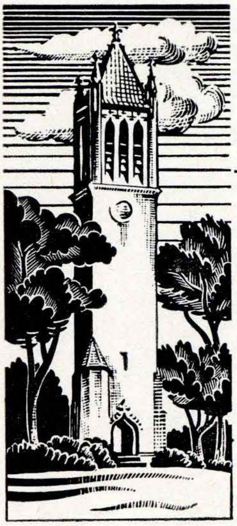
ELECTRICAL POWER TRANSMISSION

AND LOAD ANALYSIS FOR A COMBINE

By James H. Anderson and Kenneth K. Barnes



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CONTENTS

Summary 4

Introduction 5

Objectives 5

Investigations 5

  Equipment 5

    Electrical coupling 5

    Combine 6

  Instrumentation 6

    Torque measurements 6

    Electrical measurements 9

    Instrument control circuits 9

  Procedure 10

    Description of tests 10

  Data analysis 12

Results and discussion 12

  Stationary load study 12

  Slug study 14

  Load analysis and performance study in windrowed wheat 15

  Load analysis and performance study in soybeans 17

  Laboratory study of power loss in cylinder drive 17

  Laboratory study of the electrical coupling under high overloads 18

Design recommendations 18

SUMMARY

Performance studies were made to determine design criteria for electrical couplings for combines. Electric motors were mounted on a Model 60, Allis-Chalmers combine so that the combine could be driven by a single motor, by combinations of more than one motor or by a standard pto coupling. Electrical energy was supplied to the motors from a tractor-mounted and -driven generator.

Field tests were conducted in windrowed wheat and oats and in rowed soybeans. Stationary loading tests were conducted by feeding the combine from a conveyor. Drive losses of the combine and the performance of the electrical coupling under high overloads were studied in the laboratory.

During the tests, torque and speed were measured at the three basic load centers of the combine (i.e., feeding drive, cylinder drive and separating drive) simultaneously with the recording of electrical parameters.

From the studies conducted, the following conclusions were drawn:

A. Performance of the electrical system tested: (1) Speed regulation of the electrical couplings was poor compared with the pto coupling. (2) The response time of the governing system of the tractor was too slow when the electrical couplings were subjected to suddenly applied overloads. That is, the electrical system reached an inefficient or even inoperative condition before the tractor started to restore the electrical system to a state of equilibrium. (3) The performance of multiple-motor couplings was superior to that of the single-motor coupling under normal load conditions. Under extremely heavy load conditions, when the generator became overloaded, no difference was noted between the performance of the two types of couplings.

B. Load characteristics of the combine: (1) The feed rate determined to a large extent the power requirements of the cylinder drive. (2) The power requirement of the cylinder was characterized by high momentary overloads. (3) The feed rate had very little effect on the power required to drive the separating and feeding units. (4) Many of the overload conditions which resulted in jamming the cylinder were due to uneven feeding of the material into the cylinder. (5) Drive losses represented 25 to 30 percent of the total power transfer.

C. Design recommendations for application of electrical couplings to field machines: (1) Simplification of the power train is a necessity on machines such as combines if the drive losses are to be reduced. (2) The addition of a flywheel is one possible solution where high load fluctuations are detrimental to the performance of electrical couplings. (3) The feed flow must be smooth to reduce peak overload periods on machines such as combines. (4) The tractor governor should be controlled by a frequency sensing device so that the frequency of the generator output will remain constant. (5) Motors which have continually increasing torque with decreasing speed should be used for this application.

Electrical Power Transmission and Load Analysis for a Combine[1]

BY JAMES H. ANDERSON AND KENNETH K. BARNES[2]

Energy developed by a tractor engine may be transmitted to an implement or machine by a mechanical, hydraulic or electrical linkage. The mechanical systems which utilize either the drawbar of the tractor or the pto (power-take-off) shaft have been commonly used. Hydraulic systems using pumps driven by the tractor engine and "remote" cylinders are also common. The hydraulic pump and motor system has been applied to farm machines only to a limited extent. Electrical energy transmission systems for agricultural tractor-machine combinations have also been used to a limited extent.

The electrical energy transmission system consists of an electric generator driven by the tractor engine, an electric motor (or motors) supplying energy to the various functional components of the machine, and the controls and conductors linking the generator and motors.

The electrical system offers much more flexibility of power application than does a mechanical power train. Design of machines could be greatly simplified if provision did not have to be made for shafts, gears, sheaves, belts and chains. Separate electrical circuits for drives to various components of a machine would enable individual control of these components. Certain types of electrical systems lend themselves to use as standby power units for the farmstead and as power sources for electrical tools away from the farmstead.

In recognition of these advantages, there have been a number of commercially attempted applications of electrical energy transmission for field machines. These efforts have generally been unsuccessful because the designers of these systems have not had information concerning the unique requirements which the agricultural tractor-machine combination imposes upon the electrical system.

OBJECTIVES

This study was initiated to investigate the problems associated with electrical drives on farm machines. Specific objectives were:

1. To gain an insight into the problems associated with electric power transmission for combines.
2. To determine the factors governing generator and motor requirements.
3. To determine design criteria for electrical couplings for combines.
4. To determine design requirements for combines to make them more suitable for application of electric drives.

INVESTIGATIONS

To meet the objectives, combine performance data were obtained for electrical couplings and a pto coupling under a variety of loading conditions. Field studies were made in wheat, oats and soybeans. Loading studies also were made by feeding the combine from a conveyor belt, and laboratory studies were made of the performance characteristics of the electrical system.

EQUIPMENT

ELECTRICAL COUPLING

Both single and multiple-motor couplings were used as follows:

Single-motor coupling—A 7.5-hp motor driving the entire machine.

Multiple-motor coupling (9.5-hp)—A 7.5-hp plus a 2-hp motor driving the machine.

Multiple-motor coupling (10.5-hp)—A 7.5-hp plus a 3-hp motor driving the machine.

Multiple-motor coupling (12.5-hp)—A 7.5-hp plus a 3-hp plus a 2-hp motor driving the machine.

The generator was a 12.5-kw, 208-volt, 3-phase, 60-cycle, 2-pole, 3,600-rpm, 4-wire, revolving-field alternator.[3] A plot of the no load voltage versus field current for the generator is shown in fig. 1. The generator was connected directly to the tractor as shown in fig. 2. A connection diagram of the generator is shown in fig. 3. A thermal device with a push button

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[1] Project 1331, Iowa Agricultural and Home Economics Experiment Station.

[2] The authors express their appreciation for the advice and assistance of John E. Lagerstrom of the Department of Electrical Engineering and Glenn Murphy of the Department of Theoretical and Applied Mechanics.

[3] This unit is manufactured by the General Electric Company and marketed by the International Harvester Company under the trade name, "Electrall."

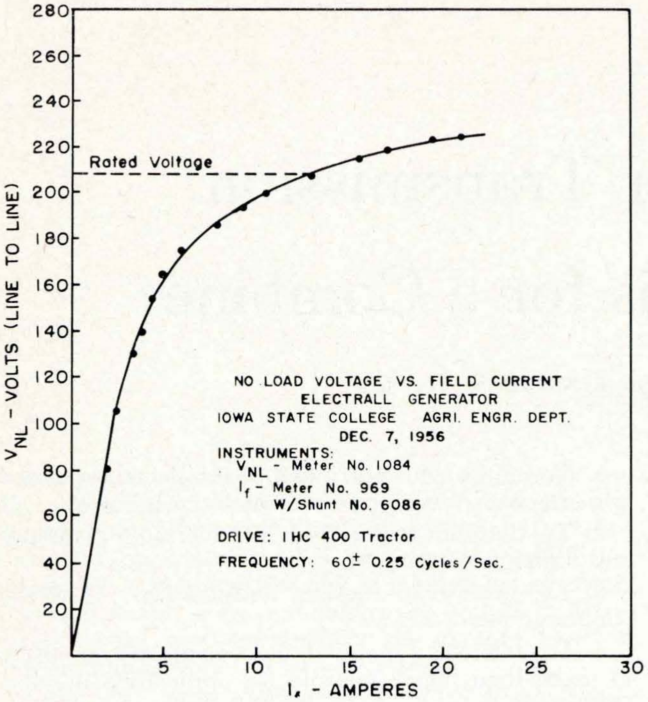

Fig. 1. No load voltage versus field current for the tractor-mounted generator used in this study.

reset was used to protect the generator against a sustained overload. In addition to the thermal protection, three 50-amp, time-delay fuses were used to protect the generator in the event of a short circuit in the load or output cable.

The motors used in the study were made available by the General Electric Company, and each motor was identified as "Farm Machine Motor" on the name plate. The motors were 208-volt, 3-phase, 60-cycle, 4-pole, 1,800-rpm, low-slip, squirrel-cage induction motors. The allowable temperature rise was 105°C.

Performance characteristics data were obtained for each of the motors used in the field study by loading them in the laboratory of the Electrical Engineering Department, Iowa State College. These characteristics are presented in figs. 4, 5 and 6.

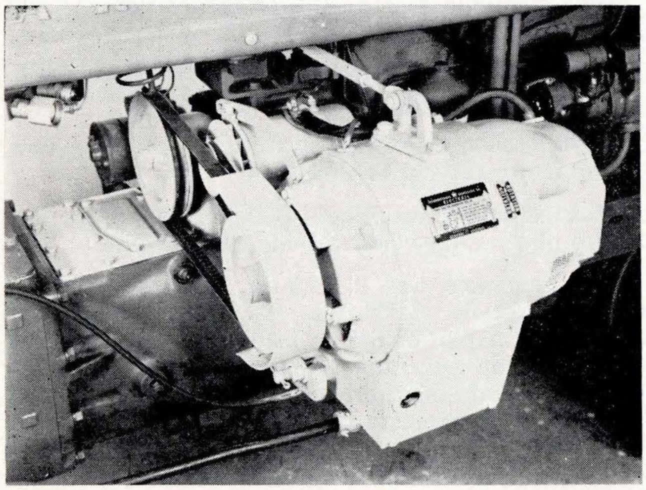

Fig. 2. Close-up view of the generator mounted on the tractor (courtesy International Harvester Co.).

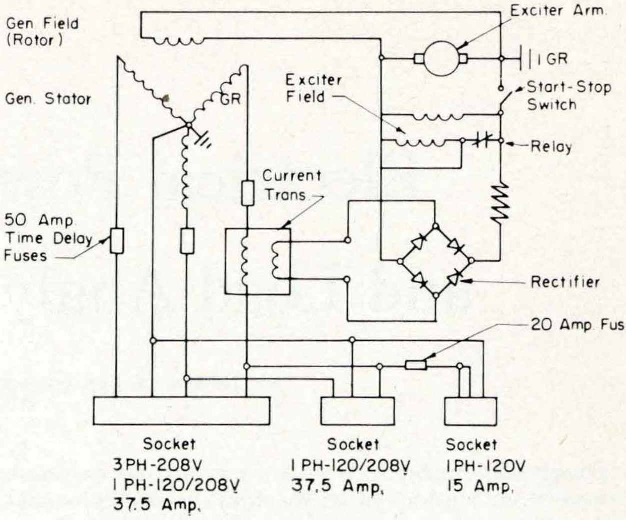

Fig. 3. Connection diagram of the generator used in this study.

COMBINE

The combine was a Model 60 Allis-Chalmers. The machine could be used as a direct-cut machine or equipped with a windrow pickup attachment.

The combine power train was modified so that the machine could be driven by the pto coupling, the single-motor coupling or the multiple-motor couplings. A schematic representation of the possible drive combinations is shown in fig. 7.

A large pulley was mounted on the front of the gear box so that power could be introduced into the system by the 7.5-hp motor. The pulley was keyed to a short shaft which was attached directly to the gear box on one end and supported by a bearing on the other end. When in use the pto was keyed to the short shaft.

