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INTERIM REPORT
BRUSHLESS DC MOTOR

November 1970

Contract No. NAS8-26213

Contractor:
General Electric Company
Avionic Controls Department
P. O. Box 5000
Binghamton, New York

Contracting Officer:
National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

Prepared by:
B. H. Hertzendorf

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FOREWORD

This report was prepared by the General Electric Company, Avionic Controls Department, Binghamton, New York, on Contract NAS8-26213 administered under the direction of the National Aeronautics and Space Administration, Marshall Space Flight Center.

This is an interim report covering the 5-month period of June 1970 to November 1970 summarizing the work performed in the design, development, fabrication, and testing of two 5.0-ft-lb brushless dc motors. A final report, summarizing the work performed in the design and fabrication of a roller gear transmission that will be driven by a brushless motor, will be issued in February 1971.

The work was a group effort with the following principle contributors and their field of effort: B. H. Hertzendorf, Project Engineer, Dr. E. W. Manteuffel, Chief Consultant, F. F. Palumbo, Motor Assembly and Test, and E. J. Parker, Designer. The program manager is G. F. Auclair.

Section 1

INTRODUCTION AND SUMMARY

INTRODUCTION

This report summarizes the work performed on contract NAS8-26213 through November 19, 1970. This contract covered the design, fabrication and functional testing of two brushless dc motors. The motors have split windings which can be connected in either a full-winding or a 1/4-winding configuration. The motors provide up to 5.0 ft-lbs output torque at speeds up to 435 rpm with the full-winding. With the 1/4-winding the motors will operate at 1.25 ft-lbs and at speeds up to 1740 rpm. The motor design has been optimized for operation in the 1/4-winding condition.

SUMMARY

A summary of the brushless dc motor specifications, along with the actual test results are presented in Table 1. The test results shown are the average values for the two motors. Test data for each motor are given in Section 4. The motor meets all the contractual requirements as shown by the data in Table 1.

Figure 1 is a photograph showing the components of the motor and Figure 2 shows the motor and test fixture mounted on the test stand. The performance tests were conducted with the motor mounted in the test fixture. Table 2 shows a summary of the average values of all the motor parameters.

TABLE 1

SPECIFICATIONS AND RESULTS

	Contract Requirement	Measured Value
Output Torque	5.5 ft-lbs (full-winding)	5.5 ft-lbs
Demagnetization Torque	> 6.6 ft-lbs	> 9 ft-lbs
Back EMF	$0.0782 \frac{\text{Volts Pk}^*}{\text{RPM}}$	$0.0782 \frac{\text{Volts Pk}}{\text{RPM}}$
Maximum Speed	1740 rpm	1740 rpm
Overspeed Capability	2440 rpm	3000 rpm
Weight	5.0 lbs (goal)	5.8 lbs
I^2R Losses	155 watts at 5.0 ft-lbs (goal)	155 watts
Core Losses	-----	4.3 watts at 1740 rpm

*Designed for 34 volts at 435 rpm, as specified in design definition report (see Reference 1).

