
.7
.8
Depth of cut in inches

Fig. 15

CONCLUSIONS

From the study the following conclusions were drawn:

1. With the rheostat control system, the metal removal rate with respect to the depth of cut was not consistent while with the adaptive control system very consistent results were obtained.

2. The metal removal rate was higher in the case of the rheostat control system but a continuous operation was obtained with the adaptive control. This, in effect, results into a less load on the cutter giving an increased tool life.

3. Power consumption was higher in the case of the rheostat control system than the adaptive control system. So adaptive control offers a potentially significant improvement in efficiency and economy.

4. The constant metal removal rate was assumed for both cases but due to the variation of forces on the tool at different depth, this was not possible. Therefore, since the results from the adaptive control were more consistent than the rheostat system, the adaptive control proved to be the better system.

It would be interesting to study the effects of adaptive control with respect to:

1. Tool life.
2. Surface finish.
3. Tool forces.

ACKNOWLEDGMENTS

It is with great gratitude that the author expresses his sincere appreciation to Professor J. J. Smaltz, major professor, without whose guidance, patience and continued encouragement this endeavour would not have been possible. The author is indebted to Dr. George F. Schrader for frequent advice and suggestions in regard to this work. The author is grateful to Mr. Bill Romig and Mr. C. L. Nelson for their help in the experiment. Thanks are due to other faculty and staff members of the Department of Industrial Engineering, Kansas State University, for their cooperation in conducting the experiment. Finally this author wishes to express indebtedness, gratitude, recognition, praise, thanks and satisfaction to his parents for the help, aid, understanding and bundle of joy they so willingly bequeathed during his college career.

REFERENCES

1. Heathkit Operational Manual for Model EC-1 Benton Harbor, Michigan: Heath Company.

2. Centner, R. M. and J. M. Idelsohn. "Adaptive controller for metal cutting process." Joint Automatic Control Conference, June 19-21, 1963, pp. 262-271.

3. A Treatise on Milling and Milling Machines. Cincinnati, Ohio: The Cincinnati Milling Machine Co., 1951.

4. Drenick, R. F. and R. A. Shahbender. "Adaptive servomechanisms." AIEF Transactions, Application and Industry, vol. 76, pt. II, November, 1957, pp. 286-291.

5. Eykhoff, Peter. "Adaptive and optimizing control systems." Transaction, professional group on automotive control, Institute of Radio Engineers, vol. AC-5, no. 2, June, 1960, p. 148.

6. Taylor, F. W. On the Art of Cutting Metals. New York: The American Society of Mechanical Engineers.

7. Wickey, J. Ronald. "D.C. Motor Control." Machine Design, vol. 33, no. 15, 16, 17, 18, 19, 20, first paper, July 21, 1961.

ADAPTIVE CONTROL FOR MILLING MACHINES

by

RAMESH MOHANLAL PARIKH

B. S., University of Utah, 1962

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1965

The purpose of this thesis was to design an adaptive control system for a milling machine that would maintain a constant torque on the cutting edge. The effect on power consumption and metal removal rate, with and without the control was studied.

A manually operated rheostat previously regulated the varying speed of feed. The adaptive control worked as a feedback control system. The adaptive control system consisted of DC operational amplifiers. Amplifiers acted as subtractor, inverter and multiplier to produce the satisfactory output voltage. Output voltage was supplied to an electronic tube which acted as a variable resistor in the place of the rheostat. Resistance in the tube depends on the load on the cutter motor. The adaptive control was connected to the field of the cutter motor and feed motor. The speed of feed motor changed depending on the load on cutter motor.

It was not possible to get a constant metal removal rate but a continuous machining operation could be obtained. Tool-life was increased due to a constant load on the cutter during intermittent or continuous cuts. Power consumption was lower in the case of adaptive control than the manual rheostat system. It was concluded that the adaptive control system offers a potentially significant improvement in efficiency and economy.