Report No: WAED 65.21E

Third Quarterly Report

For a

Brushless D.C. Torque Motor

(25 December 1964 - 25 March 1965)

Contract No: NAS 5-3934

Prepared by

Westinghouse Electric Corporation

Aerospace Electrical Division

Lima, Ohio

For

Goddard Space Flight Center

Greenbelt, Maryland

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April 26, 1965

Subject: Third Quarterly Progress Report
25 December 1964 - 25 March 1965

Ref: Contract No.: NAS5-3934
Westinghouse G. O. WGD-25805-AD, Item 2

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Yours truly,

Westinghouse Electric Corporation
Aerospace Electrical Division

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ABSTRACT

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This report covers the work performed on NASA Contract NAS 5-3934 during the third quarter of work commencing December 25, 1964 and ending March 25, 1965. This contract covers the development of a brushless d-c torque motor.

Tests taken on the completed units indicated that the magnet flux was approximately as calculated. The reluctance switch performed approximately as predicted. However, a severe cogging problem in the motor has necessitated rewinding the motor stators using a different punching and the installation of a magnetic can in the stator bore. Rework of the motors is scheduled to be complete by April 15, 1965.

Engineering evaluation of the reluctance switch and control is proceeding.

Author

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I. INTRODUCTION

This report is the third quarterly report on NASA Contract NAS 5-3934 - Brushless D.C. Torque Motor. It covers the period from December 25, 1964 to March 25, 1965. During this period, the manufacturing of the units was completed. However, a severe cogging problem (ripple torque) necessitated rework of the motor stators. The rework is now in progress and is scheduled to be complete by April 15, 1965.

Other changes were made to ease manufacturing or to improve the product as manufacturing proceeded. Some additions were made to the test procedure. An analysis of the ripple problem was made.

II. DISCUSSION

A. Manufacturing

1. Changes

During the process of manufacturing the units, several changes were made to ease manufacturing problems and to improve the product. The more important changes are enumerated below.

a. The fits of the shaft spacers with the shaft were changed to eliminate excessive stress in the spacers. The interference of the fits was reduced.

b. The varnish bake temperature of the reluctance switch was reduced to lower thermal stresses in the fine wire used for winding. This was done to improve reliability. The lower temperature is sufficient to completely cure the varnish.

c. The O-ring used for axial preload was reduced in cross-section diameter because the larger O-ring tended to bind the bearing.

d. A change was made to hold the teflon sleeve in place with a piece of heat-shrinkable polyethylene sleeving rather than tieing the teflon sleeve inside the motor. The tieing operation was too difficult to be practical.

e. Following discovery of the cogging problem, the motor punching was changed to a 45-slot punching using the same slot die as was used for the 48-slot punching. The winding was changed to have 62 turns per coil of No. 28 wire. An 8/9 pitch was used with a coil perimeter of 4.00. The skew of the stator was reversed to obtain effectively zero skew in the motor. A can made of 6 mil hypernik magnetic steel was added to the stator bore.

2. Recommendations for Future Improvements

It was noted during manufacture that several areas needed improvement. These are enumerated below and should be considered for future designs.

a. Winding and insulating the reluctance switch is difficult. The sensing windings should be wound on separate insulating bobbins and inserted over the teeth. This necessitates removal of the tooth tips; but this should improve the position discrimination of the output signal.

b. The leads on the reluctance switch are too bulky. A thinner lead should be used.

c. The perimeter of the coils on the motor stator could be reduced. This was done on the rewound units.

d. The bulk of the leads on the reluctance switch makes adjustment difficult. Because of the complicated adjustment procedure and the difficulty in making the adjustment, the possibility of freezing the reluctance switch in the correct position during manufacture should be investigated.

e. Remove the flanges from the top of the control package. This will ease the installation of the circuit boards.

B. Test Procedure

The following items were added to the General Laboratory Test Procedure. (Reference Appendix II of Second Quarterly Report.) These were added to check temperatures, to determine the effect of control voltage variations, and to measure control power.

1. <u>One Unit</u> - Place two thermocouples on the end extension of the motor winding. Read the thermocouples for stabilized temperature at 60 and 40 volts for Paragraph I for locked torque or the torque load which will allow temperature stabilization below 200°C.

2. <u>One Unit - Paragraph I</u> - When the final adjustment is reached, repeat the torque reading at each angular position with the control voltage set at 26, 27, 28, and 29 volts.

3. <u>One Unit - Paragraph I</u> - As readings are taken, measure volts and amps in the control voltage circuit. Also measure the volts and amps in the d-c motor circuit and the voltage at the motor terminals. (This voltage must be measured with an oscilloscope, since it varies.) Take oscilloscope pictures of main d-c motor current, voltage at the motor terminals, and current in the control circuit.