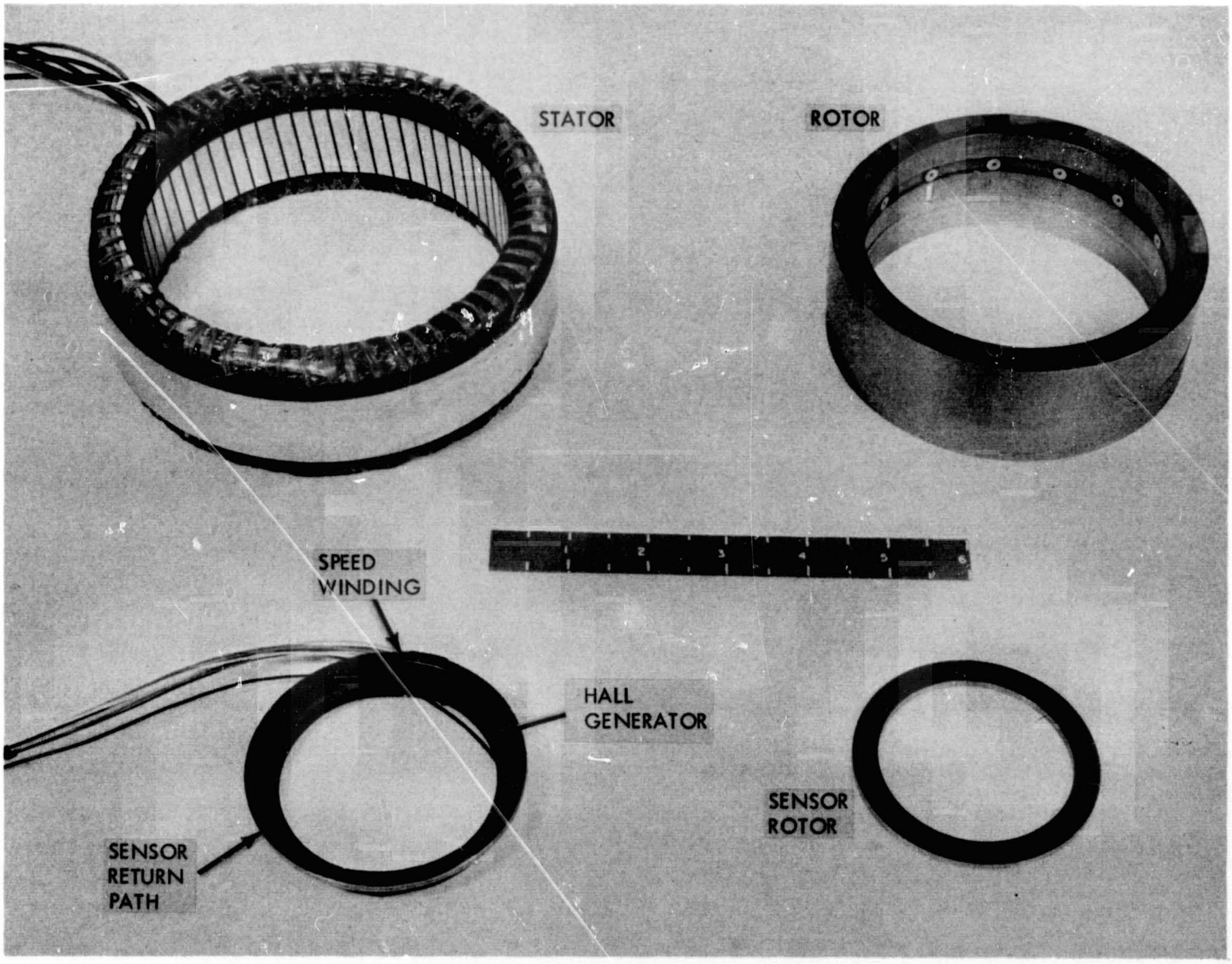


Figure 1. NASA 5.0 ft-lb Brushless DC Motor

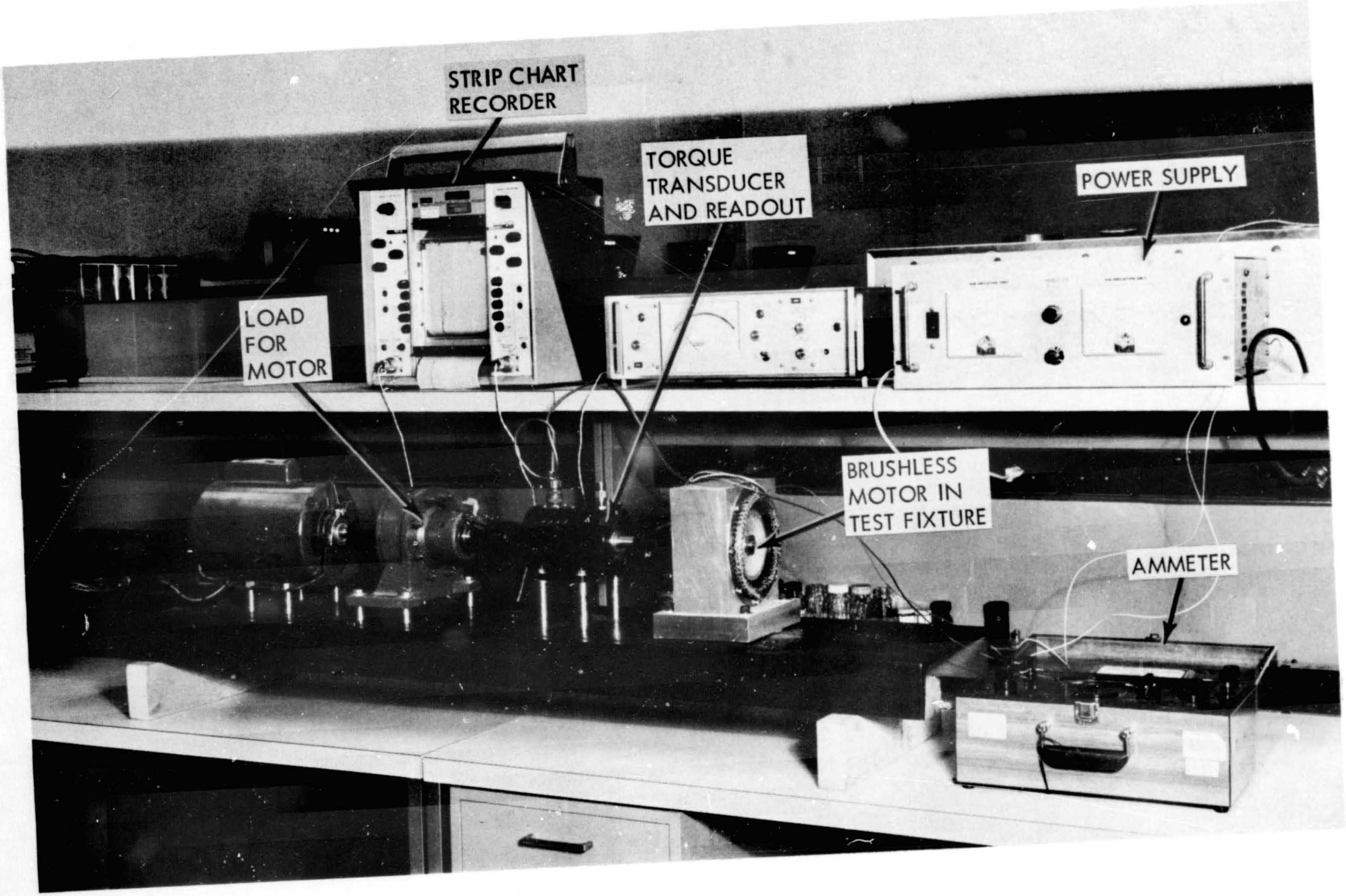


Figure 2. Brushless DC Motor Test Stand

TABLE 2
MEASURED MOTOR CHARACTERISTICS

GENERAL

MOTOR SIZE

Outside Diameter	6.145 inches
Axial Length	2.2 inches
Weight, Including Hall Resolver	5.8 lbs
Maximum Power Required (Motor Only)	336 watts at 36 volts (1/4-winding) 453 watts at 36 volts (full-winding)

PERFORMANCE DATA

	Full-Winding	1/4-Winding
Rated Torque	5.0	1.25 ft-lbs
Peak Torque Capability	>9.0	>2.25 ft-lbs
*I^2R Losses at Rated Torque	155	24.4 watts
Core Losses at Rated Speed	1.0	4.3 watts
Winding Constants:		
Torque Constant	0.550	0.138 ft-lb/amp
Current for Rated Torque	9.09	9.09 amps
Resistance, Each Phase	1.87	0.294 ohms
Generator Constant	0.746	0.187 v pk/rad/sec
Back EMF at 1740 rpm	136.0	34.0 v pk
Inductance, Each Phase	5.2	0.45 millihenries

TABLE 2 (cont'd)

MOTOR DIMENSIONS

MOTOR STATOR

Outside Diameter	6.145 inches
Inside Diameter	4.850 inches
Punchings - Material	Carpenter 49
- Thickness	0.010 inch
Stack Height	1.14 inches
Axial Length with Windings	2.2 inches
Number of Slots	60
Weight	4.12 lbs

MOTOR ROTOR

Type	Inserted Permanent Magnet
Number of Poles	14
Outside Diameter	4.830 inches
Inside Diameter	3.950 inches
Axial Length	1.10 inches
Magnet Material	Alnico 9
Weight	1.48 lbs
Maximum Speed	2500 rpm
Inertia	0.0016 slug-ft^2

HALL RESOLVER

Type	Two-Phase
Outside Diameter	3.230 inches
Overall Axial Length	0.4 inch
Rotor Type	Solid Permanent Magnet, Alnico 6, 14-pole
Hall Generator Type	GE Dwg. 854D847
Rated Output Voltage	60 millivolts

TABLE 2 (cont'd)

HALL RESOLVER (cont'd)	
Resolver Gain	**12 millivolts/volt**
Weight	**0.2 lb**
SPEED WINDING	
Gain	**$0.066 \frac{\text{volts pk}}{\text{Hertz}}$**
Resistance	**9.5 ohms**

Section 2

MOTOR DESIGN

DESIGN APPROACH

The contractual requirements for the back EMF and the design goals for weight and power loss set the basic motor requirements. A 14-pole motor was selected as the optimum design for size and power requirements. The motor was designed to have a back EMF of 34 volts at 435 rpm. The torque constant is then:

$$K_T = \frac{34\text{V}}{435\ \text{cy/min}} \left(\frac{60\ \text{min/s}}{2\pi\ \text{rad/cy}}\right) \left(\frac{550\ \text{ft-lb/s}\bullet\text{hp}}{746\ \text{VA/hp}}\right)$$

$$K_T = 0.550 \frac{\text{ft-lb}}{\text{amp}} .$$

This sets the peak motor current at 9.09 amps for 5.0 ft-lbs output torque.

STATOR DESIGN

The design goal of 155 watts power loss was considered to be of primary importance. The volume of copper necessary to give 155 watts I^2R losses resulted in a motor that weighed 5.8 pounds.

A power loss of 155 watts requires a resistance of $R = P/I^2$

$$R = \frac{155}{(9.09)^2} = 1.875 \text{ ohms}$$

Measurements of the winding resistance gave an average value of 1.870 ohms for each phase.

The motor was designed and fabricated with a 1/4-winding and a 3/4-winding. The motor design was optimized for high speed operating efficiency (1740 rpm and 1.25 ft-lbs torque), by allocating 39 percent of the stator-slot cross section to the 1/4-winding. This allocation of the stator-slot cross section results in a lower resistance and a 61 percent lower power loss for the 1/4-winding at a slight (7 percent) increase in the full-winding power loss.