For introducing power into the system with the 3-hp motor, the main separator shaft was cut and a pulley mounted on the shaft. A coupling was used when it was desired to drive the main separator shaft through the gear box.

A pulley was mounted on the right end of the lower canvas drive shaft for connecting the 2-hp motor to the cutting and feeding mechanism. This permitted the knife (or pickup attachment) and canvas to be driven either by the 2-hp motor or through the gear box after connecting the proper belts.

The mount of the 7.5-hp motor was bolted to the tongue assembly of the combine as shown in fig. 8. The 2-hp motor mount is shown in fig. 9. The motor was suspended directly beneath the cylinder on the side of the combine. The 3-hp motor was mounted directly under the grain bin. Part of the pulley for this motor is visible in fig. 8.

INSTRUMENTATION

TORQUE MEASUREMENTS

Electrical-resistance strain gauges were used to determine the torque of the main separator shaft, the cylinder shaft and the knife (or pickup attachment) and canvas shaft. The gauges were mounted in accord

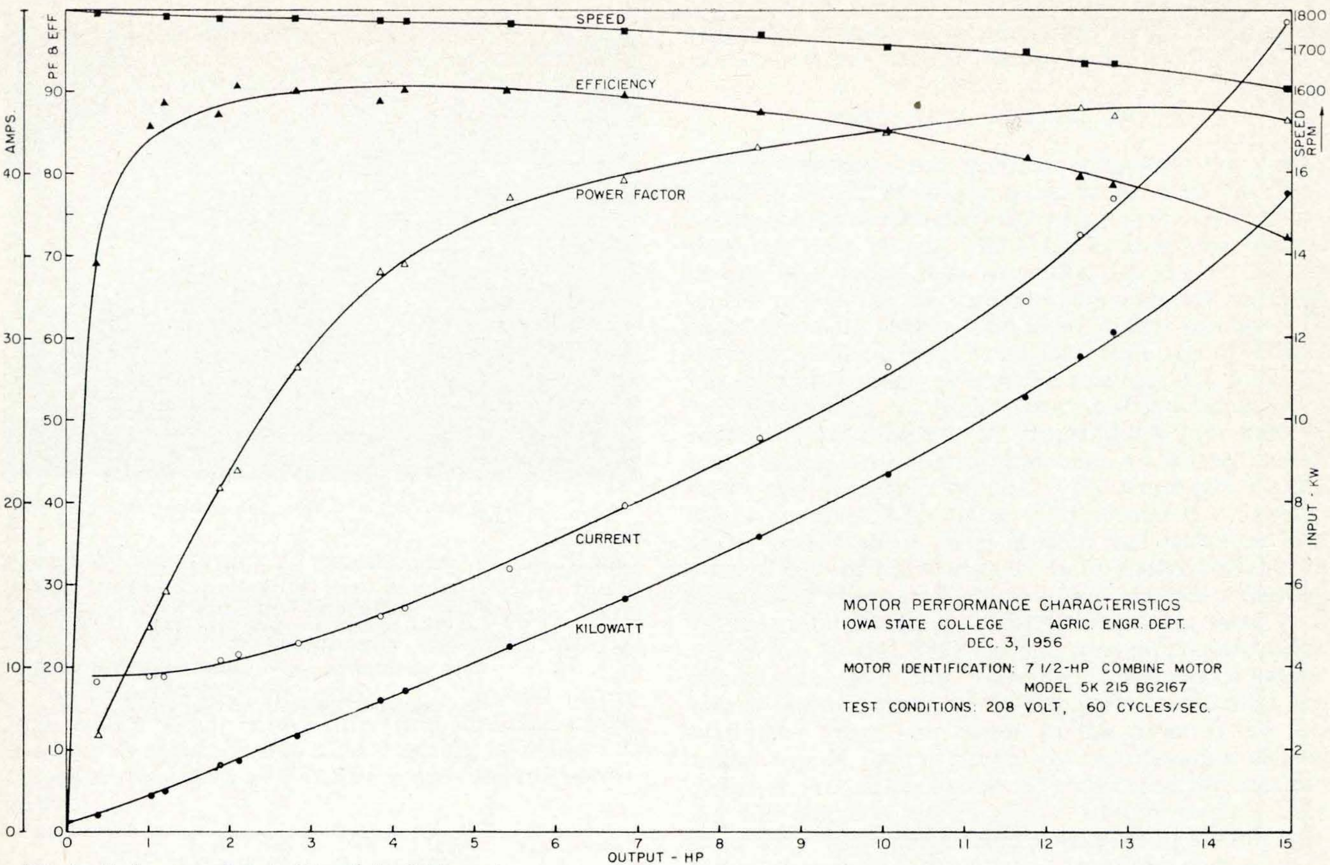

Fig. 4. Performance characteristics of the 7.5-hp motor.

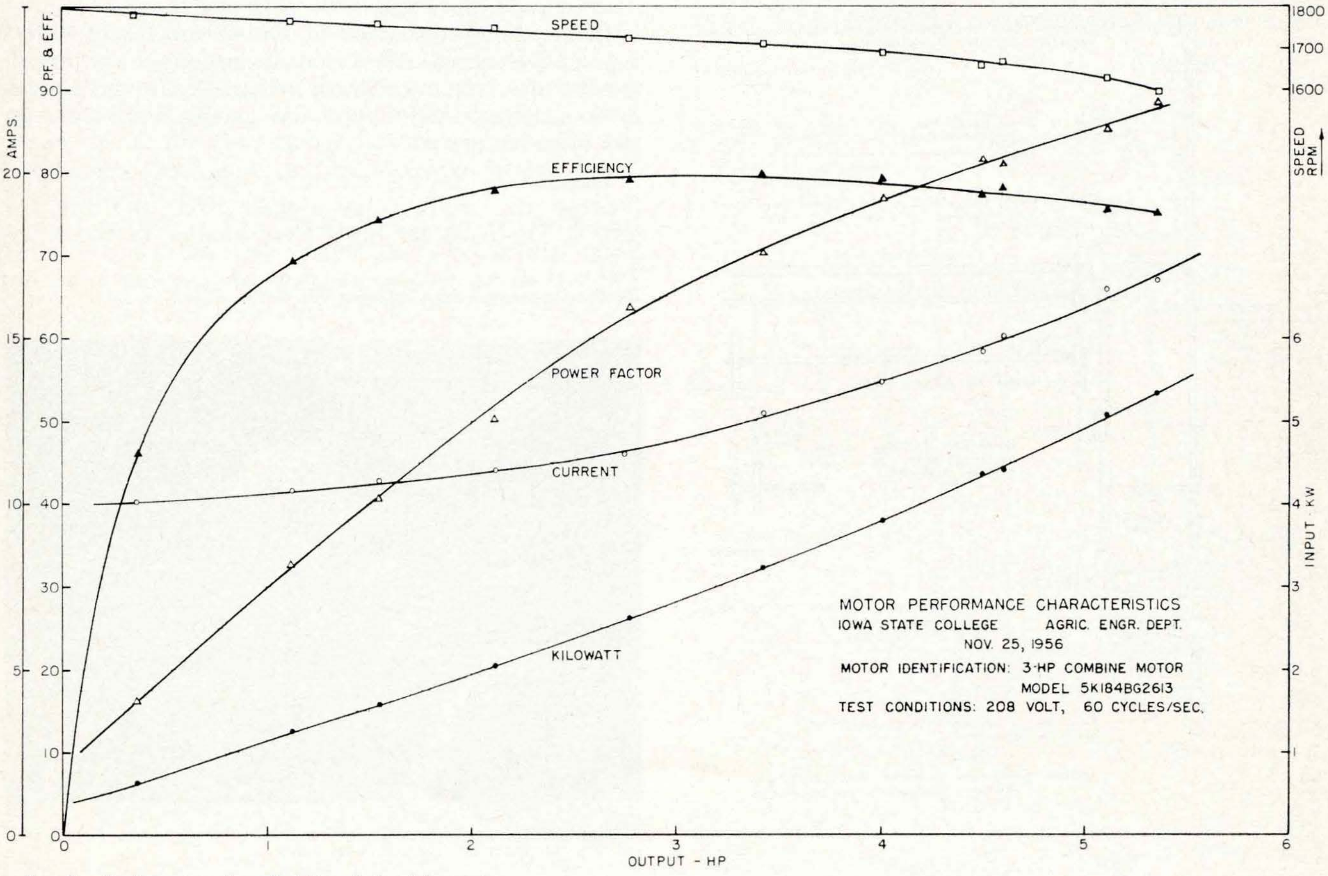

Fig. 5. Performance characteristics of the 3-hp motor.

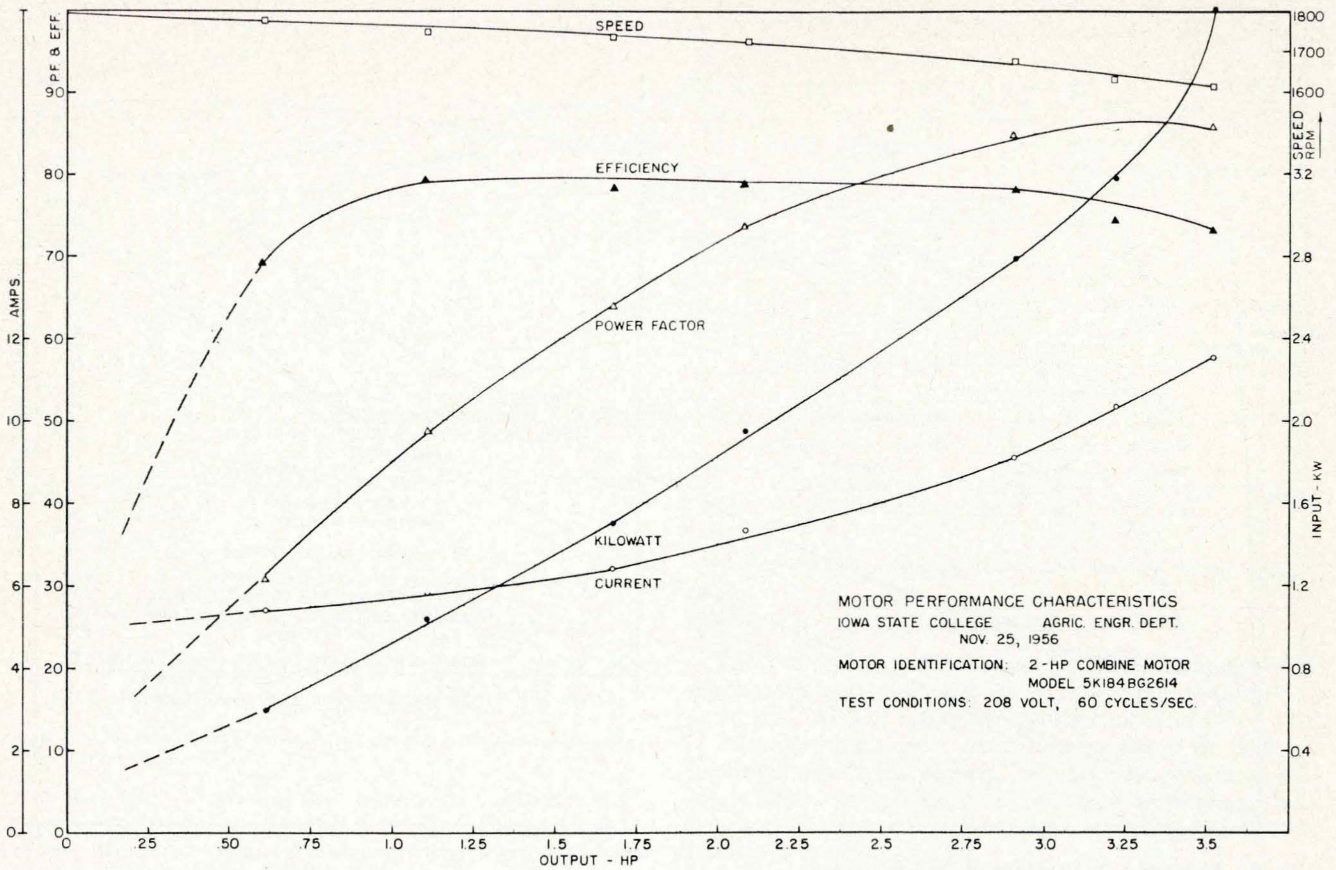

Fig. 6. Performance characteristics of the 2-hp motor.