4. <u>All Units - Paragraph G</u> - Repeat Paragraph F.

C. Design and Test Results - Motor

1. Weight

The complete motor (except with untrimmed leads and no connector) weighed 3.4 pounds versus a calculated 3.1 pounds. This was determined to be caused by the following:

a. Insufficient allowance in the calculations for lead weight on the reluctance switch.

b. Insufficient allowance for varnish absorption in the electrical parts.

c. An error in the shaft weight calculations.

It is expected that the weight of the new motor wound primary will be reduced due to the shorter perimeter. Also some weight will be removed when the leads are trimmed. It is believed, however, that the motor will end up slightly high in weight. The control package weight agreed almost exactly with calculations at 1.38 pounds.

2. Ripple Torque Problem

It was noticed on the completed motor that severe reluctance cogging existed between the permanent magnet rotor and the motor stator. A crude measurement of the torque gave 15 oz-in. To investigate the effect of skew on the cogging torque, a stack of loose punchings was machined to have a slip fit in the frame so that the skew could be changed. Only slight reduction in the cogging effect could be obtained with practical amounts of skew.

Next a graphical layout was made with the stator slots and PM poles laid out in a straight line to approximately a 5 to 1 scale. A 48 slot and a 45 slot punching were laid out. The flux fringing area permeance and the air-gap permeance over the poles were graphically integrated as the stator and rotor moved relative to each other. The integration was performed for 5 positions in one slot pitch. The results showed that the permeance variation of the 45 slot punching was negligible compared to the permeance variation of the 48 slot stator.

A stack of loose 45 slot punchings was made and tested as before. The results gave approximately 5 oz-in. of cogging torque. Again, skewing any practical amount had only a small effect.

A can made of 0.008 inch thick unannealed Hiperco 27 magnetic steel was installed crudely in the stator (after machining the stator bore oversize) with a gap left at the seam. In spite of the cogging introduced by the seam gap, it was determined that the cogging torque was reduced to below 1 or 2 oz-in. It was felt that this was sufficient indication to go ahead with the redesigned 45 slot stators with a can in the bore.

The final can configuration is made of 0.006 inch thick hypernik steel butt-welded with an electron beam welder and having a shrink fit in the stator bore. The hypernik steel was chosen for its sharp magnetic saturation point and for ease in welding.

The layout was also used to determine the effective conductors with 30 and 60 degree switching angles for delta and wye connections using both two and three-phase conduction. It was determined that the least electrical ripple (as distinguished from the cogging effect) was obtained with zero skew for the 45 slot punching. It was also determined that use of an 8/9 pitch would not lower the torque or increase ripple.

It was also determined that a 60 degree switching angle using a delta connected winding with three-phase conduction gave the least ripple. The ripple at zero speed for the 30 degrees switching angle for a wye connection was 11.8 percent; the ripple for the 60 degree switching angle, delta connected winding, with three-phase conduction was 9.8 percent. The ripple torque at higher operating speed for the former rose to approximately 27 percent at certain combinations of voltage and speed while the ripple torque of the latter decreased to below 5 percent.

Use of a 60 degree switching angle implies that two power switches must be operated simultaneously to take advantage of the lower ripple. This would entail some sort of positive device for insuring that the two power switches operate exactly alternately. Since work on the project has progressed too far for major modification, it was decided to leave this for future improvements. Winding the stator with a delta connection was considered in case it was desired later to make the change. However, a 30 degree switching angle with a delta connection gave approximately 19 percent ripple at zero speed. Consequently, the winding was left wye connected. The winding was recalculated as follows:

Turns per coil = TPC = 62
Flux per pole = Φ = 15.46 (from previous calculations)
Perimeter = PER = 4.0
Ohms per 1000 feet of No. 28 wire = Ω = 66.17
Emperical factor = 1.05
Heat Factor = HF = 1.2

Number of slots = Sp = 45
Effective phases = 2.05 (from layout)
Desired total resistance with three legs connected = 38.5
(for I = total armature current = 1.0 amp at 40 volts with 1.5 volts drop in the switches).
Desired phase resistance = 38.5/1.5 = 25.7

$$\text{Hot resistance per phase} = \frac{(\text{HF})(\text{PER})(\Omega)(\text{TPC})(\text{Sp})(1.05)}{(\text{Phases})(12)(1000)}$$

$$= \frac{(1.2)(4)(66.17)(62)(45)(1.05)}{(3)(12)(1000)} \doteq 25.8$$

$$\text{Conductors per phase} = \frac{(\text{TPC})(\text{Sp})(2)}{\text{Phases}} = \frac{(62)(45)(2)}{3} = 1860$$