The detailed calculations for the motor (see Reference 2) resulted in the following parameters:

D_A = rotor diameter = 12.27 cm

ℓ_A = rotor length = 2.79 cm

B_{max} = flux density in air gap = 5820 gauss

fw_1 = winding distribution factor = 0.876

The number of turns can then be found from the following equation:

$$N = \frac{K_T\ (13.556 \times 10^6)}{(0.1)\ fw_1\ D_A\ \ell_A\ B_{max}}$$

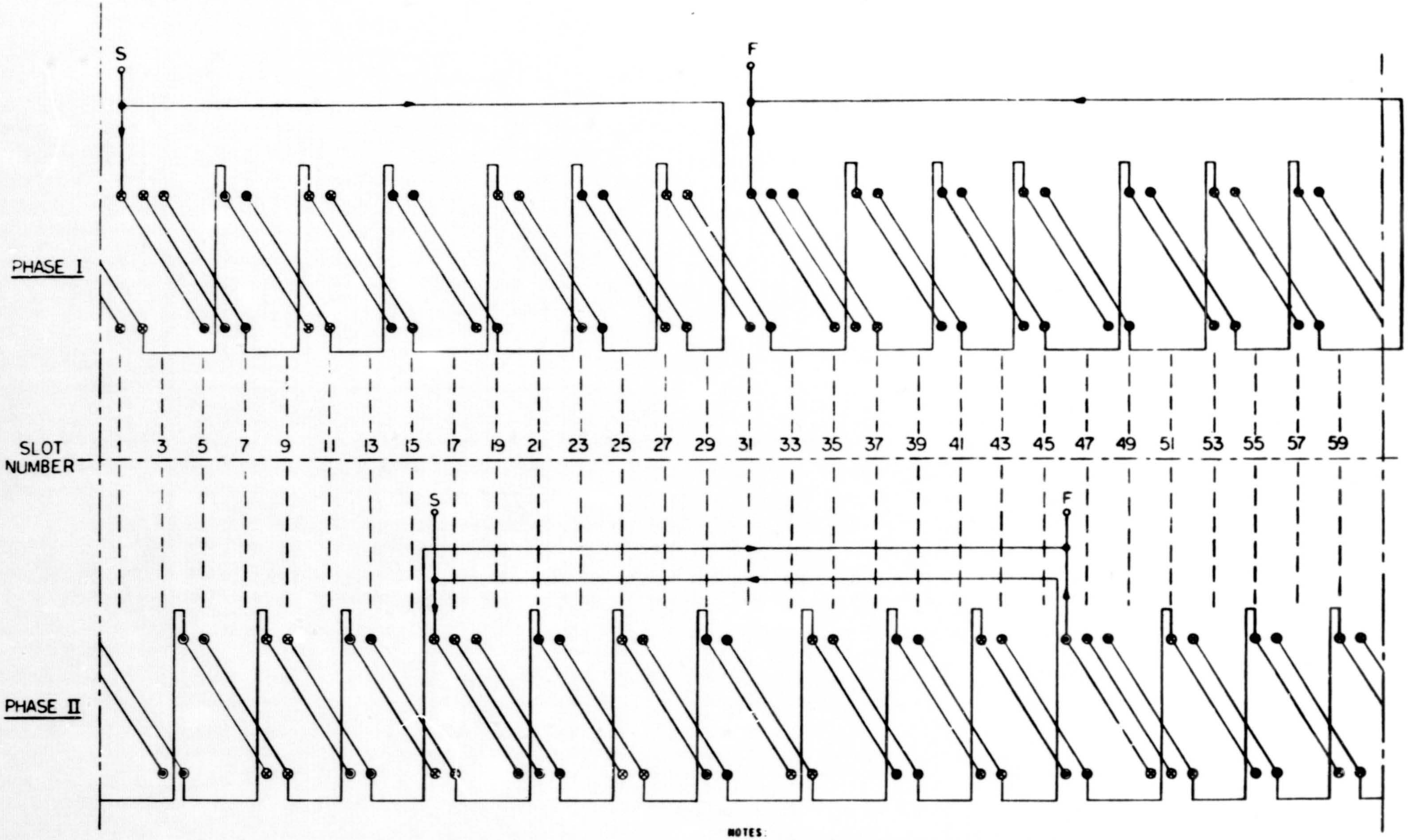
$$N = \frac{0.55\ (13.556 \times 10^6)}{(0.1)\ (0.876)\ (12.27)\ (2.79)\ (5820)}$$

$$N = 427 \text{ turns}$$

The 3/4-winding has 315 turns and the 1/4-winding has 105 turns for a total of 420 turns.

The winding selected is shown in Figure 3. The resistance of each winding is:

$$R_W = \frac{N\ \ell_n}{A_{cu}} \cdot \rho$$



NOTES:

1. SYMMETRICAL TWO PHASE FRACTIONAL SLOT WINDING FOR $p = 7$; $m = 2$, $q = 2\ 1/7$; $N_S = 60$
2. WINDING SCHEME:

   EACH PHASE CONSISTS OF A 105 TURN AND A 315 TURN WINDING BOTH HAVING THE SAME WINDING SCHEME SHOWN BELOW. EACH WINDING CONSISTS OF TWO PARALLEL CONNECTED STRINGS OF 15 SKEINS WOUND AS FOLLOWS:

   FOR 105 TURN WINDING 7 TURNS PER SKEIN OF 4 X NO. 29 AWG AND 4 X NO. 30 AWG WIRE (ML INSULATED) IN PARALLEL

   FOR 315 TURN WINDING 21 TURNS PER SKEIN OF 3 X NO. 29 AWG AND 1 X NO. 30 AWG WIRE (ML INSULATED) IN PARALLEL

   THE 105 TURN WINDING MUST BE INSERTED INTO SLOTS FIRST. MEAN TURN LENGTH: APPROXIMATELY 5.7 INCHES

Figure 3. Winding Diagram

Where

N = number of turns per section

ℓ_m = mean turn length of windings

A_{cu} = area of conductor

ρ = resistivity of copper

For the 105-turn winding:

$N = 105$

$\ell_m = 5.7$ inches

$A = 8 \times \#29 + 8 \times \#30 = 1427.8 \times 10^{-6}\ \text{in}^2$

$\rho = 0.6787 \times 10^{-6}\ \Omega\text{- inch}$

$$R_W = \frac{105\ (5.7)\ \text{in}}{1427.8 \times 10^{-6}\ \text{in}^2} \times 0.6787 \times 10^{-6}\ \Omega\text{-inch} = 0.285\ \text{ohm}$$

For the 315-turn winding:

$N = 105$

$\ell_m = 5.7$ inches

$A = 6 \times \#29 + 2 \times \#30 = 755.1 \times 10^{-6}\ \text{in}^2$

$\rho = 0.6787 \times 10^{-6}\ \Omega\text{-inch}$

$$R_W = \frac{315\ (5.7)\ \text{in} \times 0.6787 \times 10^{-6}\ \Omega\text{-in}}{755.1 \times 10^{-6}\ \text{in}^2} = 1.614\ \text{ohms}$$

To minimize core losses the punchings used were 10-mil thick nickel-steel (Carpenter 49). The use of silicon steel, which is only available in 14-mil thickness, would reduce the weight approximately 0.14 pound but increase the core losses by about 7.5 watts (from 4.3 to 11.8 watts).

ROTOR DESIGN

The mechanical rotor design was very similar to the design of previously fabricated rotors. The rotor consists of 14 Alnico 9 magnets separated by soft iron pole pieces. The iron pole pieces are screwed and epoxied to a titanium support ring. The magnets are also epoxied to the support ring. The entire assembly is restrained by a thin titanium shrink ring. Figure 4 shows the details of the rotor construction. The shrink ring is designed to restrain the magnets, in case of epoxy failure, over the entire temperature range -300°F to +250°F and provides a 2-1 safety factor based on a speed of 2400 rpm (see Reference 3).

