DEVELOPMENT AND TESTING OF A DUAL-WOUND DC MOTOR GEARHEAD

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ABSTRACT

The development and testing of a novel design of dual-wound DC motor and integral gearhead is described. Extensive testing has proved its ability to operate in vacuum over the temperature range -45 to +85 deg C, with a life in excess of 250 hours.

The unit has a rated torque output of 1.5Nm with a nominal output speed of 30rpm and could be used as a prime mover in many medium speed space applications. Its high overall efficiency means that it can be backdriven.

Motors, mechanisms, vacuum testing.

1. BACKGROUND

Virtually all active satellite mechanisms have an electric motor of some sort: in most instances stepper motors are used where precise positional control is required. Permanent magnet DC motors are less common, but one application for them is in the deployment and retraction of solar arrays. DC motors have the advantage that their controls are simple; in the limit an on/off switch and a DC power supply are all that is required.

This paper describes the development and testing of a permanent magnet DC motor with a dual wound armature and an integral gearhead. This unit, which is the only space qualified dual-wound motor gearhead in Europe, has been extensively tested and could be used in other applications such as, for example, in extendable masts.

The motor was developed by Moore Reed Ltd., under contract to ESA. This company worked in conjunction with OTM Servomechanisms Ltd who produced the gearheads.

The performance requirements were based on those of the Space Telescope Solar Array (STSA) secondary deployment mechanism. The bi-stems which deploy the blanket are stored on cassettes on either side of the array and the deployment and retraction of the array is controlled by a DC motor gearhead.

2. PERFORMANCE REQUIREMENTS

The principal requirements for the motor gearhead were as follows:-

1. The unit should have a nominal rated output torque of 1.5 Nm with an output shaft speed of 30 rev/min.

2. It should be able to operate in vacuum over the temperature range +85 to -45 degC.

3. The unit should have full electrical redundancy.

4. The unit should be able to be backdriven to permit emergency operation by an astronaut.

5. In addition the motor gearhead must fit within the cassette envelope and must be capable of surviving Shuttle launch loads and vibrations.

The maximum duration of operation of the unit at any one time was expected to be 10 minutes.

3. MOTOR GEARHEAD DESIGN

The main design features of the motor gearhead are described here.

3.1 Motor

The characteristic of a DC permanent-magnet motor is that, for a given voltage, output speed is inversely proportional to output torque. The novel feature of the motor described here is that it has two separate windings on the same armature. The windings are radially separated but electrically isolated and each is connected to its own eleven-segment commutator. The arrangement is shown schematically in Fig.1. The wire gauge and number of turns on each armature is adjusted so that each has the same torque-current characteristic. The ferrite permanent magnets are bonded to the stainless steel housing. The wear rate of conventional graphite brushes in vacuum is very high because of the well-known phenomenon of dusting wear. After some initial trials a proprietary brush compound (designated 046-45) was chosen for the brushes. This contains mainly molybdenum disulphide and gives a low rate of wear in vacuum but has the slight disadvantage that the brushes must be purged with an inert gas (such as nitrogen or argon) when the motor is operated in air.

The armature was supported on dry lubricated (Bartemp) bearings which are lubricated by transfer from a sacrificial cage made from a PTFE/MoS_2/glass fibre composite. Such bearings are well proven in many satellite mechanisms.

Each commutator had a pair of spring-loaded brushes mounted in a holder. The position of each holder relative to the housing was initially adjusted to give optimum commutation.

3.2 Gearhead

To achieve the required output speed, a reduction gearbox coupled the motor to the output shaft. A reduction of 160:1 was obtained with five passes of spur gears. The layout of the gearhead is quite conventional with the gears supported on layshafts, and each layshaft runs on miniature ball bearings. The layout is shown schematically in Fig.1. This arrangement results in a high overall efficiency (about 90%) which means that the motor gearhead combination can be backdriven. All the gearhead components were made from austenitic (S80) stainless steel with the gears and shafts being hardened by a commercial nitriding process. This process is a thermo-chemical diffusion treatment which produces a hard surface layer about 0.2mm deep.

Both the motor and gearhead were made to international frame size 18 (nominal outside diameter 45mm).