Total effective conductors = Z = 2.05 x 1860 = 3810

$$\text{Torque} = \frac{(22.6)(P)(\phi)(Z)(I)}{\text{Parallel paths}} \quad \text{oz-in.}$$

$$= \frac{(22.6)(8)(15.46)(38.10)(1)}{1} = 106.7 \text{ oz-in.}$$

The can in the stator bore will shunt some of the flux but it is difficult to exactly assess the effect. The approximate effect was calculated in the following manner. The total mmf for the teeth and yoke of the stator was calculated at 59.8 ampere turns for one-half pole pitch.

Length of can for one-half the distance between poles = 0.143
Amp turns/inch = 59.8/0.143 = 420
From a magnetization curve of hypernik, the flux density = 101.5 Kl/in^2
Area of can = (0.006(0.53) = 0.00316
Flux = (101.5)(0.00316) = 0.321 Kl.
Total flux = (2)(0.321) = 0.641 because of having 2 sides to a pole.
If torque varies directly as flux,

$$\text{New torque} = \frac{15.46-0.641}{15.46} (106.7) = 102 \text{ oz-in.}$$

This calculation should be conservative since the total flux should increase because of the easier magnetic path.

D. Design and Test Results - Control

1. Weight

The complete control unit weighed 1.38 pounds. This agrees very closely with the calculated weight of the manufactured configuration and is 0.37 pounds lighter than the proposed weight of 1.75 pounds.

2. Drive Oscillator

The reluctance switch drive oscillators were operated with 28 volts d-c applied. The frequency of oscillation was measured with an oscilloscope and found to be approximately 4.7 kilocycles. The output waveform of the oscillator exhibited high switching spikes (approximately 50 volts); therefore, de-spiking is required to prevent damage to the oscillator transistors and also improve the discrimination between the coupled and uncoupled output voltage of the reluctance switch. Two ways to accomplish de-spiking are:

a. Place a series resistor-capacitor (RC) network across the saturation transformer winding.

b. Use Zener diodes in place of diodes for commutation.

Zener diodes will be incorporated into the units. The existing diodes can be removed and replaced with Zener diodes without adding additional components. The RC network is undesirable because it will load the oscillator and increase the input power requirements.

3. Reluctance Switch Operation

The coupled and uncoupled output voltages of two reluctance switches were measured with an oscilloscope while being driven with the oscillator. The maximum output voltage during the coupled state varied from 10.5 volts peak to 13.0 volts peak. The voltage during the uncoupled state varied from 1.5 volts peak to 3.5 volts peak. These values agree closely with the design points.

4. Motor Operation

Although a cogging problem in the motor necessitated redesign of the motor stator, a motor was built using the original stator design and operated with the control unit. The trigger circuits were adjusted so that the conduction period of each power switch was approximately 150 electrical degrees. A crude adjustment of the reluctance switch was also made. A rough measurement of the locked torque indicated approximately 110 oz-in. The input current at locked rotor with 40 volts d-c applied to the motor was measured to be 0.8 amperes at the low torque point and 0.95 amperes at the high torque point. More accurate measurements of these parameters will be made on the redesigned motor in the test laboratory after precise adjustments of the reluctance switch stator position and conduction angles of the switches are made.

The motor was checked for reversing capability. Alternate application of power to the two reluctance switches changed the direction of rotation as expected.

5. Control Power

While operating the motor, the input current and voltage to the drive oscillator were measured. With 28 volts d-c applied to the oscillator, the input current was 0.08 amperes. This represents 2.24 watts of control power and is lower than the proposed value of 2.5 watts. The input power to the oscillator represents the power required by the oscillator, reluctance switch, trigger circuits, and base drive for the Darlington Amplifiers.

III. NEW TECHNOLOGY

There is no new technology to report for this period.

IV. PROGRAM FOR NEXT REPORTING INTERVAL

In the next quarter, the motors will be reworked and tested. Modifications will be made as necessary and two complete units will be delivered to NASA. A final comprehensive report will be written including recommendations for improvements and further development.

V. CONCLUSIONS AND RECOMMENDATIONS

It has been concluded that the original motor design must be modified to use a 45 slot punching with a flux-shunting can in the stator bore to limit reluctance cogging. Calculations indicate that minimum torque will still be obtained. The improvements in the motor will be left to future development. Some minor changes in the control circuitry may be necessary after test.