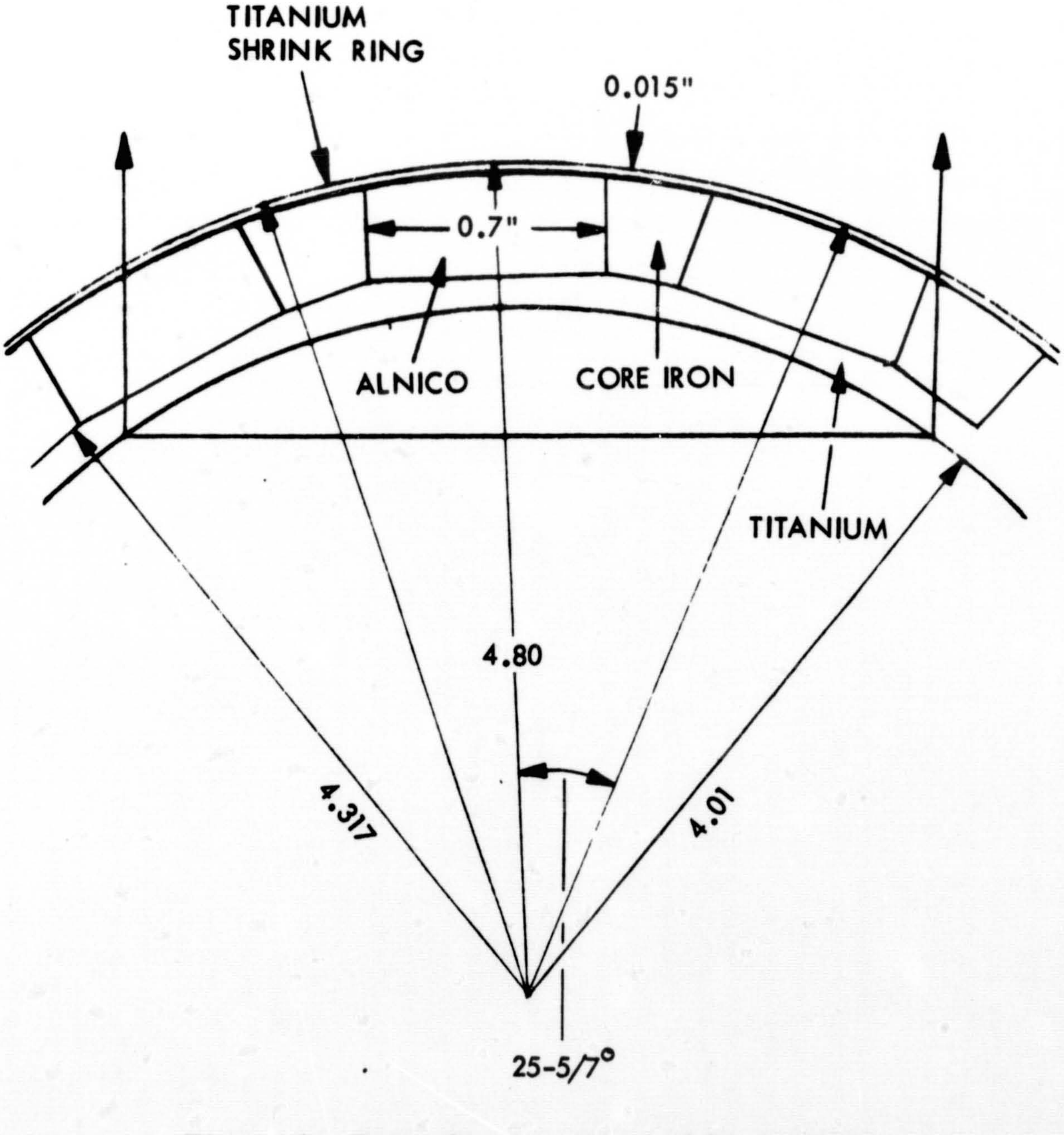


Figure 4. Rotor Construction and Dimensions

RESOLVER DESIGN

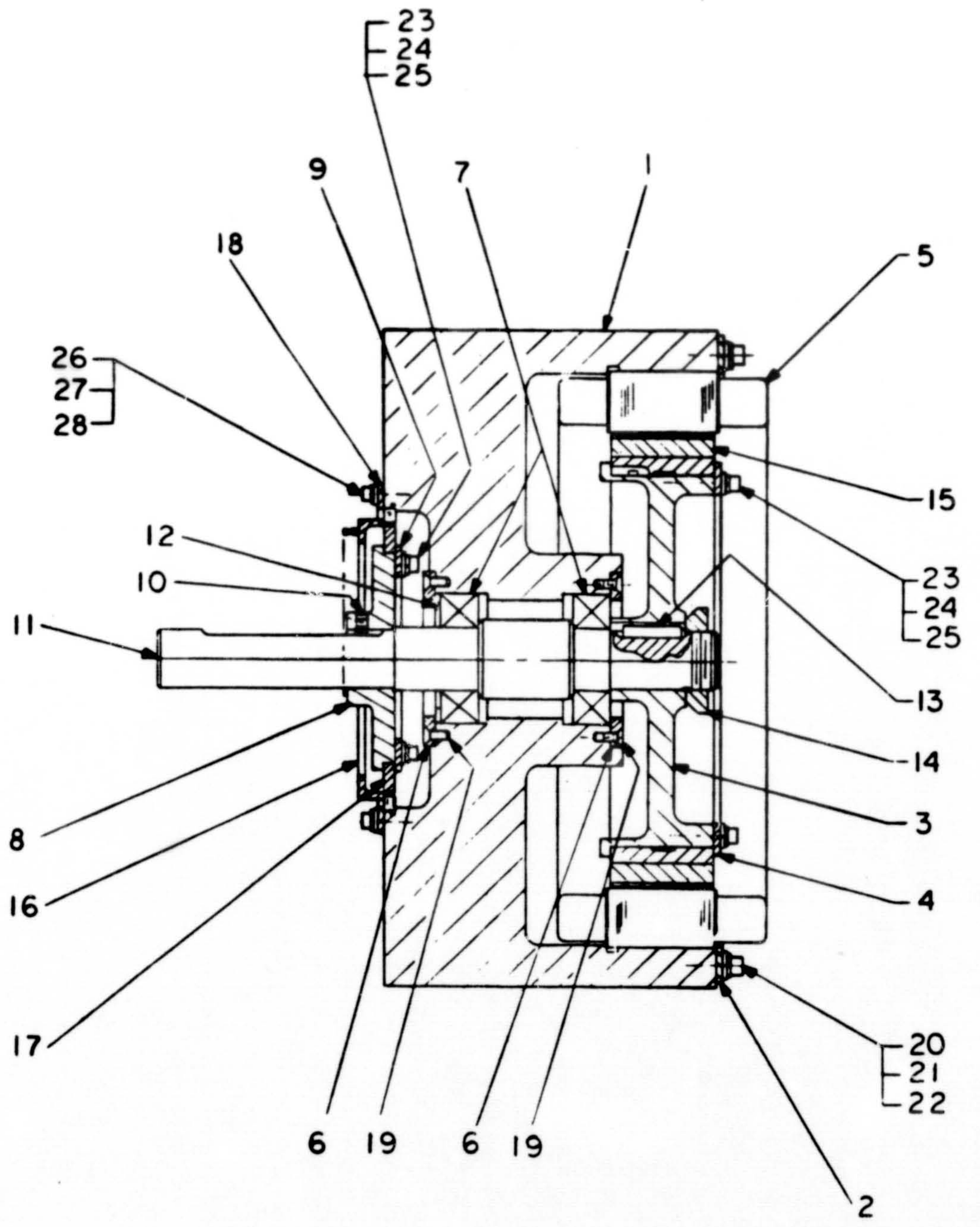
The resolver provides sine and cosine signals to the electronics of the brushless dc motor. The magnet is a 14-pole ring magnet of Alnico 6. The two Hall generators are run independently with a selected resistor to set the Hall output voltage at 60 millivolts for a 5.0-volt input signal. The Hall generators are mounted in a thermoplastic ring with a thermal coefficient of 8×10^{-6} in/in/°F since the coefficient of expansion of the return path is 7.2×10^{-6} in/in/°F these two materials are fairly well matched.

Section 3

OPERATING INSTRUCTIONS

The following operations must be performed for the motor to operate correctly. Figure 5 shows the motor mounted in the test fixture ready for operation.