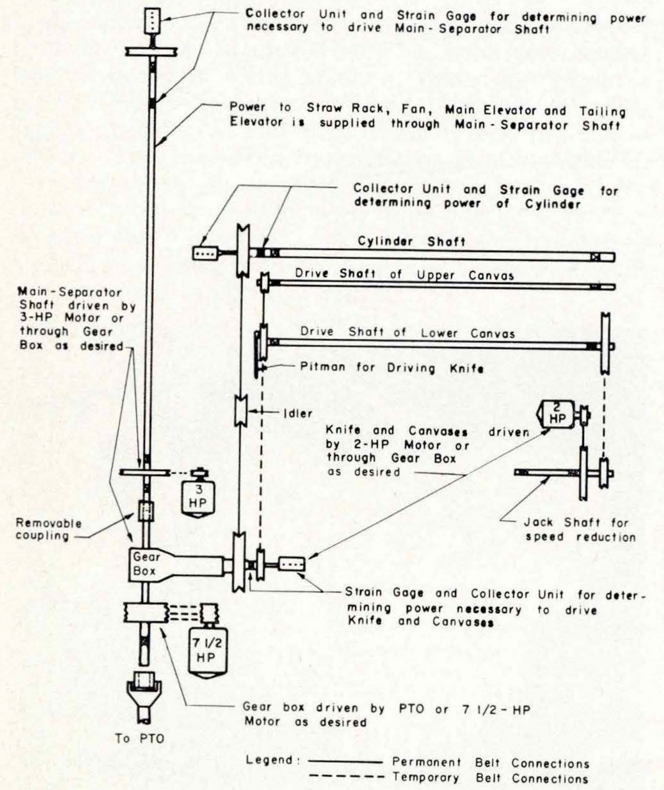

Fig. 7. Schematic representation of the drive combinations available on the combine.

with the theory discussed by Dobie and Isaacs.[4] SR-4 type C-7 electrical-resistance strain gauges were used for the main separator shaft and the knife and canvas drive shaft, and SR-4 type C-5 gauges were used on the cylinder shaft.

Mercury-bath collector units were used for conducting the strain-gauge signals from the rotating shafts. The collector units were similar to those de-

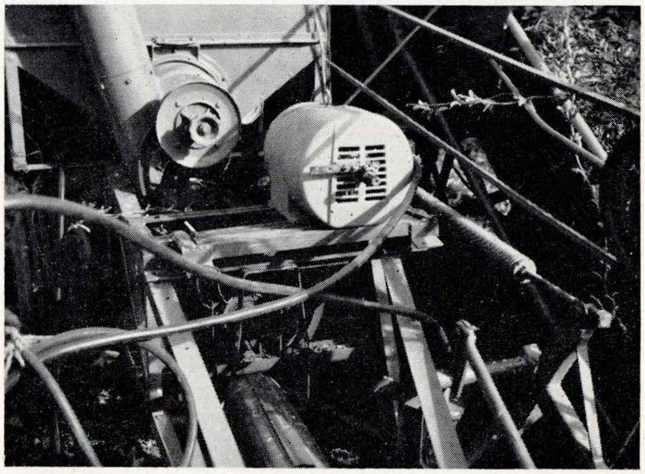

Fig. 8. The mounting and position of the 7.5-hp motor. Note pulley beneath the grain bin for the 3-hp motor.

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[4] W. B. Dobie and P. C. Isaacs. Electrical resistance strain gauges. The English University Press, Ltd., London. 1948.

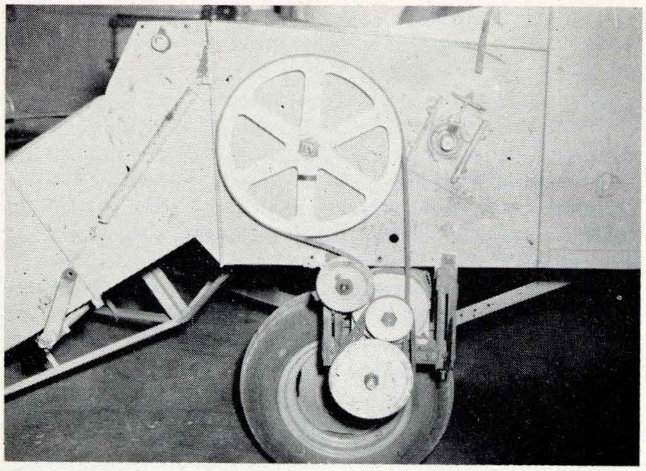

Fig. 9. The mounting and position of the 2-hp motor.

signed by Burrough.[5] A two-channel, Model-BL222, Brush oscillograph with two Model-BL320, Brush amplifiers was used for recording the signals. Each channel of the oscillograph was equipped with an event marker.

The instruments were carried in a special instrument trailer which bolted directly to the side of the combine as shown in fig. 10. A 110-volt, 60-cycle, DC generator was used as a power source for the instruments.

ELECTRICAL MEASUREMENTS

Two General Electric, strip-chart, 3-phase, recording wattmeters were used to record the power input to the motors. Chart speeds of 60 and 120 inches per minute were used. The charts for the wattmeters were driven by the 110-volt generator described. The paper drives for the strain-gauge equipment and the wattmeters were energized by the same switch which synchronized the charts.

An Esterline-Angus, spring motor-driven, recording voltmeter was used to record the electrical-coupling generator voltage. A paper speed of 0.2 of an inch per second was used in all the tests.

Fig. 10. Instrument trailer fastened to the side of the combine.

INSTRUMENT CONTROL CIRCUITS

One wattmeter was used for measuring the power input to the 7.5-hp motor at all times, with the other wattmeter used for measuring the power input to the 3-hp and 2-hp motors. With this in mind, the control circuit was designed as shown in fig. 11.

The power for the electrical coupling was brought in to the main switch. The main switch was used to de-energize the circuits to all motors in case of a short circuit. On the load side of the main switch, a circuit was established for each motor, and provisions were made for inserting current transformers into the circuit for use with the wattmeters. An off-on switch (A)[6] and shunting switches (B) were put in the circuit for the 7.5-hp motor. This permitted the motor to be turned off or on as desired and permitted the current coils of the wattmeter to be shunted when the motor was starting. Protection was provided for the 7.5-hp motor by three 30-amp, time-delay fuses.

For the 2- and 3-hp motors, a common wattmeter circuit was used. This prevented simultaneous power measurements; however, it did permit switching the wattmeter from one motor to the other while the trailer was in motion simply by the operation of two switches. An off-on switch (C) was used for energizing the common circuit and a selector switch (D) used for selecting the motor. The off-on switch permitted the meter to be shunted when the motors were being started. Power could be measured for either motor by diverting the current through the wattmeter

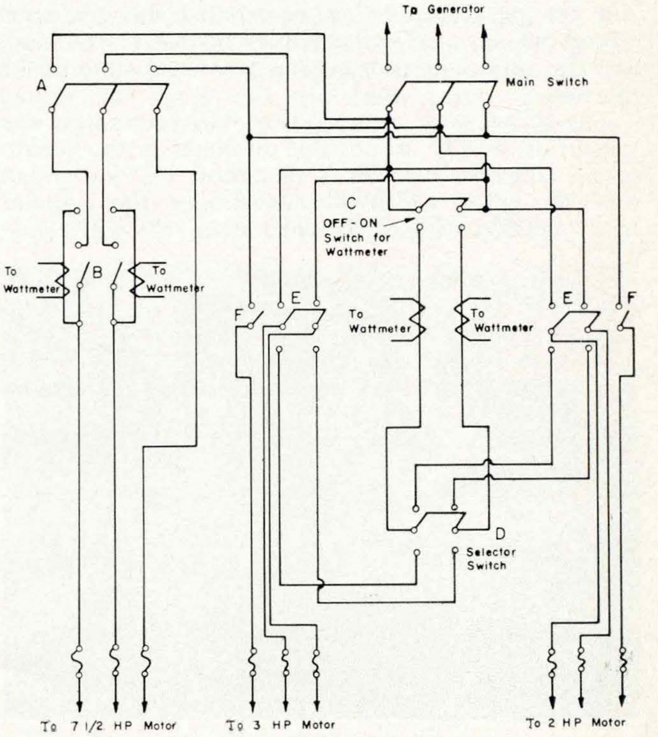

Fig. 11. Instrument and motor control circuits.

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[5] Burrough, D. E. Power and torque distribution in farm machine drive shafts. Agr. Engr. 34: 382-4. 1953.

[6] Letters refer to fig. 11.

circuit and making the appropriate selection with the selector switch. Note that the double-pole, double-throw switch (E) in the individual motor circuit was used to complete the circuit through the wattmeters. The single-pole, single-throw switch (F) in the individual motor circuit was used for breaking the third line when it was desired to cut the motor off without using the main switch. The 3-hp motor was fused with 16-amp, time-delay fuses, and the 2-hp motor was fused with 12-amp, time-delay fuses.

PROCEDURE

Six different tests were conducted on the electrical coupling and the combine performance. Each of these tests was designed for a specific purpose.

DESCRIPTION OF TESTS

Stationary load study: Because of the varying conditions in the field, a stationary loading study was set up whereby the combine could be fed by means of a conveyor belt as shown in fig. 12. The purpose of the test was to obtain data on the performance of the single-motor coupling, the multiple-motor couplings and the pto coupling at various load levels.

Four loading levels were selected for the study. The feed rates were: 75, 100, 125 and 150 pounds per minute. The conveyor always required 20 seconds to clear itself, and the feed rate was determined by the amount of material placed on the conveyor belt. Unthreshed wheat straw was used for the tests; therefore, the above weights included the weight of both straw and grain. The straw was dry and brittle.

Measurements were made of generator voltage, power input to the motors, and the speed and torque of the cylinder, main separator and canvas shafts. The tractor governor was set so that the generator would deliver rated voltage and frequency at no load, and the same governor setting was used throughout the test.

The straw was weighed for each run and was spread as evenly as possible throughout the length of the conveyor belt. Since the straw was not spread over the entire width of the cylinder, the cylinder load obtained with a particular feed rate was somewhat higher than the cylinder load obtained for the same feed rate when combining from a windrow in the field.

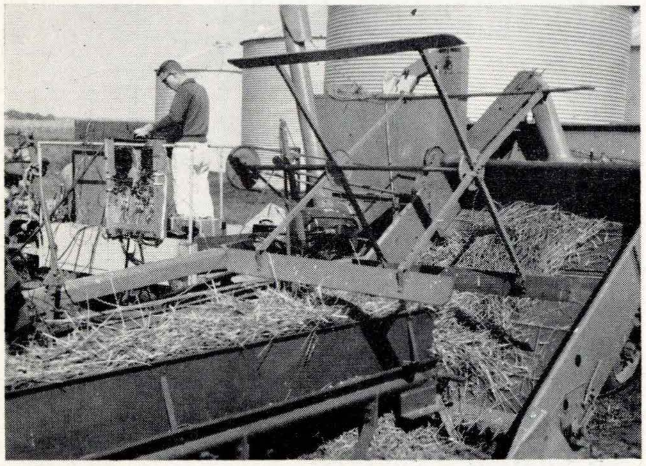

Fig. 12. Conveyor belt feeding of the combine in the stationary load study.