4. TEST METHOD

4.1 Test arrangement

The philosophy was to subject the units to realistic thermal vacuum tests to compare the performance both in air and in vacuum over the temperature range +85 to -45 degC. This is a typical temperature range for many spacecraft mechanisms. In addition to tests at these temperatures, the units also underwent a non-operating survival test at -60 degC. The units were installed in a small 4 inch vacuum chamber at ESTL as shown in Fig.2. The output shaft was coupled via a ferrofluidic feedthrough to an external dynamometer which measured the output torque. The temperature of the motor gearhead was controlled by surrounding it with a copper heater/cooler, the temperature of which was controlled by circulating fluid through it from an external temperature-controlled bath. This type of conductively coupled control eliminated the need for extended periods of cooling between operations in vacuum. In practice, a period of 50 minutes between motor energisation was found to be sufficient. Another advantage was that the temperature of the unit could be varied whilst the chamber (and rotary feedthrough) remained at room temperature. Three thermistors were attached to monitor the temperature, one on the motor casing and two on the gearhead.

The motor was powered from a DC power supply which was set to deliver a particular voltage, 30 volts for a high voltage case or 22 volts to simulate a low voltage condition. The power supply current limit was set to 600 mA, so that high currents could not be supplied to the armature, thereby avoiding overheating. The current consumed by the motor was monitored by measuring the voltage drop across a 1 ohm resistor in series with the motor. The output torque in all the tests was 1.27Nm (180 oz.in).

4.2 Data Monitoring

Motor current and dynamometer torque were recorded continuously during each performance test on a chart recorder. In addition current, output speed and the temperatures of the three thermistors were logged at 1 minute intervals during each 10 minute run on the ESTL data logger. During life testing data was logged once during each motor operation.

4.3 Dynamometer

Initially, a purpose built friction dynamometer was used. This comprised a steel shaft with two polyacetal friction pads spring loaded against it. The reaction torque of the brake was measured by a strain-gauged beam. This device was capable of exerting torques up to 7Nm and, because of the friction characteristics of the polyacetal, the torque exerted was independent of speed. In practice the torque remained within 5% of the initial set value during a 10 minute run. For the tests on the second Qualification model, a Magtrol hysteresis dynamometer was used instead of the friction brake and this gave an even more consistent torque output.

4.4 Test Procedure

For each of the units tested, the functional test programme was similar in that it comprised the sequence of tests detailed in Table 1. The Life Test sequence is also detailed in Table 1. Detailed step-by-step Test Procedures were written for each of the models tested [1,2,3]. Each test had full Product Assurance.

5. MODELS TESTED

The models tested were as follows:

Type	Motor	Gearhead
Prototype	Size 11	Size 11 (100:1 ratio)
11/18	Size 11	Size 18 (160:1 ratio)
1st Qual	Size 18	Size 18 (" ")
Eng.Model	Size 18	Size 18 (" ") Modified Design
Flight Std	Size 18	Size 18 (" ") Modified Design
2nd Qual	Size 18	Size 18 (" ") Modified Design

A resume of the models tested and the outcome is shown in Table 2.

The prototype model referred to above was a commercial unit comprising a size 11 motor and size 11 100:1 gearhead. In fact two gearheads were supplied each lubricated with a different grease (Braycote 602 and Fomblin Y VAC 3). These prototypes were used to both assess the behaviour of the greases over the range of temperatures and to develop the test method. As a result of these tests [4], Braycote 601 grease for the gearhead, and 046-45 brushes were selected.

The next stage was to test a size 11 motor (with a single winding) coupled to a size 18 gearhead of 160:1 ratio (referred to as the 11/18 model). This underwent a full functional and life test. Following this, a first Qualifcation model dual-wound motor gearhead also underwent full functional and life testing. As a result of a gearhead bearing failure during the life test, (after a total running time of 82 hours 40 minutes) the gearhead design was modified. An extended life test was carried out (in air) on an engineering model motor coupled to a gearhead of the revised design to confirm its durability. This model ran successfuly for over 200 hours. The test was continued, but after some 240 hours one of the layshafts suffered a fatigue fracture. Since then a second Qualification model and a Flight standard model, with a revised gearhead design, have successfully completed, respectively, Qualification and Acceptance tests.