1. The main rotor and the sensor rotor must be mounted on their hubs. The keeper on the main rotor must not be removed during this operation.
2. The sensor rotor and hub must be mounted on the shaft with the aid of the jack screws before the sensor return path is mounted in the test fixture.
3. The sensor return path must be carefully placed into the test fixture. Care must be taken to fit the speed winding in the appropriate slot in the test fixture.
4. The motor stator should be carefully mounted in the test fixture so that the windings are not scrapped.
5. The motor rotor must be mounted on the shaft with the aid of the jack-screws. When the rotor is inside the stator the nylon screws may be used to remove the keeper from the rotor.
6. For proper operation the current in the motor windings must be in-phase with the magnetic field in the air gap. The current in the windings is a function of the Hall generator output voltage, and the voltage induced in the windings is a function of the magnetic field in the air gap. Therefore, if the Hall generator output voltage is in-phase with the voltage induced in the winding that the Hall generator is going to drive, the motor will be properly aligned. The Hall generators should have about 5 volts on the input leads and their output connected to an oscilloscope or a recorder. The motor should be rotated externally with the output leads of one section connected to another channel of the indicating instrument. The main stator is then rotated until the two voltages are in-phase.
7. After performing steps 1 through 6 the motor is ready to be connected to the electronics. Figure 6 shows the required interconnections.



1	FIXTURE
2	RETAINING RING
3	ROTOR HUB
4	RETAINING RING
5	MOTOR STATOR
6	BEARING RETAINER
7	BEARING
8	SENSOR ROTOR HUB
9	RETAINING RING
10	SET SCREW
11	SHAFT
12	PRELOAD WASHER
13	KEY
14	HEX NUT
15	MOTOR ROTOR
16	SENSOR RETURN PATH
17	SENSOR ROTOR
18	RETAINING RING
19 thru 28	MOUNTING HARDWARE

Figure 5. Brushless DC Motor in Test Fixture

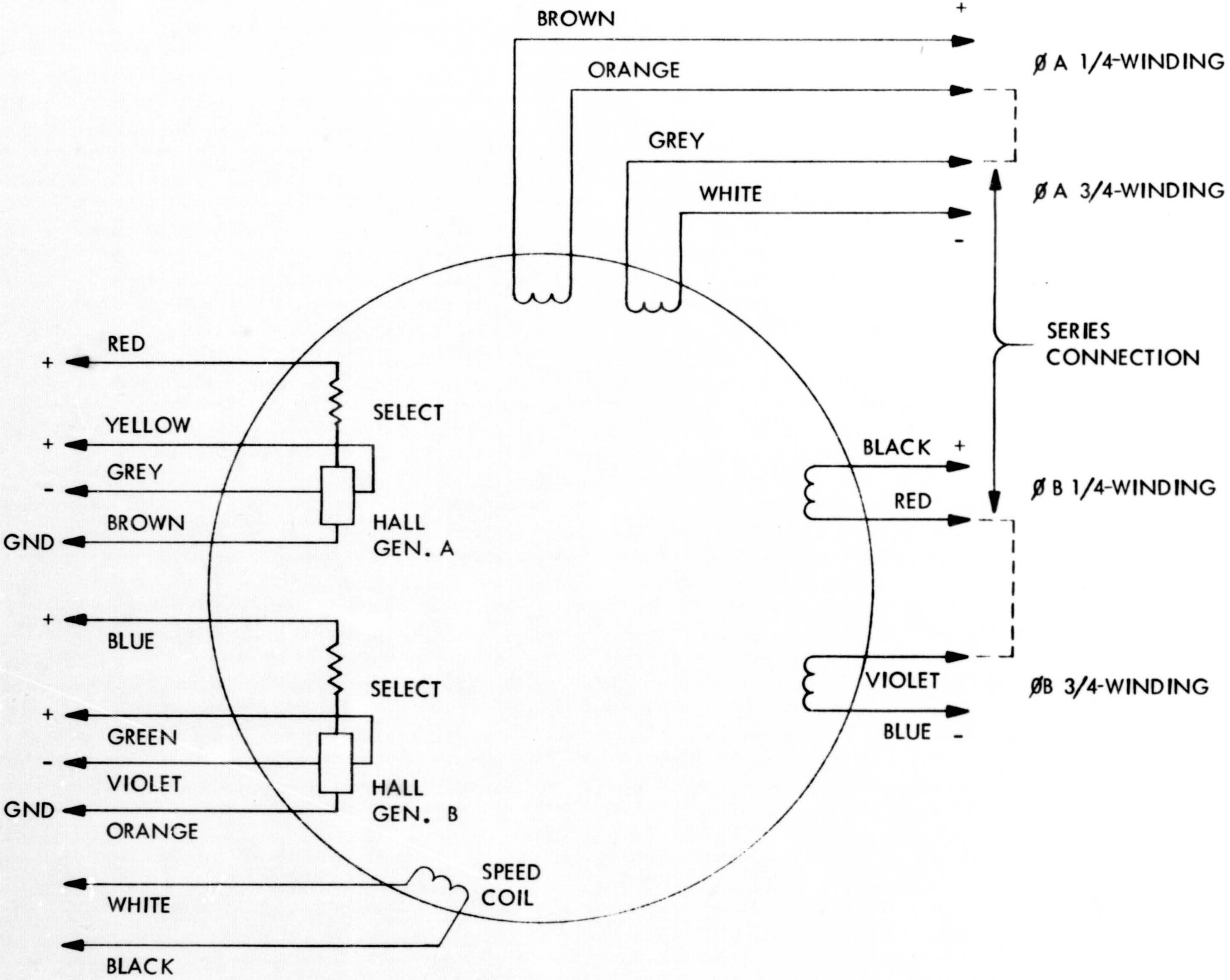


Figure 6. Motor Interconnections

Section 4

MOTOR TESTING

INTRODUCTION

The testing performed on this program consisted of separate tests of the rotor, stator and sensor and functional tests taken to determine the operating characteristics of the motor. A description of these tests and the results obtained are discussed in the following paragraphs.

STATOR TESTS

Resistance and insulation resistance were measured on the windings of each stator. The results are listed in Table 3.

TABLE 3

MOTOR RESISTANCE

	Calculated	Stator 1	Stator 2
Brn-Or	0.296	0.2950	0.292 ohm
Red-Blk	0.296	0.2945	0.296 ohm
Grey-Wh	1.62	1.568	1.580 ohms
Blue-Vio	1.62	1.576	1.574 ohms
Insulation Resistance	>10 Megs	OK	OK

ROTOR TESTS

Both rotors were externally rotated at 2500 rpm to verify their mechanical integrity at 40 percent overspeed.

MOTOR TESTS

After magnetization the back EMF of each motor was adjusted by varying the gap of the keeper on the face of the rotor. Figure 7 is a graph showing the variation of the back EMF in the 1/4-winding at 1740 rpm with the gap between the keeper and the rotor. This graph shows that the back EMF can be adjusted from 37 to 30 volts by varying the keeper gap. A high back EMF results in a lower top speed (for a given supply voltage) and a lower current to reach rated torque. The core losses are also slightly greater for a higher than nominal back EMF. The back EMF for the two motors is tabulated in Table 4. The values of inductance measured with the rotor in place are shown in Table 5.

TABLE 4

BACK EMF AT 1740 RPM

	Calculated	Motor 1	Motor 2
Brn-Or (ϕ1, 1/4-windings)	34 V	33.4 V-pk	34 V-pk
Red-Blk (ϕ2, 1/4-windings)	34 V	33.4 V-pk	34 V-pk
ϕ1	136 V	134 V-pk	136 V-pk
ϕ2	136 V	134 V-pk	136 V-pk

TABLE 5

AVERAGE INDUCTANCE AT 1000 HERTZ

	Calculated (millihenries)	Motor 1 (millihenries)	Motor 2 (millihenries)
1/4-Winding	0.42	0.45	0.45
Full-Winding	5.4	5.13	5.23

Figure 8 is a graph of output torque versus current in the full-winding. This graph shows that the output torque is linear to 9.0 ft-lbs.