Slug Study: Tests were conducted to evaluate the performance of the electrical couplings and the pto under conditions of momentary overloads. This study was made in the field with windrowed oats. Particular attention was given to analyses of the cylinder speed during overload periods and the time necessary for the cylinder to regain its normal speed.

To clarify terminology, the following definitions are given:

—Slug: A mass of straw which causes an overload condition at the cylinder.

—Cylinder slugging: A condition in which the cylinder has received a slug but has not stopped.

—Cylinder jamming: A condition in which the cylinder is stopped because of an overload condition. This may be caused by a sustained overload or it may be caused by a very high momentary overload.

—Overloaded cylinder: A cylinder which receives a load of such intensity that the speed drops 5 percent or more.

—Slug density: A number indicating the number of windrows making up a slug.

—Slug length: The length of the slug in feet.

Slugs were created by superimposing additional windrows on the original windrow. The superimposed material was obtained from adjacent windrows and was placed on the original windrow by hand. Care was taken to place all material in the same manner as the original windrow so that the material would feed into the cylinder properly. All slug lengths were 10 feet, and the slugs were placed far enough apart to allow the coupling being tested to restore the machine to equilibrium before another slug entered.

The tractor governor was set to give a rated voltage and frequency. This resulted in a forward speed of 3 feet per second. The feed rate was 50 pounds per minute when combining a single windrow. This was a very light load, and the performance of all the couplings tested was satisfactory.

Slug densities of 2, 3, 4, 5, 6 and 8 were used in the study; however, only the results of the last two are discussed in this report. With a slug density of 6, the combine was alternately driven by the pto coupling, single-motor coupling and multiple-motor coupling (10.5-hp). The grain was very dry. With a slug density of 8, the combine was driven in turn by the pto coupling, multiple-motor coupling (10.5-hp) and multiple-motor coupling (12.5-hp). The grain was damp and tough. Measurements were made of generator voltage, power input to the motors and speed and torque of the cylinder and the main separator shafts.

The slug study was designed so that the slug duration would be approximately equal to slug durations encountered under field conditions. With the tractor speed of 3 feet per second, the slug entered the cylinder in 3.3 seconds; considerably more time was necessary, however, for the slug to clear the cylinder.

Load-analysis and performance study in windrowed wheat: Field tests were conducted to get an insight into the nature and magnitude of the loads under field conditions. The yield of the wheat was approximately 40 bushels per acre, and the stand was thick. An 8-foot swath was windrowed to get a good load on the cylinder. A forward speed of 3 feet per second gave a feed rate of 130 pounds per minute. Before cutting, the wheat was 3 to 4 feet tall.

The field was divided into 110-foot lengths. The 110-foot length windrow represented one-fiftieth of an acre and allowed ample time for the machine to return to equilibrium. Two replications were made for each drive combination. The strain-gauge instruments were not working properly in part of the tests, and part of the charts were of no value. As a result, only one good record on each coupling was available for analysis.

In conducting these studies, the combine was lined up with the windrow to be harvested, and the complete length of the windrow was harvested before the machine was stopped. With some of the electrical couplings, exceptions to this procedure occurred when the cylinder jammed before reaching the end of the plot, and it was necessary to stop and clear the cylinder. The instruments were turned on at the beginning of the run, and a complete record of the entire run was made.

Tests were made with the single-motor coupling, the multiple-motor coupling (10.5-hp), the multiple-motor coupling (12.5-hp) and the pto. Measurements were made of generator voltage, wattage input to motors, speed and torque for the three load centers. Field conditions are shown in fig. 13.

Load-analysis and performance study in soybeans: The study was conducted in a heavy growth of soybeans which were fully mature but not overly dry. Morning glory vines were present and entangled with the beans. Fig. 14 shows the condition of the crop and field.

The single-motor coupling, the multiple-motor (10.5 and 12.5-hp) couplings and the pto coupling were tested. It was necessary to operate the tractor at maximum governor setting to maintain the motor speeds. The pto coupling was also tested at maximum governor setting.

No attempt was made to lay out plots. The machine was driven down the row, and the instruments were turned on for a period of 5 to 10 seconds as the machine moved through the field. Ten of these intervals were recorded for each coupling, and the data were taken from these intervals. Measurements were made on power input to the 7.5-hp motor and the torque and speed for the component parts of the combine.

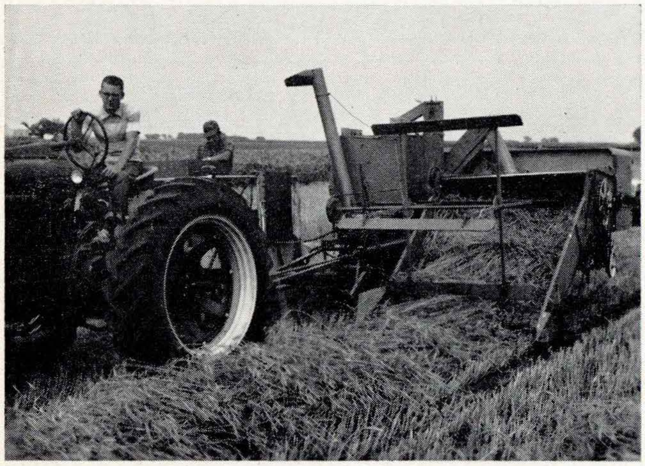

Fig. 13. Combining windrowed wheat.

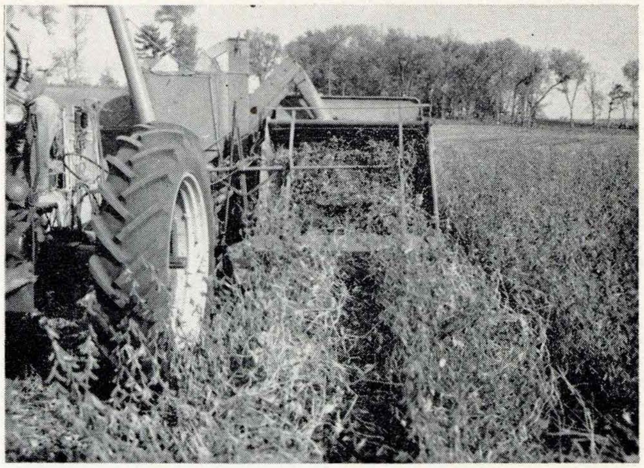

Fig. 14. Combining soybeans.

Laboratory study of power loss in the cylinder drive: A laboratory study was conducted to determine the drive efficiency of the cylinder drive. An AC generator was mounted on the combine and connected to the cylinder. A resistance load rack was used for loading the generator. This permitted loading the cylinder at the strain gauge up to 12 hp.

Power was supplied to the motor by a 220-volt, 60-cycle infinite bus. Power at the motor shaft was obtained by measuring motor input and using the kw input versus hp output curve for the motor. Power at the cylinder was determined from the speed and torque data taken with the strain gauge equipment. The formula used for calculating the drive efficiency was:

$$\text{Drive eff.} = \frac{\text{Hp at cylinder}}{\text{Hp at motor shaft}} \text{ x } 100$$

Laboratory study of the electrical coupling performance:

A laboratory experiment was set up to load the electrical coupling under conditions somewhat analogous to field conditions. The 7.5-hp motor was connected to an electric dynamometer so that it could be loaded as desired. To represent the other motors, a pure resistive load was used as shown in fig. 15.

Tests were conducted with resistive loads of 10 ohms and 22.5 ohms per phase. Since the voltage of the generator dropped as the load was increased, the resistive load also decreased. The resistive load of 10 ohms per phase was 3,000 watts when the generator voltage was 173 volts (line to line), and the 22.5 ohms per phase resistive load was 1,280 watts when the generator voltage was 170 volts.

The study was conducted with the same governor setting as used in the stationary load study. The gen-

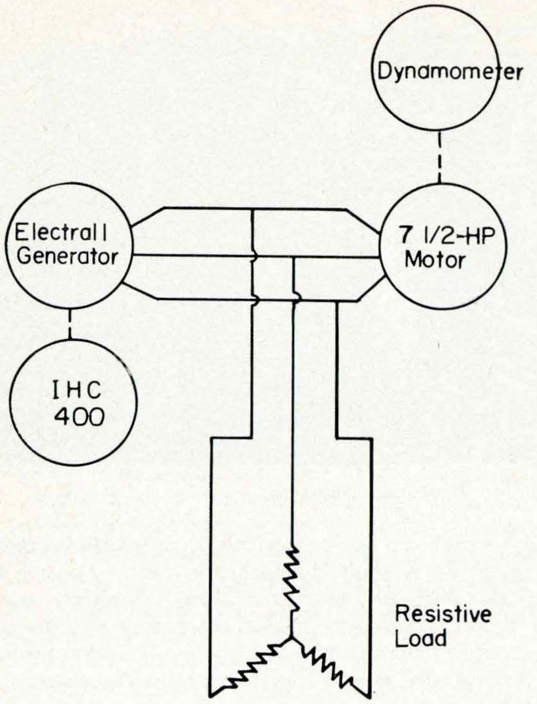

Fig. 15. Diagram of the laboratory loading of the electrical coupling.

erator voltage and frequency, motor input and speed and dynamometer hp were obtained from the tests.

DATA ANALYSIS

Two methods were used in the analysis of the strain-gauge charts. These were: stratified sampling of the charts for obtaining average load data and continuous analysis of the charts for studying the nature and magnitude of the loads.

In the stratified sampling, 10 readings were taken from each chart, and the mean of the 10 readings was used to represent the mean load of the particular unit being measured. The charts were divided into 15-centimeter sections, and 12.5 centimeters were sampled within each section as shown in fig. 16. The 12.5-centimeter sample of chart represented a time interval of 1 second. Since the chart was manufactured with lines 0.5 centimeters apart, this gave six possible starting points for the 12.5-centimeter length.

In the continuous sampling, the charts were divided into 12.5-centimeter lengths as shown in fig. 16. The area under the 12.5-centimeter trace was measured with a planimeter, and the mean torque determined from the area.

In determining the mean generator voltage and power input to the motors, the average ordinate was estimated by eye. Planimeter checks were made on several estimated readings, and close agreement was found.

RESULTS AND DISCUSSION

STATIONARY LOAD STUDY

Table 1 summarizes the results of the stationary load study. The means are the arithmetic means of 10 one-second observations. The data taken from operation with the pto may be considered to be the torque and power developed in response to load when an "unlimited" power supply was available.