6. RESULTS

The results of the performance tests on each model are summarised in Table 3 and the Life Tests results in Table 4. Fig.3 a,b and c summarise the start voltage, no load speed and breakaway torque results. The performance results show that, in general, a current of 300mA was required for a torque output of 1.27 Nm. The main departure from this was for operation in vacuum at 85 degC where currents of up to 390-400mA for the first Qualifcation Model were recorded with correspondingly lower output speeds. Breakaway torques were higher at -45 degC compared with other temperatures, indicative of higher gearhead friction. However, the average currents during functional tests at -45 degC were similar to those at room temperature. The inference is that although the grease is stiff at low temperatures, it is rapidly channeled away from the moving surfaces when the unit is powered. From the data obtained in these tests the torque-speed-current graphs shown in Fig.4 have been drawn.

7 DISCUSSION

7.1 Armature temperatures

During the performance tests in vacuum the resistance of the armature was measured at the beginning and end of each run. The variation of armature resistance with temperature is shown in Fig.3d. With these results, some indication of the temperature rise in the armature could be obtained, although the accuracy was poor due to the variation of brush/commutator resistance which is in series with the armature. Of particular concern was the temperature rise superimposed on an ambient temperature of 85 degC. There was an indication from these results, later corroborated by a nodal thermal analysis of the motor, that the temperature after a 10 minute run under these conditions could have exceeded 183 degC. This is the melting temperature of the solder used to join the armature wires to the commutator. In fact, the motor in the 11/18 unit failed in an open circuit manner during its life test due to local solder depletion. For subsequent motors a higher melting point solder was used and no similar problems were experienced. The armature temperature variation for the 85 degC case and the temperatures inferred from resistance measurements are shown in Fig.5.

7.2 Gearhead failures

The layshaft bearings are located in end plates as shown in Fig. 1. During the Life Test on the first Qualification model one of the bearings on the third layshaft disintegrated. This bearings was the most highly loaded of its size in the gearhead, although the calculated load was well within the manufacturer's rated capacity. A detailed investigation concluded that the most likely cause of failure was small angular misalignment of the layshaft which would result in high ball/cage forces. The chosen remedy was to revise the tolerances of the layshafts and to replace the bearing with a double bearing.

A gearhead built to this revised design performed satisfactorily during an extended life test up to 240 hours. At this point, the third layshaft fractured. The cause of this fracture was investigated in detail [5]. The fracture originated at the root of the shoulder where the shaft enters the bearing. It transpired that the ends shaft had been ground to size after nitriding thereby removing the nitrided layer from the part of the shaft which inserted into the bearing. The failure occurred by fatigue, initiated at the highly stressed shaft root where the nitride layer ended.

In all subsequent gearheads a larger blend radius was introduced at the change of section of the layshaft to reduce the stress concentration, and all machining operations were completed before nitriding.

8. CONCLUSIONS

This novel design of dual-wound permanent magnet DC motor and integral gearhead has been developed and extensively tested. The unit has full electrical redundancy and can be backdriven.

The policy of stepwise development of models followed by realistic testing has revealed the life-limiting features and enabled design modifications to be implemented to overcome these problems. Although the results in this paper relate to the performance requirements of the STSA secondary deployment system, the concept could be applied to other satellite mechanism applications. The unit can operate over a wide temperature range, certainly adequate for many applications, and has a proven long life.

9. REFERENCES

1. ESTL/TP/065 Issue 4 Qualification and Life Test Procedure.

2. ESTL/TP/067 Issue 1 Accelerated Life Test Procedure.

3. ESTL/TP/068 Issue 1 Acceptance Test Procedure.

4. J C Anderson. Report No. ESA (ESTL) 068, Performance and Life Testing of Motor Gearheads, January 1985.

5. NCT Report No. 1185/437.

10. ACKNOWLEDGEMENTS

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TABLE 1

FUNCTIONAL AND LIFE TEST SEQUENCE

Functional test sequence

	Start volts	No-load speed 30V	No-load speed 22V	Breakaway torque (unpowered)	Performance 10min 30V	Performance 1.27 22V
Winding 1 cw/ccw	x	x	x	x	x	x
Winding 2 cw/ccw	x	x	x	x	x	x
both windings cw/ccw	x	x	x	x	x	x

Note x indicates that the test was repeated for clockwise (cw) and counterclockwise (ccw) output shaft rotation.