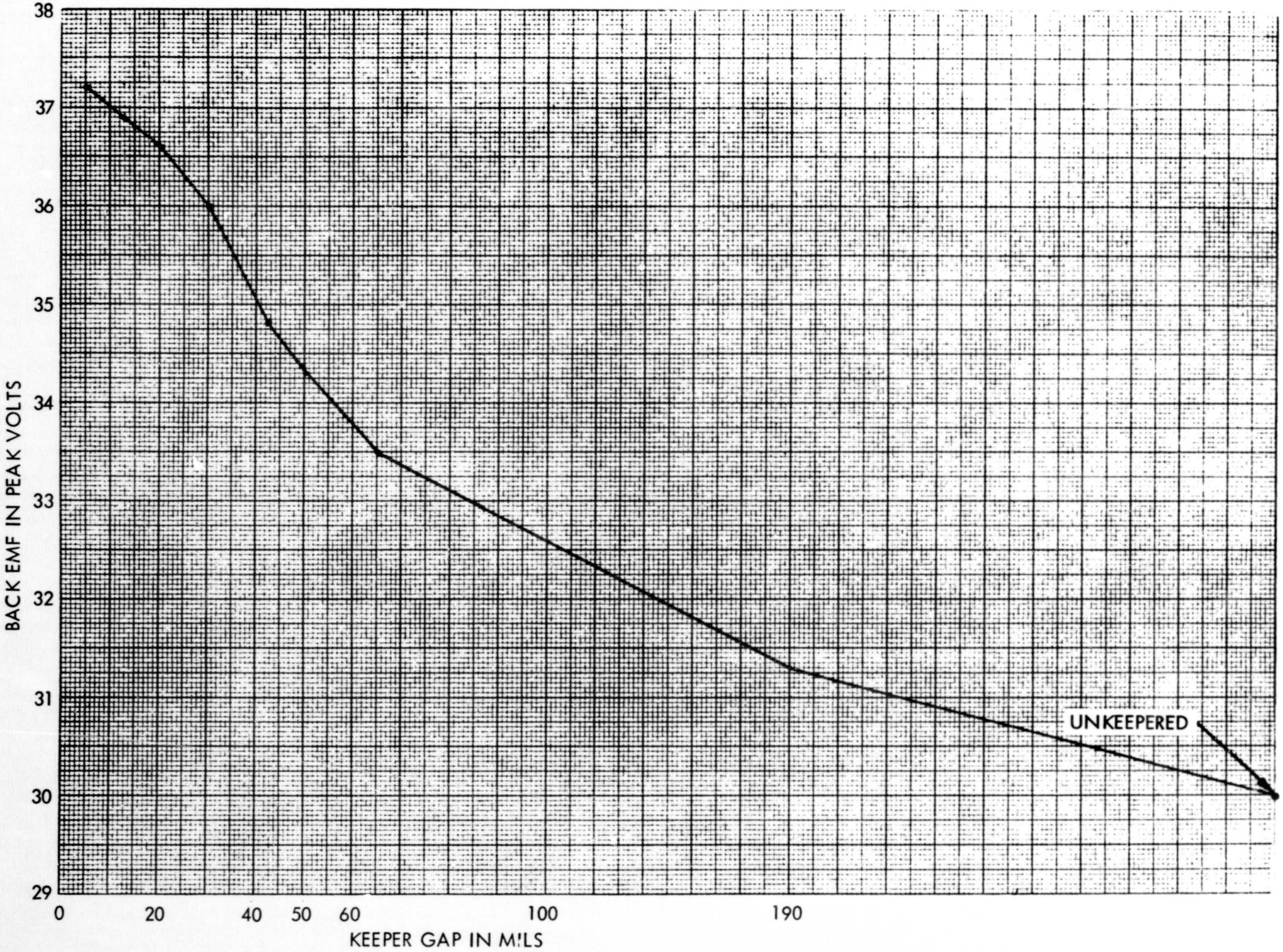


Figure 7. Keeper Gap versus Peak Volts at 1740 RPM (Magnet 1)

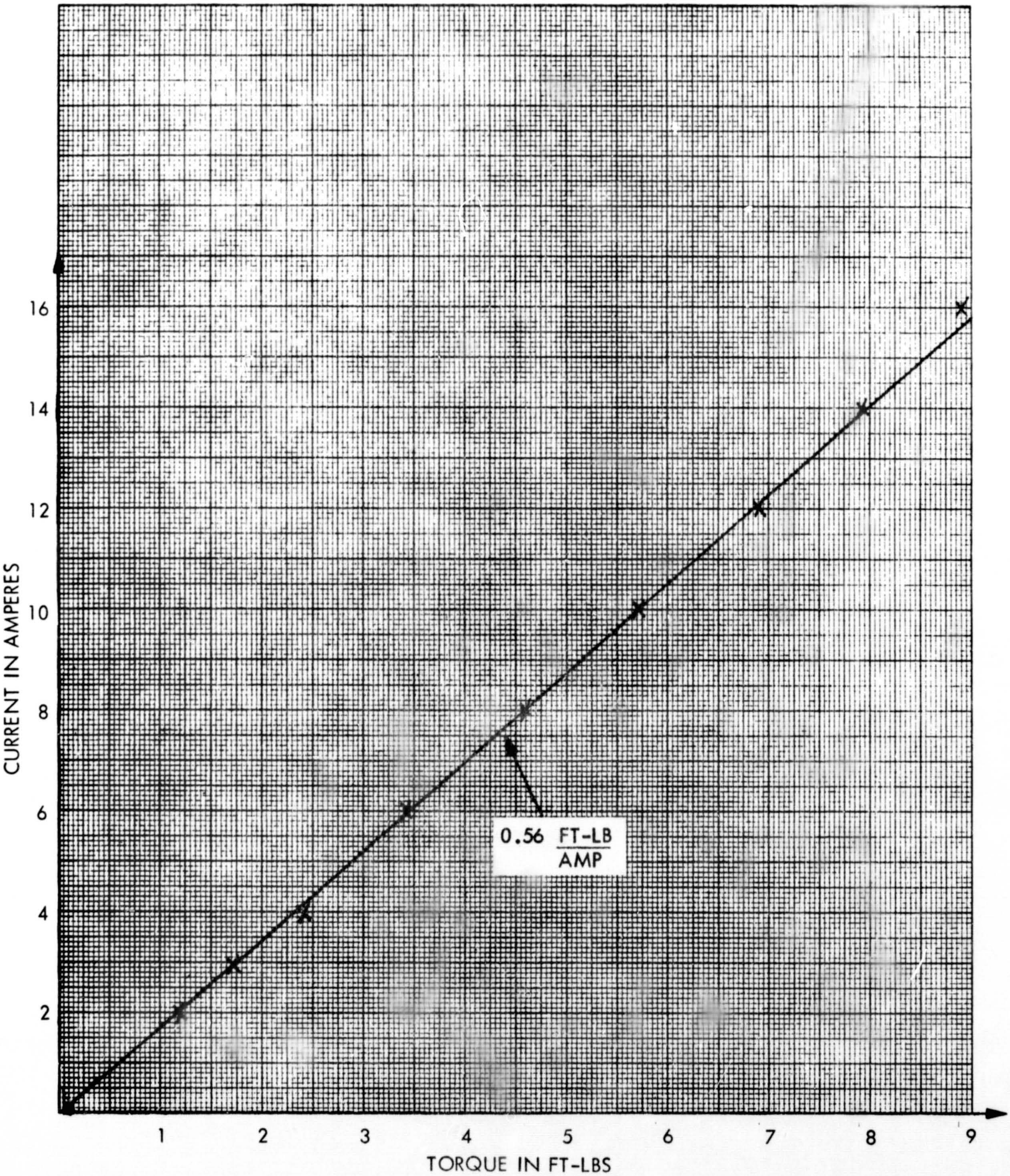


Figure 8. Torque versus Current (Motor 1, ϕA)

A plot of the core losses versus speed is shown in Figure 9. At 1740 rpm the core loss is about 4.3 watts which compares closely with the calculated value of 4.0 watts.

The breakaway torque which is a combination of reluctance torque and friction torque is approximately 0.004 ft-lb.

SENSORS TESTS

Both sensors were set for a gain of ± 12 mv/volt. The Hall generators are driven in parallel each with its own selected resistor. Each sensor ring has a speed coil wound around the return path. Table 6 shows the data for both sensors. Figure 10 is a plot of speed versus output voltage.