With the pto the mean torque and power of the cylinder shaft increased with increasing load while the mean torque and power of the main separator shaft were not influenced by load. The standard deviations of the torque and power to the cylinder shaft are high, indicating a fluctuating load and an

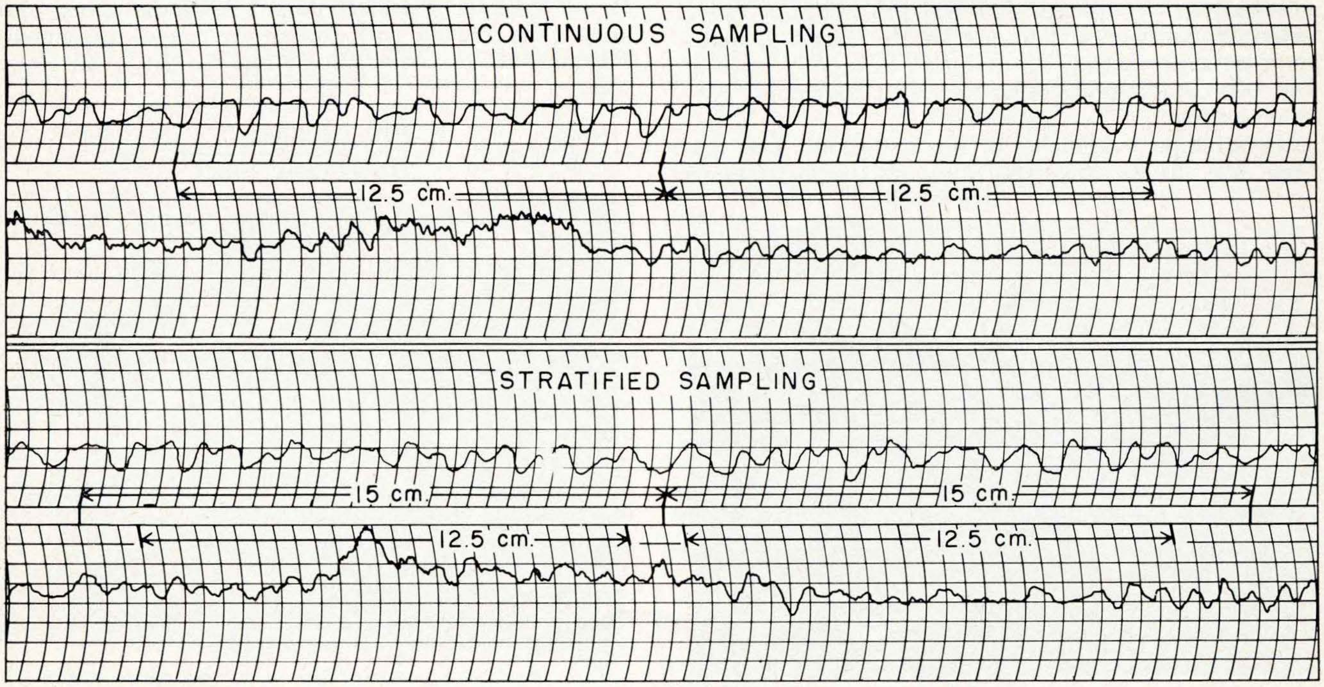

Fig. 16. Methods of sampling strain-gauge charts.

TABLE 1. SUMMARIZED RESULTS OF STATIONARY LOAD STUDY.

Coupling	Feed rate lb/min	Cylinder shaft						Main-separator shaft					
		Torque lb.-ft.		Speed rpm*		Power hp		Torque lb-ft		Speed rpm		Power hp	
		Mean†	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Pto	75	19.9	9.6	1,515	38.8	5.7	2.6	16.0	1.2	535	12.7	1.63	0.15
	100	23.5	10.0	1,522	24.3	6.8	2.9	16.0	1.3	542	11.0	1.65	0.16
	125	34.3	17.3	1,503	41.1	9.8	4.9	14.8	1.3	535	12.8	1.51	0.16
	150	36.3	22.0	1,490	50.5	10.3	5.9	. . .	. .	. . .	. . .	. . .	. . .
Single-motor	75	17.5	5.5	1,471	44.1	4.9	1.4	12.7	1.2	525	18.1	1.27	0.14
	100	16.9	7.7	1,465	73.2	4.7	1.8	. . .	. .	519	25.7	. . .	. . .
	125	25.7	7.6	1,435	62.2	7.0	1.9	13.3	1.7	509	21.2	1.29	0.34
	150	28.6	5.0	1,322	106.9	7.2	1.1	12.0	1.5	471	38.5	1.08	0.16
Multiple-motor 10.5-hp	75	19.4	6.5	1,499	42.1	5.6	1.7	16.4	0.7	575	8.4	1.80	0.09
	100	22.7	6.9	1,430	71.4	6.2	1.7	14.8	1.0	564	11.6	1.58	0.13
	125	27.7	9.9	1,330	131.1	7.0	2.2	15.0	1.3	551	26.0	1.58	0.19
	150	27.3	10.8	1,301	377.2	7.8	2.6	13.4	1.2	548	52.4	1.40	0.19
Multiple-motor 12.5-hp	75	19.4	7.0	1,464	49.2	5.4	1.7	. . .	. .	570	13.5	. . .	. . .
	100	25.6	7.9	1,433	73.4	7.0	1.9	16.8	1.6	562	14.3	1.80	0.20
	125	26.1	7.7	1,399	100.8	7.0	1.6	17.0	1.0	558	15.4	1.80	0.14
	150	33.6	6.3	1,142	170.9	7.3	2.1	17.1	0.8	532	19.4	1.73	0.12

* No-load speed for pto, 1,520 rpm, for electrical drives, 1,500 rpm.
† Each figure is the mean of 10 one-second observations.

ability of the power train to respond to these fluctuations. The speed of the cylinder shaft remained relatively constant as indicated by the minor decrease in speed with increasing load and the low standard deviations of the speeds.

Under the various electrical couplings, the torques and powers developed at the cylinder shaft under the higher feed rates were lower than developed with the pto under the same feed rates. The standard deviations of torque and power were also lower than for the pto indicating the electrical coupling's inability to respond to fluctuating loads. Under higher loads, the electrical coupling's speed dropped substantially and the standard deviations of speed were relatively high and increased with increased load, indicating the poor ability of the electrical coupling to maintain a constant speed.

The time variations of speed, torque and power at the cylinder for typical stationary load tests with three different couplings at a 150-pound-per-minute feed rate are given in fig. 17. The 1-second point was about the time the material started entering the cylinder. The torque plot for the pto in fig. 17 indicates that the load pattern of the cylinder is very irregular. For example, the torque at the 3-second point is only 7.8 pound-feet; however, at the 5- and 6-second points, the torque is approximately 45 pound-feet. This same general relationship is noted throughout the trace.

The performance of the pto coupling was satisfactory although the cylinder load was characterized by high peak overloads. The plot of the speed in fig. 17 shows that the pto coupling maintained the cylinder speed at a high level during the entire run. Although the speed dropped to slightly less than 1,400 rpm at the 13-second point, the speed recovery was very rapid. The pto coupling is a rigid connection between the engine drive shaft and the load; therefore, the tractor responds quickly to any increase in load. The governor response is fast during a load increase, and the tractor begins to restore the coupling to a state of equilibrium immediately.

The ability of the pto coupling to maintain the cylinder speed allows the cylinder to pulverize a mass of straw very quickly. This results in keeping the cylinder's threshing ability at a high level during peak overload periods.

The inability of the electrical couplings tested to maintain the speed at the cylinder is evident from the cylinder speed versus time curves in fig. 17. This can be checked by inspecting the 2-, 3- and 4-second points of the multiple-motor records. Between points 2 and 3 and between points 3 and 4, the torque increased; however, the speed decreased enough to offset the torque increase and this resulted in practically no change in power at the cylinder. At the 4-second point, the speed dropped to such an extent that the electrical coupling was no longer an efficient means of power transmission. The wattmeter and voltage data for this test showed that the motor input averaged over 14,000 watts and the generator voltage averaged about 170 volts for remainder of the run. At high slips and low voltages the motor current is abnormally high, and the motor dissipates the input as heat instead of converting it to mechanical energy.

Between the 4- and 8-second points in fig. 17, the multiple-motor coupling was very slow in restoring cylinder speed. To further aggravate the situation, at reduced cylinder speeds the cylinder lost its ability to thresh the grain from the straw and to push the straw through the cylinder. Because the material was not pushed on through the cylinder while still more material entered the cylinder, the duration of the overload condition was prolonged. Between the 4- and 8-second points the majority of the power at the cylinder was used to overcome the friction of the packed material.

Since a prolonged overload condition prevented the coupling from restoring the cylinder speed, the next slug at the 9-second point put the coupling into an even more inefficient state. At the 10-second point the cylinder speed dropped so markedly that the coupling delivered only 4 horsepower to the cylinder. The motor was very close to pull-out torque and an unstable condition. Although the motor continued to lug the load, any additional load probably would have succeeded in stopping the motor.

The plots for the single-motor coupling show that

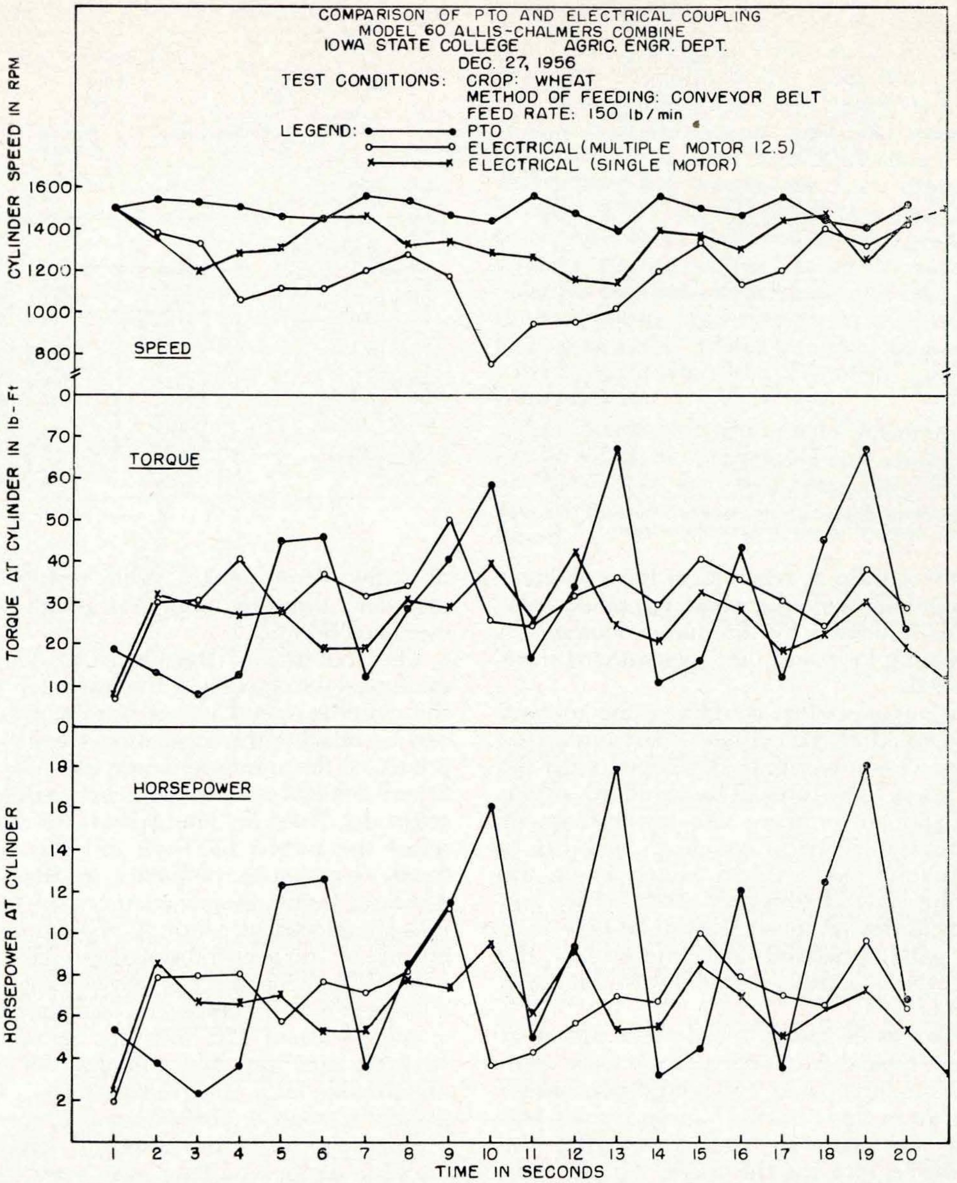

Fig. 17. Comparison of pto and electrical couplings at a feed rate of 150 pounds of wheat per minute.

the torques the single-motor coupling and the multiple-motor coupling delivered to the cylinder were practically the same during the first 4 seconds except at the 4-second point. Figure 17 shows that the load for the single-motor coupling leveled off and allowed the coupling to restore cylinder speed before the second slug entered the cylinder.