The above test sequence was repeated at ambient
vacuum 20 deg C
" 85 deg C
" -45 deg C
" 20 deg C

Life test sequence

Duty cycle time minutes (30v 1.27Nm)

	On(cw)	Off	On(ccw)	Off
Air (nitrogen purge)	10	10	10	10
Vacuum	10	50	10	50

TABLE 2 SUMMARY OF MODELS TESTED

Configuration	Purpose of Test	Outcome
Size 11 single wound motor Size 11 gearhead	To select grease and test brush materials.	Braycote 601 grease and Boeing 046-45 materials chosen.
Size 11 single wound motor Size 18 gearhead.	Performance and Life Test on 160:1 gearhead	Performance test satisfactory. Gearhead bearing failure during life test.
Qual motor gearhead (18/18)	Full performance and life test.	Performance test satisfactory. Gearhead bearing failure during life test (82 hours 40 minutes)
Eng. motor Qual. gearhead (18/18)	Extended (200 hour) life test on modified gearhead	Layshaft fracture after 240 hrs.
Qual. motor gearhead (18/18)	Full performance and life test.	Satisfactory (250 hours)
Flight standard model (18/18)	Acceptance Test	Satisfactory

TABLE 3 SUMMARY OF FUNCTIONAL TEST DATA

Model	Test Condition	Voltage	Current(mA)	Speed(rpm)
11/18	Ambient 20 deg C	30	300	40
	Ambient 20 deg C	22	300	27
	Vacuum 20 deg C	30	320	38
	Vacuum 20 deg C	22	310	25
	Vacuum 85 deg C	30	300	37
	Vacuum 85 deg C	22	330	20
	Vacuum -45 deg C	30	370	38
	Vacuum -45 deg C	22	370	25
	Vacuum 20 deg C	30	330	39
	Vacuum 20 deg C	22	330	25
First Qual.	Ambient 20 deg C	30	300	35
	Ambient 20 deg C	22	300	27
	Vacuum 20 deg C	30	320	34
	Vacuum 20 deg C	22	310	26
	Vacuum 85 deg C	30	300-390	28-34
	Vacuum 85 deg C	22	360-405	18-22
	Vacuum -45 deg C	30	310-335	22-25
	Vacuum -45 deg C	22	275-315	23-26
	Vacuum 20 deg C	30	285-340	33-39
	Vacuum 20 deg C	22	300-320	24-29

Cont'd

TABLE 3 SUMMARY OF FUNCTIONAL TEST DATA
Cont'd ..

Second Qual.	Ambient 20 deg C	30	290-310	34-36
	Ambient 20 deg C	22	275-290	25-29
	Vacuum 20 deg C	30	295-350	34-39
	Vacuum 20 deg C	22	290-320	25-28
	Vacuum 80 deg C	30	330-365	33-40
	Vacuum 80 deg C	22	310-350	23-30
	Vacuum -45 deg C	30	305-340	30-35
	Vacuum -45 deg C	22	295-315	23-26
	Vacuum 20 deg C	30	300-330	32-37
	Vacuum 20 deg C	22	270-315	23-26
Flight Standard	Ambient 20 deg C	30	300	34-39
	Ambient 20 deg C	22	267-290	25-29
	Vacuum 20 deg C	30	290-330	33-37
	Vacuum 20 deg C	22	270-320	23-27
	Vacuum 85 deg C	30	350-380	25-38
	Vacuum 85 deg C	22	345-365	21-28
	Vacuum -45 deg C	30	290-310	30-35
	Vacuum -45 deg C	22	265-280	23-26
	Vacuum 20 deg C	30	270-306	32-38
	Vacuum 20 deg C	22	270-305	22-27