TABLE 6

SENSOR CHARACTERISTICS

	Sensor 1	Sensor 2
Gain	0.0646 Vp/Hz	0.0674 Vp/Hz
Winding-Resistance	9.0 ohms	10 ohms
ϕ1 Hall Generator	13 mv/v	12.9 mv/v
ϕ2 Hall Generator	13.4 mv/v	13.2 mv/v

The Hall generators are operated with less than 15 ma drive current, and the magnetic field in the sensor gap is about 2550 Gauss.

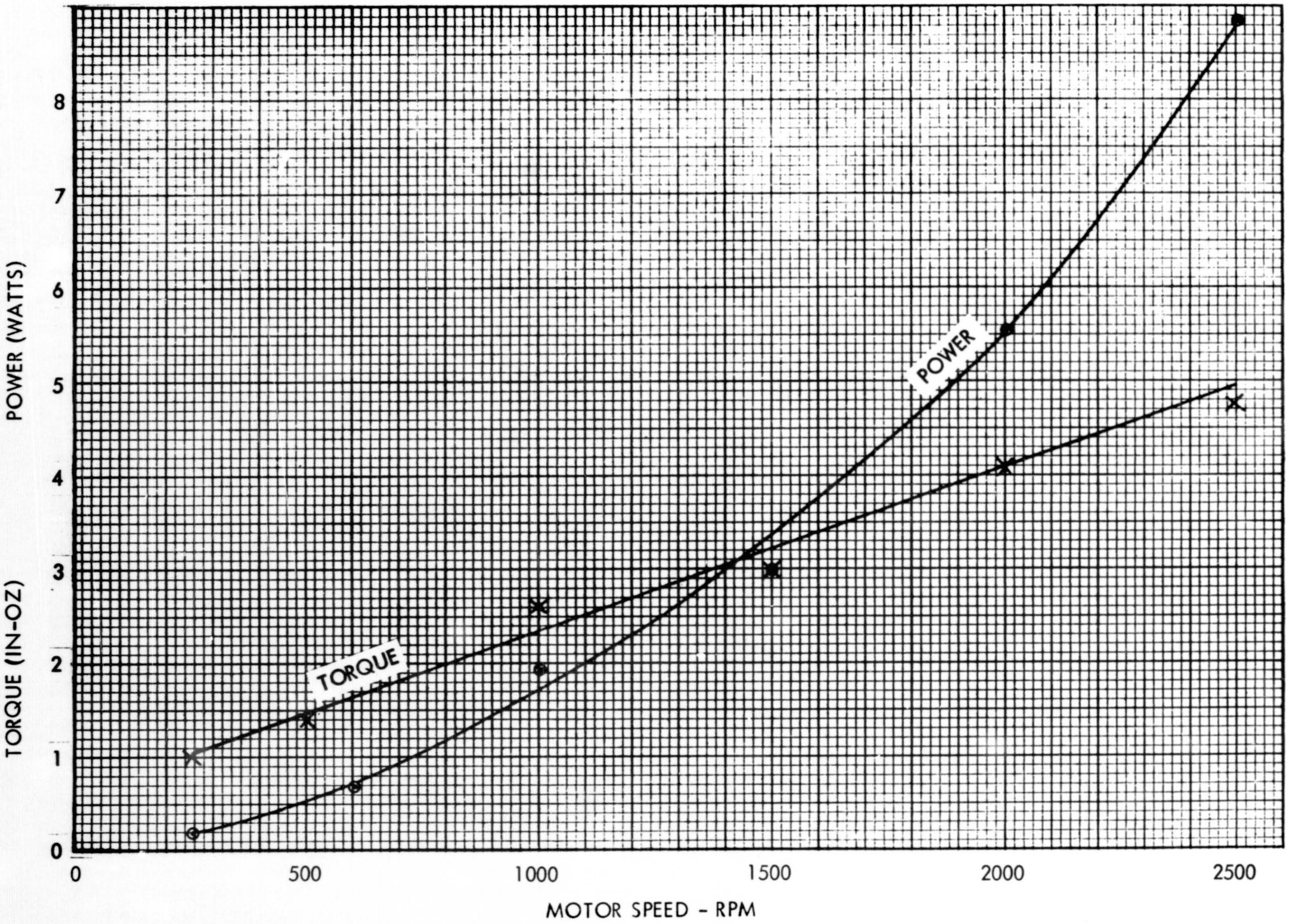


Figure 9. Core Losses (Motor 1)

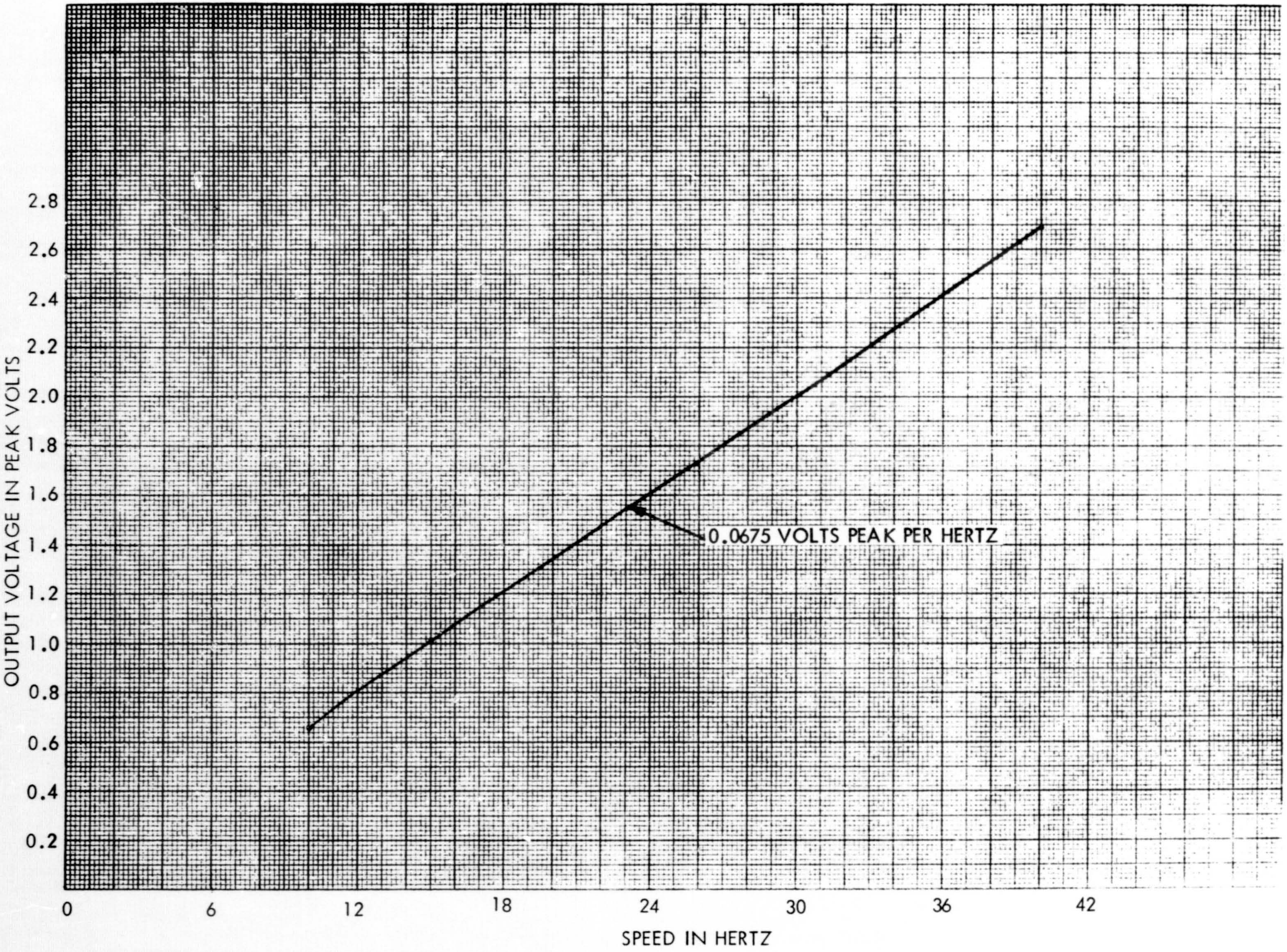


Figure 10. Output Voltage of Speed Winding (Sensor 2)