The difference in the performance of the single-motor and the multiple-motor couplings can be explained by the sequence of events during the first 5 seconds of the run. Figure 17 shows that at the 1-, 2- and 3-second points of the runs very little difference existed between the torque plots for the two couplings. The cylinder speed of the multiple-motor coupling, however, was higher at the 3-second point than the cylinder speed for the single-motor coupling, and consequently the cylinder power for the multiple-motor coupling at the 3-second point was greater than the cylinder power for the single-motor coupling. This indicates that with the same load pattern, the single-motor coupling was forced to absorb more energy from the flywheel action of its drives than the multiple-motor coupling. The same general relationships existed between the 18- and 19-second points.

From these studies, it was concluded that the sequence of events which takes place in a relatively short time determines the performance of the electrical coupling. If the electrical coupling is to be successful, it must maintain the cylinder speed at a high level during slugging conditions. Merely because the cylinder does not jam is no indication that the performance of the coupling is satisfactory.

SLUG STUDY

Figures 18 and 19 show how the couplings responded to several typical slugs. The material presented in the graphs represents two different slug densities, and each will be discussed separately.

The various plots in fig. 18 show that for a slug of a given density the duration of the overload period was considerably shorter with the pto coupling than with the electrical couplings. The speed and torque plots follow the same general pattern for all couplings during the first 3 seconds. At the 3-second point, cylinder power was approximately the same for all drives, and the cylinder speed for both electrical couplings was lower than the cylinder speed for the pto coupling. The inability of the electrical couplings to push the material on through the cylinder is evident in the duration of the slug. The duration of the overload period was prolonged unless the drive could deliver sufficient power to the cylinder to maintain the cylinder speed during an overload period.

During a prolonged overload period, the cylinder may continue to lose speed or it may begin to increase speed depending upon how the material continues to enter the cylinder. If there is a discontinuity in the feed flow or if the feed rate is reduced, the coupling begins to restore the cylinder speed as shown in the plot of the multiple-motor coupling (10.5-hp) at the 5-, 6- and 7-second points. But if the material continues to feed in at the same rate, the coupling continues to let the cylinder speed drop as shown in the plot of the single-motor coupling at the 5-, 6-, 7- and 8-second points. In either case, the overload period is prolonged, and the possibility of the cylinder jamming is always present. The field data which are presented later indicate that slugging conditions similar to these actually occur during normal combining operations.

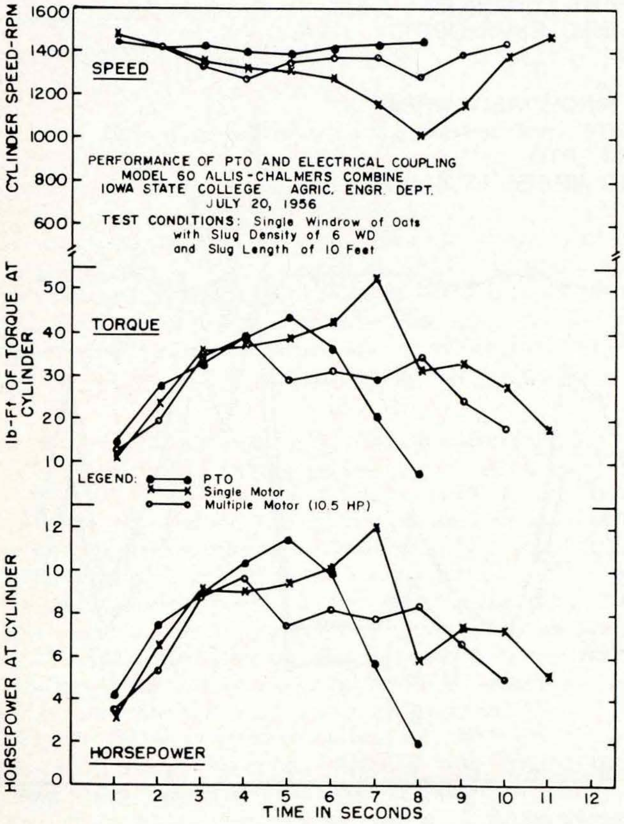

Fig. 18. Performance of the pto, single-motor coupling and the multiple-motor coupling (10.5-hp) under slugging conditions.

Figure 19 compares the performance of the multiple-motor (12.5-hp) coupling for two different slugs of the same density. The torque increased very rapidly during the first second of slug 2 while cylinder speed decreased very rapidly. Although the torque remained practically constant between the 2- and 5-second points, the speed continued to drop and resulted in a gradual decrease in the power at the cylinder. For slug 1, the torque increased less rapidly and the cylinder speed decreased less rapidly. As a result, more power was delivered to the cylinder during slug 1 than during slug 2 for the entire plot. If the load increases gradually and allows enough time for the governor to respond, the electrical coupling maintains its speed much better than if the load increases rapidly. In the case of a rapid increase in load, the tractor does not start to respond to the overload until after the coupling is in an inefficient condition. Then the tractor has a very difficult time restoring the coupling to a state of equilibrium.

In presently designed combines, the slugging action under normal combining operations does not lend itself to the electric drive. Part of the slugging in field operations is due to uneven feeding, and the rapid load increases often result in jamming the cylinder when electrical couplings are used.

LOAD-ANALYSIS AND PERFORMANCE STUDY IN WINDROWED WHEAT

In both the stationary load and the slug studies,

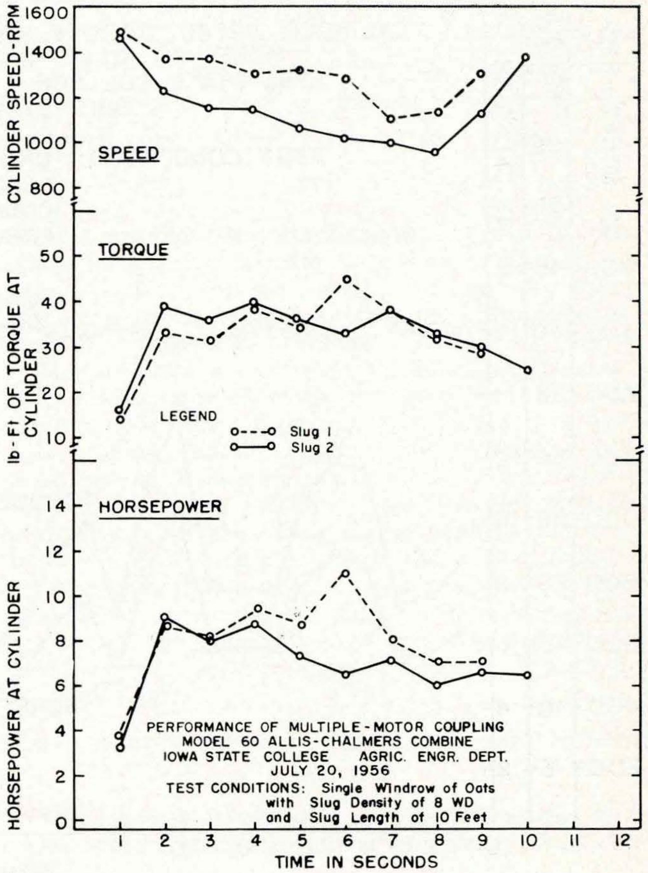

Fig. 19. Performance of the multiple-motor coupling (12.5-hp) under slugging conditions.

attempts were made to set up various load levels and high momentary overload periods. While these two studies did not represent field conditions, a study of field data revealed some striking similarities.

The average load levels of the cylinder in windrowed wheat ranged from 6.26 to 8.38 hp. The power demand of the feeding mechanism was only a small portion of the combine load and remained practically constant.

Figure 20 shows the performance of the pto coupling in windrowed wheat. The load was far from being constant and was characterized by great variations. The torque and power demands of the cylinder increased very rapidly at the beginning of a peak. There was also evidence that the peak loads were caused by uneven feeding of the cylinder. It is particularly evident that, during the period between 25 and 28 seconds, very little material was entering the cylinder because the load was very light. The interval between 28 and 32 seconds indicates a period of very high feed rate. The same evidence of uneven feeding can also be noted in the other peak periods.

Observations indicated that the uneven feeding was due to the material slipping on the canvas and to the "grabbing" action of the cylinder. The slipping of the material on the canvas caused the material to bunch into large masses. Once the mass of material started to enter the cylinder, the "grabbing" action pulled the complete mass of the material into the cylinder. Some "grabbing" by the cylinder is necessary for continuous feed flow when the material is not bunching. Other possible causes of peak overloads are green weeds, damp straw or old stubble; however, none of these conditions were responsible for the peak overloads in the study being discussed.

With the nature and magnitude of the cylinder demands established for this particular study, it is interesting to study their effect on the electrical coupling. The voltage charts in fig. 21 indicate the effect of peak overloads on the electrical system. The peak overloads resulted in lowering the voltage on the generator. Of the several high momentary overload periods plotted on the chart, points A and B on the multiple-motor coupling and point C on the single-motor coupling are the most severe. The voltage variations on the multiple-motor chart are more extreme than on the single-motor chart. Since the multiple-motor coupling had more motor capacity than the single-motor coupling, the generator was much more likely to become overloaded during peak loads when using the multiple-motor coupling.

Near the end of both traces the cylinder jammed, and the generator was cut off. Note that in both cases, the voltage was reduced to nearly 160 volts at the time of jamming. At points A, B and C the voltage was reduced to approximately 180 volts, and the system was very near to being unstable. Any additional load at either of these points probably would have jammed the cylinder.

From the load-analysis and performance study on

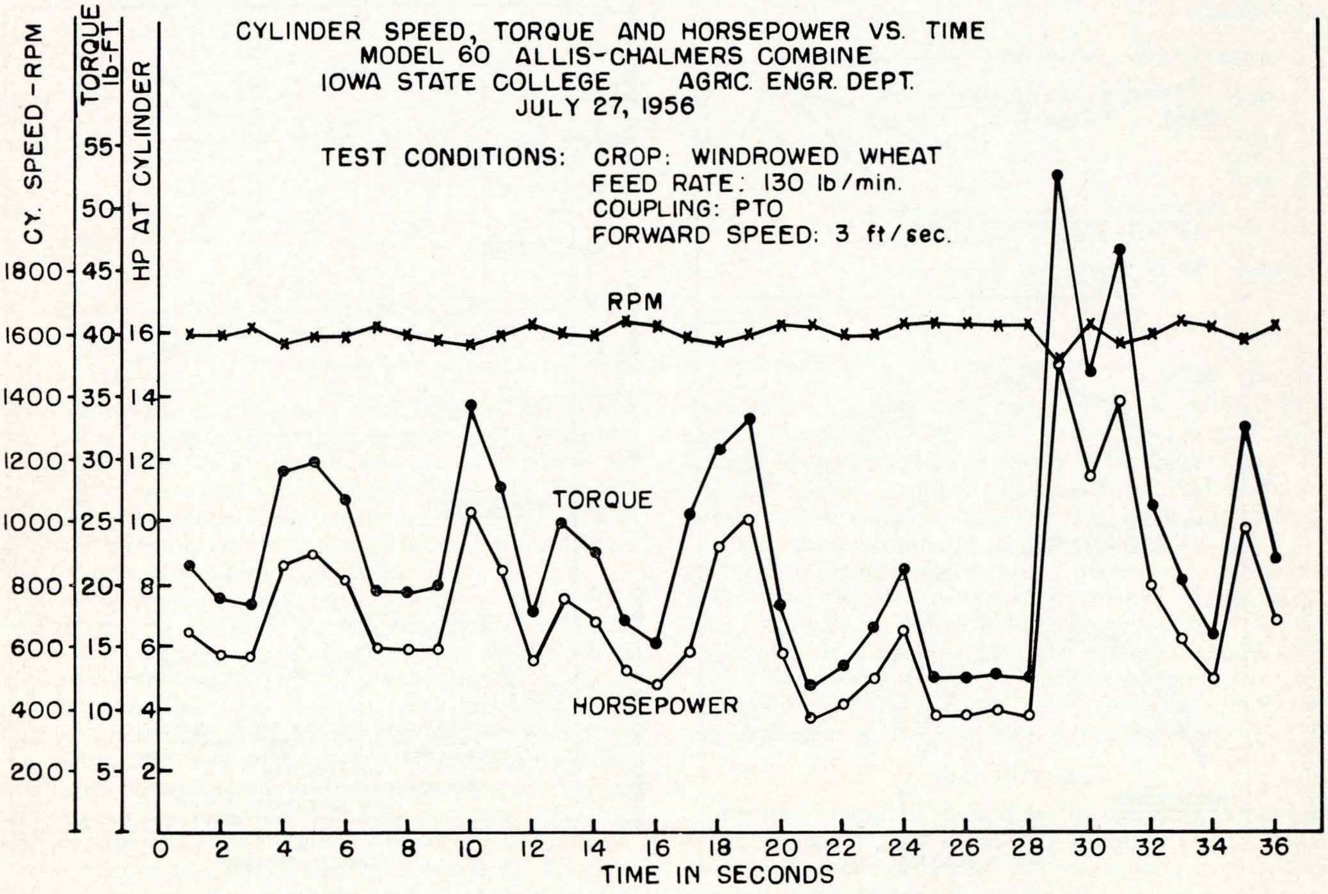

Fig. 20. Cylinder speed, torque and power versus time when combining windrowed wheat with pto coupling.