TABLE 4 SUMMARY OF LIFE TEST RESULTS

Model	Test Condition	Current(mA)	Speed(rpm)	Duration
11/18	Ambient	330	37	30h 10m
First Qual	Ambient (winding 1)	280	33	25h 50m
	Ambient (winding 2)	310	34	28h 30m
	Vacuum (winding 1)	330	33	17h 30m
Extended Life Test	Ambient (winding 1)	360	32	135h 38m
	Ambient (winding 2)	360	33	69h 7m
Second Qual	Ambient (winding 1)	330	32	46h 0m
	Ambient (winding 2)	360	33	47h 50m
	Vacuum +50 deg C			
	(winding 1)	300	33	6h 30m
	(winding 2)	320	34	7h 30m
	Vacuum -30 deg C			
	(winding 1)	330	32	7h 30m
	(winding 2)	320	33	7h 20m
	Vacuum 20 deg C			
	(winding 1)	295	36	48h 50m
	(winding 2)	300	36	44h 0m

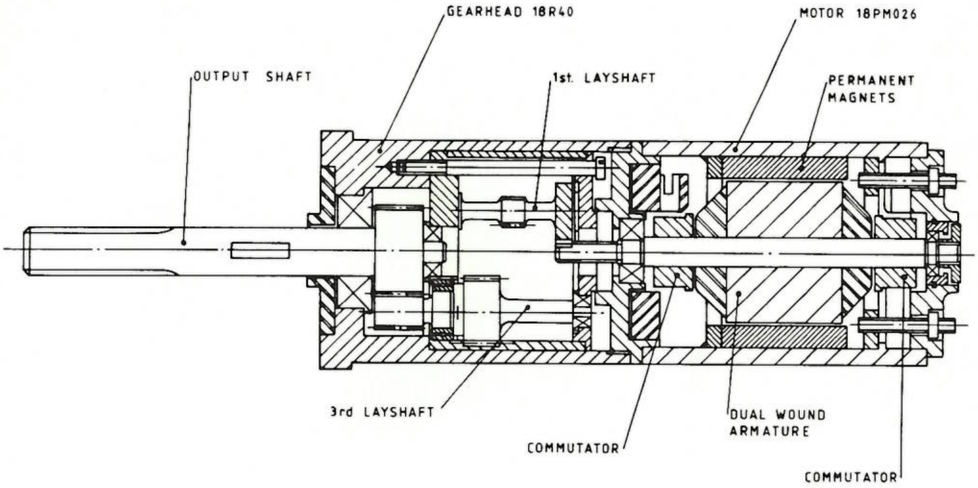

FIG. 1 SECTION VIEW OF DUAL WOUND MOTORGEARHEAD
(NOTE 2ND LAYSHAFT OMITTED FOR CLARITY)