Section 5

CONCLUSIONS AND RECOMMENDATIONS

The brushless dc motors developed under this contract met all the contract requirements. These brushless dc motors are suitable for operation either as a power drive or as a high output torque servomotor. Environmental testing and the development and fabrication of electronic circuitry to power the motors has been carried out under previous contracts. (See References 4 and 5)

REFERENCES

1. Experimental Brushless DC Motor Design Definition Package, August 5, 1970

2. Magnetic Calculations for Brushless DC Motor Project Memo 70-91-24, November 11, 1970, Dr. E. W. Manteuffel

3. 5.0 ft-lb Brushless Motor Shrink Ring, Project Memo 70-90-18, August 14, 1970, M. F. O'Connor

4. Final Report Brushless DC motor and Controller, March 1970, Contract NAS8-25-085, B. H. Hertzendorf and E. W. Manteuffel, ACD 9854

5. Brushless DC Torque Motor Development, January 31, 1970, Dr. E. W. Manteuffel and B. H. Hertzendorf, ACD 9849

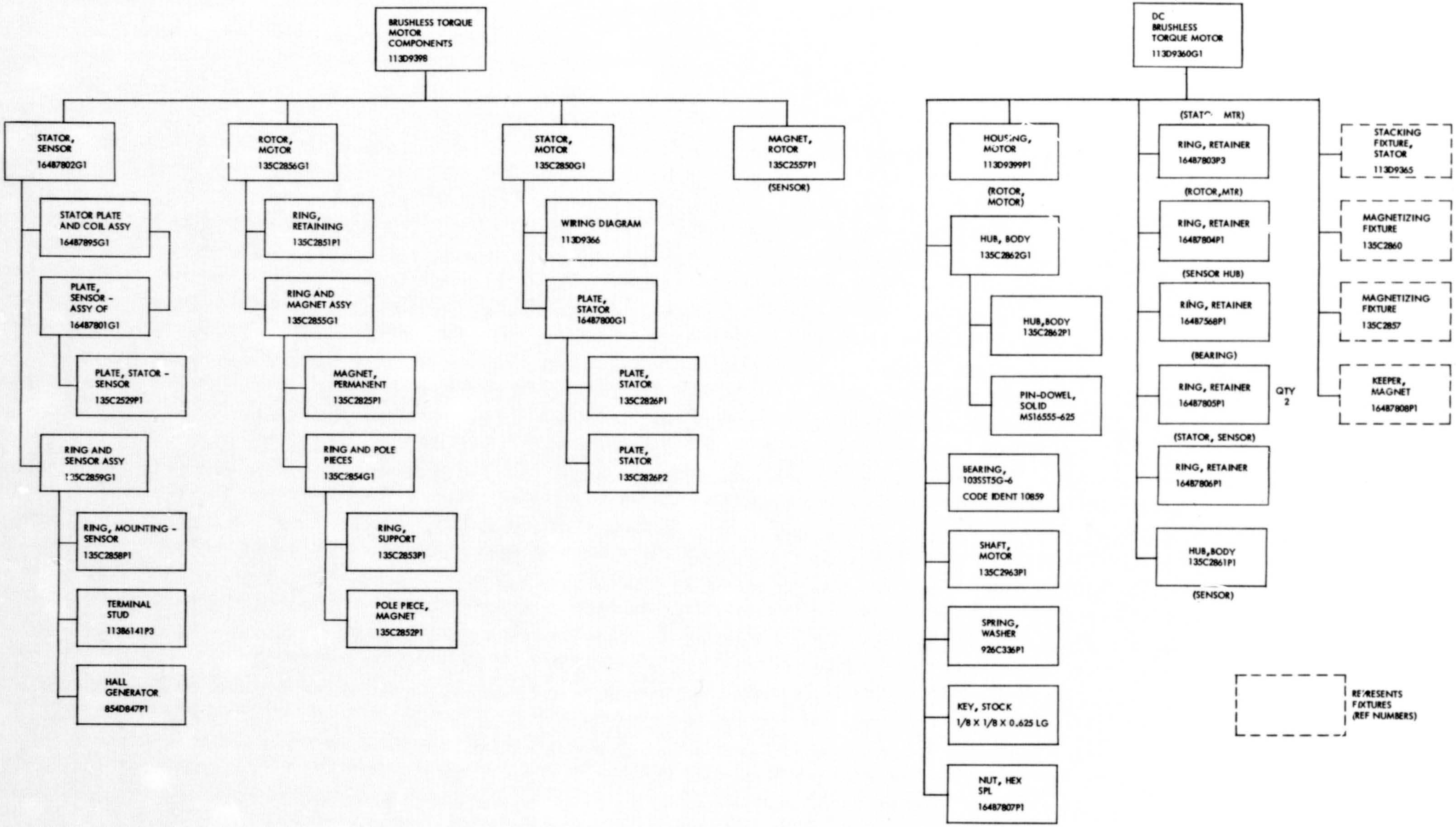


Figure 11. NASA Brushless Torque Motor Drawing Structure

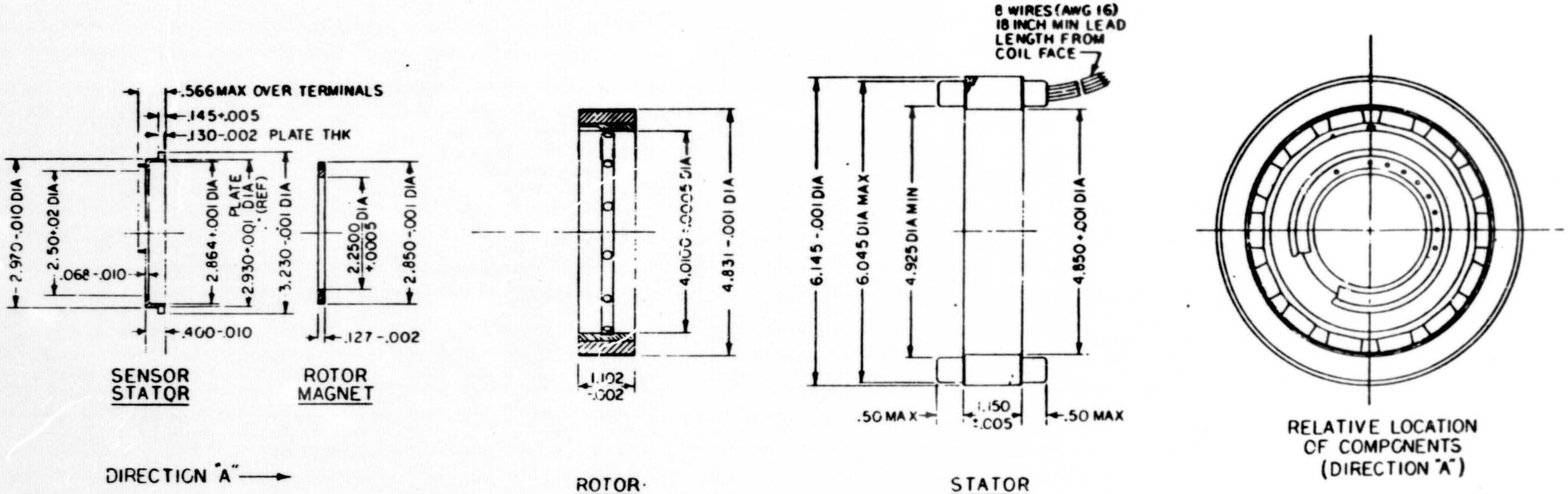


Figure 12. 5.0 Ft-Lb Brushless Torque Motor Components