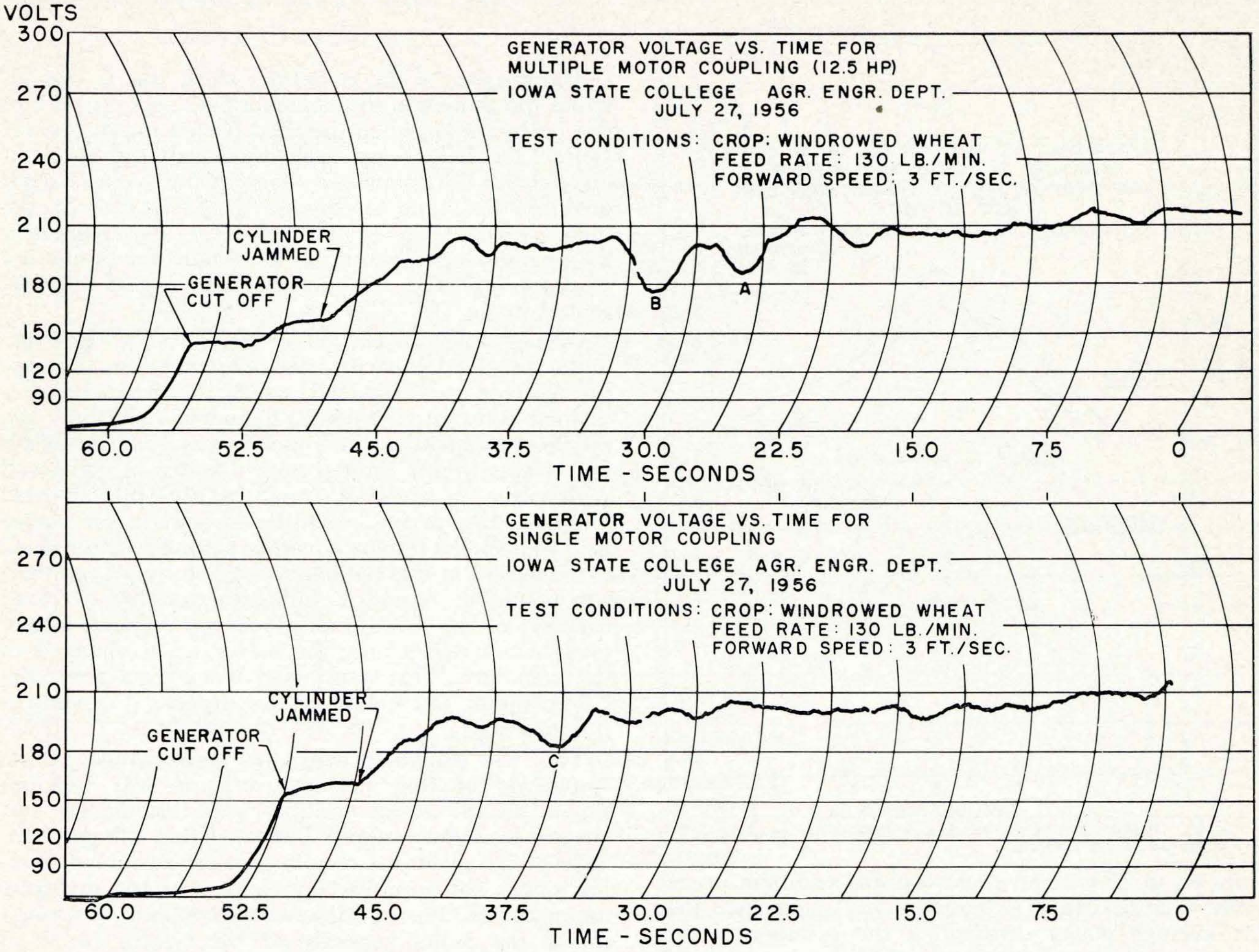

Fig. 21. Effect of high momentary overloads on generator voltage.

windrowed wheat, it was concluded that the cylinder load is characterized by high peak overloads. The pto coupling is able to carry through these peaks. The electrical coupling is not a rigid coupling and does not always have the ability to carry through the peak overload periods. These results again point up the necessity of considering the machine design as well as the electrical design aspects of the problem.

Load-Analysis and Performance Study in Soybeans

Figure 22 shows the performance of the pto coupling and the multiple-motor coupling (12.5-hp) during typical overload periods in soybeans. With the reduced cylinder speed (300 to 500 rpm for the combine used) necessary for combining soybeans as compared with wheat or oats, the flywheel action of the cylinder is less effective, and cylinder jamming is much more likely during a sudden overload.

Figure 23 shows the variation of the power demands of the 7.5-hp motor when it was driving the entire machine and when it was driving the cylinder alone. A comparison of the two demand charts shows that the cylinder is the controlling factor. The top chart shows that the demands of the cylinder drive are characterized by extreme variations. Although the variations in the motor demands are not as extreme when the single motor is driving the entire machine, they are nevertheless present.

Another point worth noting in comparing the charts is the difference between the profile of the peak periods. With the 7.5-hp motor driving the cylinder only (multiple-motor coupling), the duration of the peak periods is less than when the 7.5-hp motor is driving the entire machine. This indicates that the performance of the electrical coupling is improved by the use of multiple motors. Since the multiple-motor coupling had a greater motor capacity, it operated in a more efficient state during the overload (provided the generator was not overloaded) and consequently was able to push material through the cylinder faster.

Laboratory Study of Power Loss in the Cylinder Drive

This study was conducted to determine the drive efficiency of the cylinder drive at different load conditions.

As can be seen in fig. 24, the drive efficiency varies

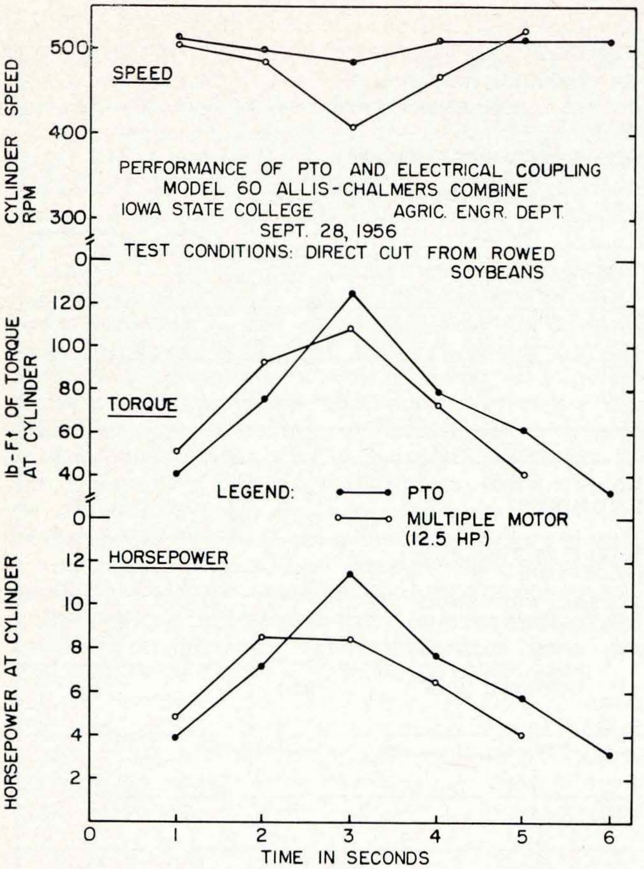

Fig. 22. Performance of the pto and multiple-motor coupling (12.5-hp) when combining soybeans.

from 65 to 75 percent under normal combine operations. This statement is based on the assumption that the average power demand of the cylinder of this combine in most operations would be between 5.5 and 12 horsepower depending upon the crop and crop conditions. The drive included the V-belt connection from the motor, the gear box and a second V-belt connection (see fig. 7).

Assuming that the power loss in the universal joints of the pto is the same as the power loss in the V-belt drive connecting the motor to the combine, fig. 24 also represents the drive losses of the combine when the pto is driving the machine.

Although no data are available on drive efficiency to the other load centers, it should be noted that the power train (when driven from a central drive) is essentially the same as that for the cylinder drive. Thus, it is concluded that the total drive losses in the machine represent 25 to 35 percent of the total power transfer. The average efficiency is probably around 70 percent.

The high drive losses characterizing presently designed combines make it imperative that the combine be redesigned to eliminate some of these losses if the electrical couplings are to be satisfactory. An efficiency of 65 to 70 percent can be expected from the electrical coupling. Decentralization of drives could put the electrical coupling on a competitive basis with the mechanical coupling so far as losses are concerned, and at the same time offer many possibilities for machine simplification.

Laboratory Study of the Electrical Coupling Under High Overloads

The purpose of the laboratory study was to demonstrate the reduction in maximum overload capacity of the 7.5-hp motor when supplied from a limited power source. The loads were applied gradually by means of an electric dynamometer; consequently, the tractor governor had time to respond to the load when the motor was driven by the generator. Approximately 25 seconds were required to obtain the necessary readings for each data point. These results are presented in fig. 25.

Curves A, B, C and D in fig. 25 show that the motor overload capacity was reduced when the supply voltage was reduced while the frequency remained constant. Curves E, F and G show how the overload capacity of the motor was reduced when power was from a limited power source as compared with curve A which is from the 208-volt, 60-cycle building supply (an "unlimited source"). For curves E, F and G, the tractor governor setting was the same as that used in the stationary load study. A comparison of curves A and E indicates that the overload capacity of the 7.5-hp motor was not reduced to any great extent when only the motor was connected to the generator. This shows that when used alone the 7.5-hp motor did not have the capacity to overload the generator.

This test explained why the performance of the electrical coupling during overloads was not improved by the use of multiple-motor drives. The stationary load study results indicated that the performance of the electrical coupling under sustained overloads was not improved by the use of the multiple-motor drives. The multiple-motor coupling (12.5-hp) raised the motor capacity of the system from 7.5 to 12.5 hp. If the motors were supplied from an infinite bus, the overload capacity of the coupling would be increased by the same ratio as the motor capacity. In the stationary load study, the addition of the 2- and 3-hp motors acted like the additional resistance load. Since the generator output was limited, the addition of the resistive load or of the other motors overloaded the generator.