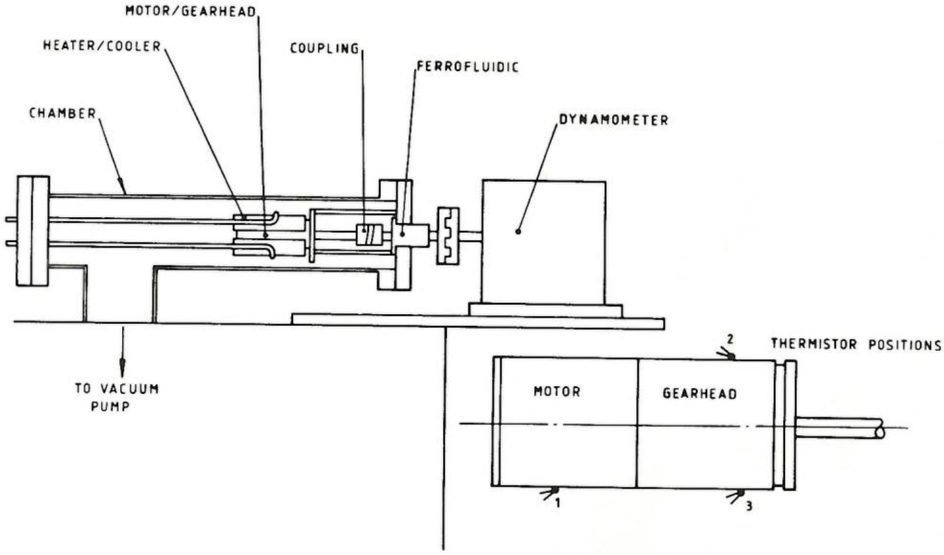

FIG. 2 SCHEMATIC OF TEST ARRANGEMENT

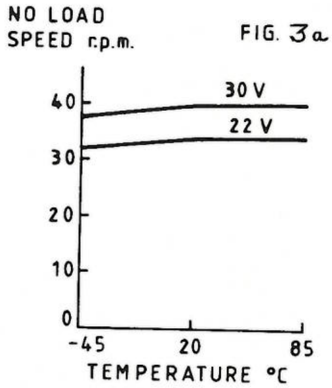

FIG. 3a

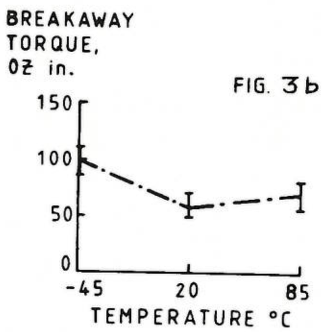

FIG. 3b

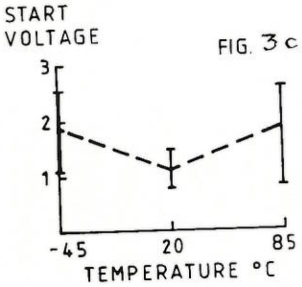

FIG. 3c

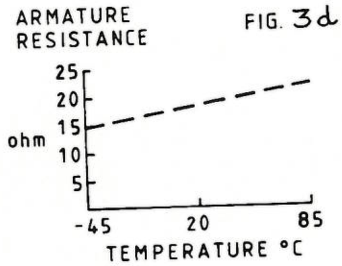

FIG. 3d

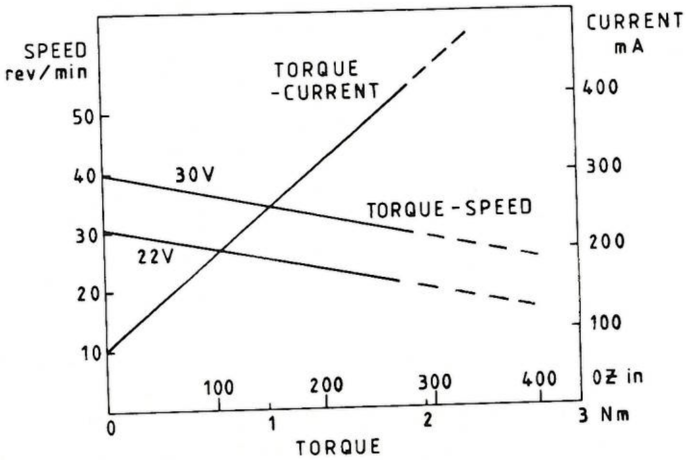

FIG. 4 TORQUE - SPEED - CURRENT CHARACTERISTICS

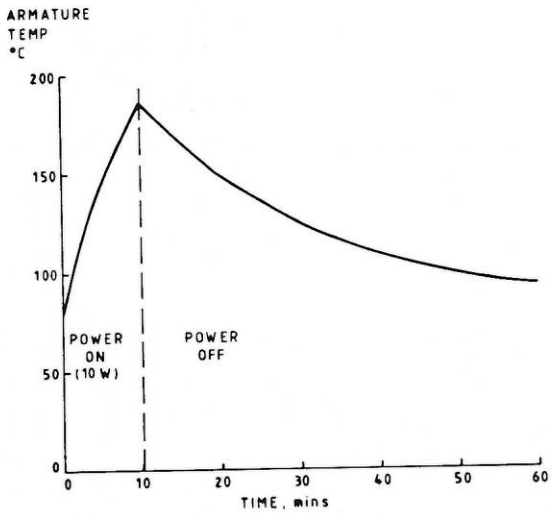

FIG 5 PREDICTED ARMATURE TEMPERATURES