DESIGN RECOMMENDATIONS

The success of the electrical coupling depends not only upon proper electrical design but also upon proper mechanical design. Both the electrical system and the field machine designs must be such that the two complement each other. The design of the electrical system must be based on a study of the load characteristics of the farm machine, while the design of the farm machine must lend itself to the application of electrical couplings.

Simplification of the power train is a necessity on such machines as combines. The losses in the various drive mechanisms represent 25 to 35 percent of the total power transfer on many presently designed combines. Through decentralization of the drives and the use of multiple-motor couplings, part of the drive losses can be eliminated. This would put the over-all

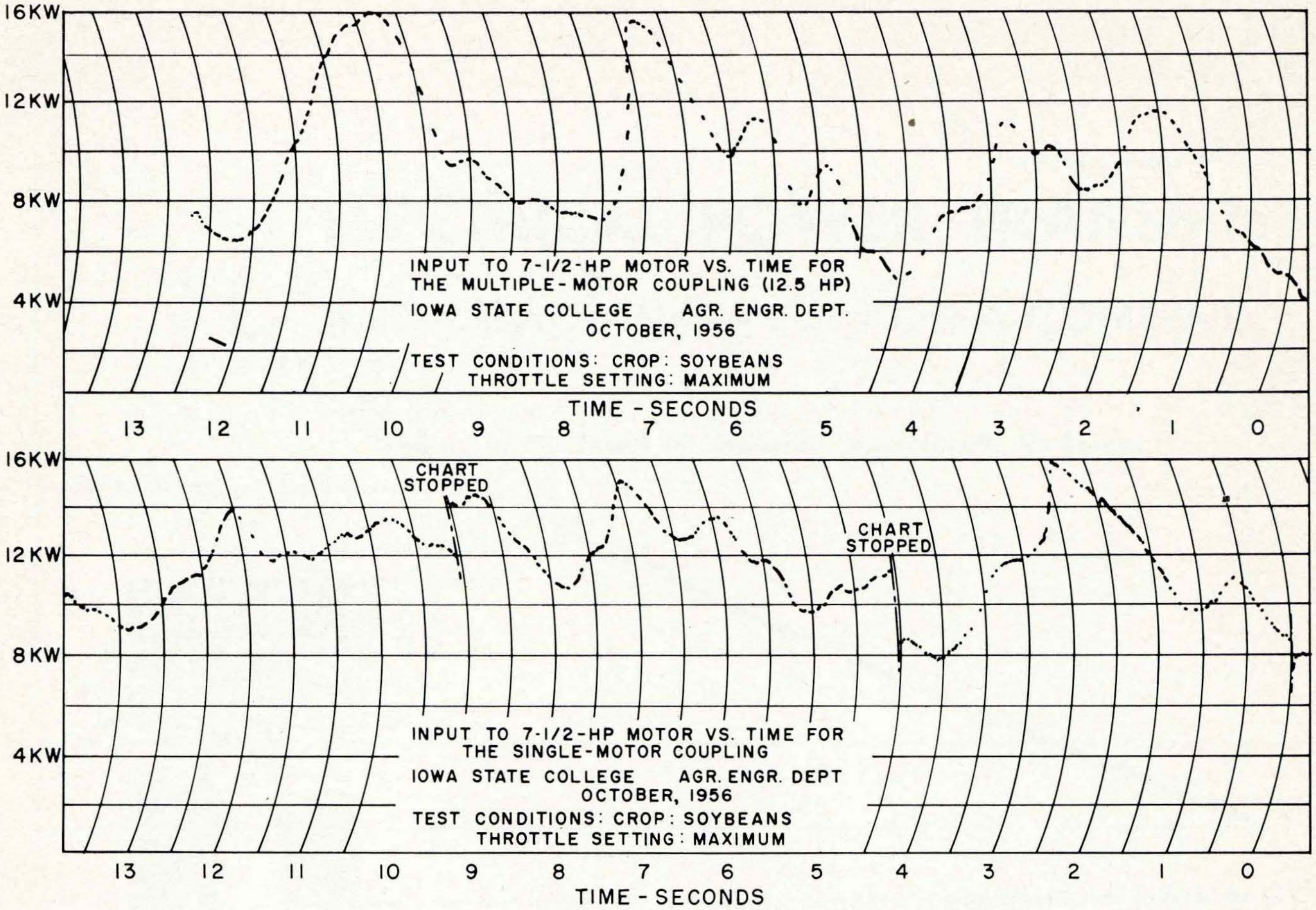

Fig. 23. Variation of the power demand for the 7.5-hp motor when driving the entire machine and when driving the cylinder alone.

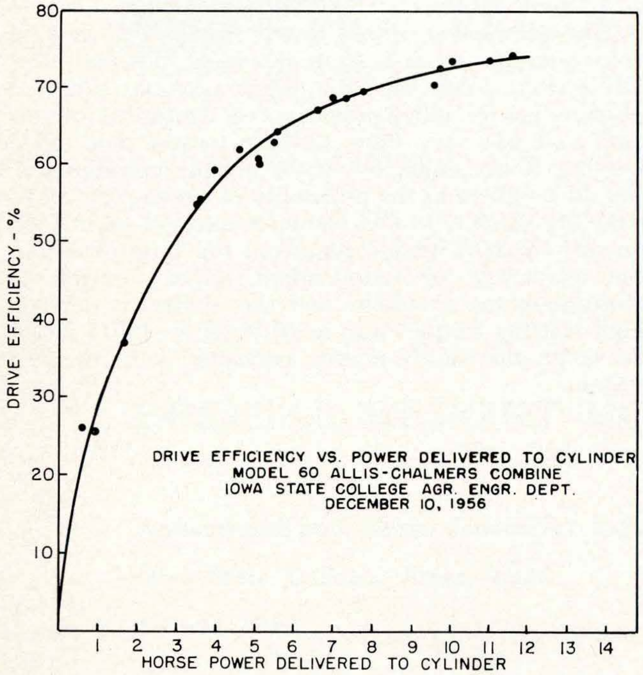

Fig. 24. Drive efficiency of the cylinder drive versus power delivered to the cylinder.

efficiency of the electrical coupling on a competitive basis with the pto coupling.

On machines which have great load fluctuations, the addition of a flywheel will improve the operation of an electrical coupling. Adding a properly designed flywheel would permit the electrical coupling to operate at a higher level of efficiency during the overload periods. The possibility of reaching an unstable condition would be greatly reduced.

Farm machinery design must insure that the feed rate will be as even as possible. Irregular feeding is a major cause of peak overloads on such machines as combines. The nature of the peak loads caused by uneven feeding is detrimental to the performance of an electrical coupling. The increase in load occurs very rapidly and often results in the electrical coupling reaching an inefficient state before the tractor engine has had time to respond.

When designing an electrical system, special consideration must be given to the design of the magnetic circuit of the generator. Since the generator size is limited, the generator also will be subjected to high peak overload periods. The magnetic circuit must be designed with sufficient capacity to permit the voltage regulator to correct for the IR voltage drop and the drop because of armature reaction. Saturation of the magnetic circuit during overloads results in re-

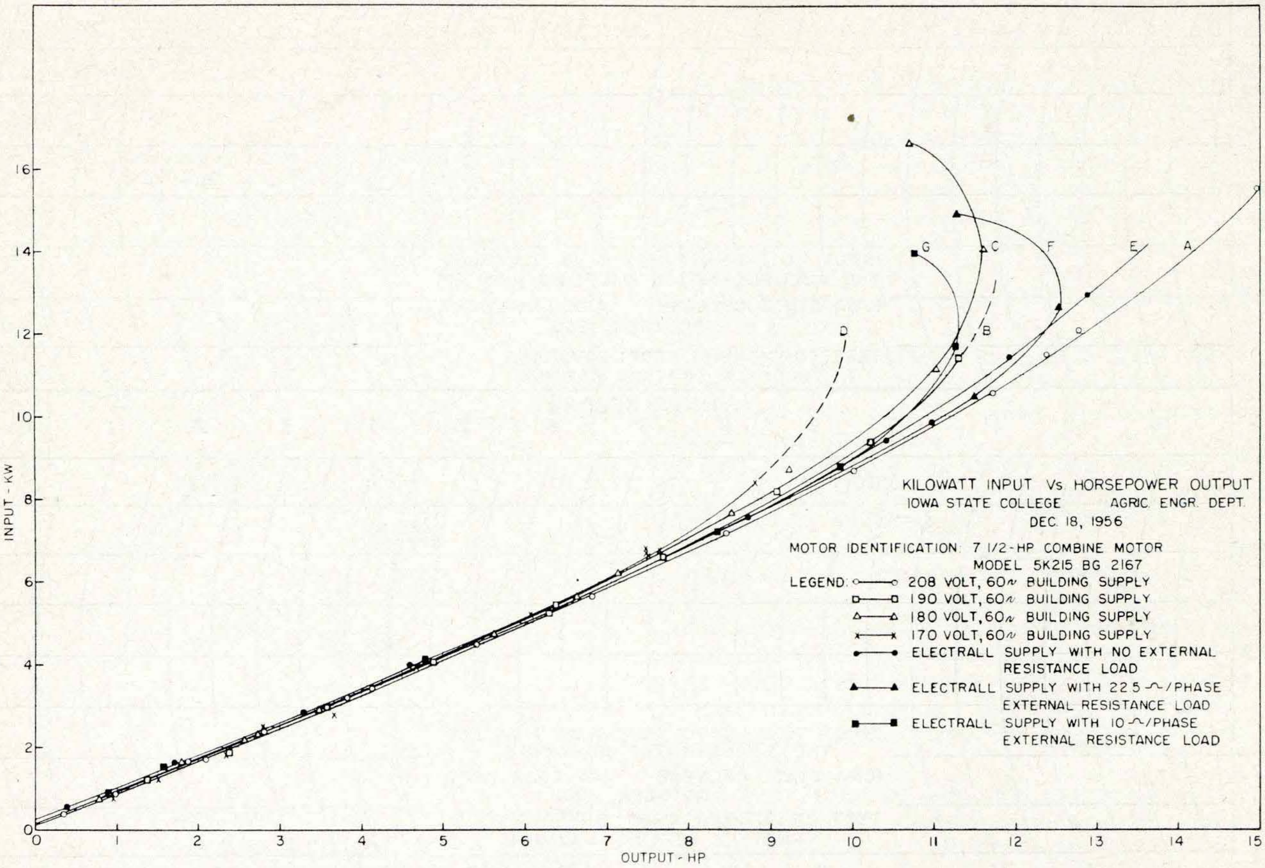

Fig. 25. Kilowatt input versus horsepower output for the 7.5-hp motor when supplied from various power sources.

ducing the effectiveness of the voltage regulator.

The tractor governor should be controlled by a frequency sensing device to maintain the frequency of the generator output. The flyball-type governors used on tractors make it necessary for the tractor engine to slow down before the throttle is adjusted. This lowers the frequency output of the generator and consequently the base speed of the motors. The reduction in generator speed also has a tendency to offset the effect of the voltage regulator. If the generator were driven at a constant speed, the electrical coupling would maintain the speed of the driven machine at a much higher level.

If motor loads were smoothed out by flywheel action and uniform feeding and if generator frequency were maintained, motor selection could be based on average power demands instead of on the peak demands of a load center. This would insure more efficient power transfer through the electrical coupling and would improve its over-all performance.

The electrical coupling tested was an AC system; consequently, no discussion has been devoted to a DC system. Since the DC system provides excellent possibilities for independent speed control of motors and also has very high starting torques and good lugging ability under overloads, further consideration should be given to the possibility of developing a DC coupling. A straight DC system would not permit the use of standard motors found on the farmstead, but the advantage of independent motor control on multiple-motor couplings and the ability to develop high starting torques and good lugging ability might outweigh the disadvantages associated with the DC system.