A Brushless Despin Drive and Control for a Communication Satellite Antenna

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This paper describes a brushless despin mechanical drive and control system used to orient a high-gain communications antenna from a spin-stabilized satellite. This drive scheme can be readily adapted to applications requiring three-axis stabilization and high reliability. The paper reviews both the design and the performance test results.

I. Introduction

One of the promising techniques for communications satellite operation is to employ a steerable antenna to achieve high gain and still retain the inherent advantages of spin stabilization. This paper describes a mechanically despun antenna developed at Philco-Ford Space & Re-entry Systems Division, with Ball Brothers Research Corporation acting as the subcontractor for the mechanical subassembly. This antenna, designed for operation in the 7- to 8-GHz frequency band, consists of three major elements: the motor drive assembly, the control electronics, and the RF antenna. The total system weight is approximately 12 lb, including redundant control electronics, while the average power is less than 5 W. The unit has been designed for a 5-year lifetime and possesses features readily adaptable to a variety of despin applications. The antenna is designed to provide earth coverage from synchronous altitude. The required peak gain is 18.0 dB with the half-power point at 9.5 deg off axis.

Figure 1 shows the general arrangement of the antenna in the spacecraft. The despun horn-reflector combination is concentric with the spacecraft spin axis. Radiated energy is focused on the reflector by means of a horn and RF lens and then reflected through an angle of 90 deg so that the beam is continually directed toward the center of the earth as the satellite spins. Also shown in the figure is the location of earth sensors which provide the basic steering signal for the antenna motor drive. Radial and axial thrusters are used to maintain longitudinal station and to periodically correct spin axis attitude as required for proper earth coverage.

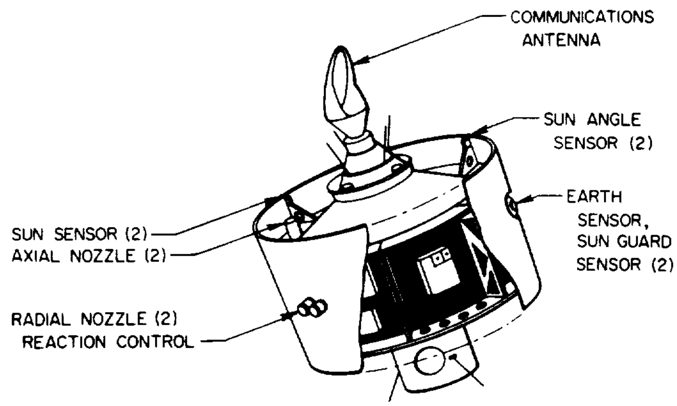

Fig. 1. Spacecraft arrangement showing antenna and drive assembly

II. Despun Antenna System

The despun antenna system consists of the following major subassemblies:

(1) RF subassembly, consisting of radiating aperture (horn, lens, reflector), orthomode-transducer, polarizer, and rotary joint (not discussed in this paper).

(2) Motor drive assembly, consisting of bearings with lubrication provisions, motor, resolver, angular rate pickoff, and position pickoff.

(3) Control system, consisting of an earth sensor assembly, which provides the earth center reference signal, and control logic circuitry, which drives the motor with respect to the earth reference signal.

A. Motor Drive Assembly

The antenna is supported and positioned by the motor drive assembly. There are two pertinent considerations in the mechanical design of this component: (1) the requirement to withstand the launch environment without the complexity of a caging mechanism and (2) the requirement of a mission lifetime of 5 years, which influences the selection of lubrication and bearing configuration and the selection of a drive motor that avoids sliding electrical contacts. The final configuration is shown in Fig. 2.

1. Bearings and lubrication. The basic bearing size is dictated by the RF waveguide, which has a 1-in. bore. Bearings chosen were of the thinnest available cross section large enough to go over the waveguide and have a capacity sufficient to withstand launch loads with a large safety factor.

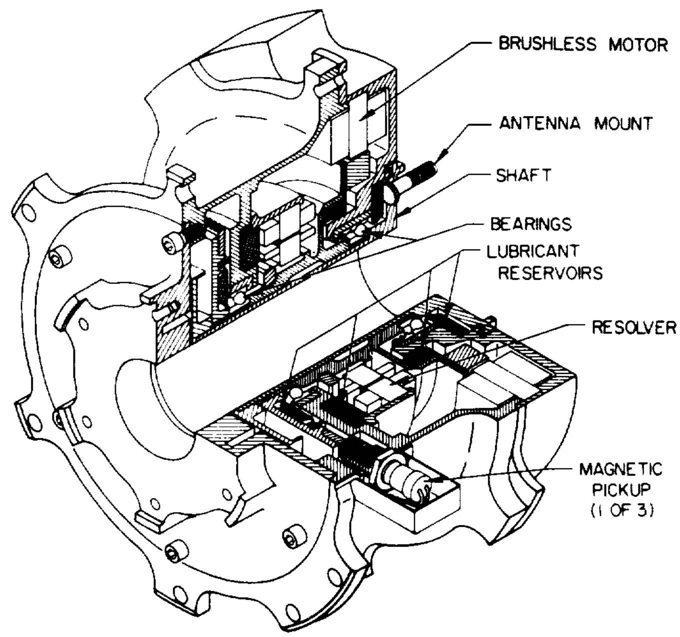

Fig. 2. Cutaway of drive assembly

In order to have a one-piece ball separator with fully enclosed pockets, one shoulder of the outer race is relieved to permit assembly. The bearings are placed back-to-back on opposite ends of the shaft. The outer race of the antenna-end bearing is slip-fitted in the housing and preloaded axially outward by a light spring. The spring is installed in a cup that is cut to length at assembly to give just enough axial play on the shaft to compensate for differential expansion between the housing and shaft when the unit heats to its maximum operating temperature. Spring preload is sufficient to locate the shaft firmly and is well below the minimum thrust capacity of the bearings for 5 years of operation at 110 rpm and maximum achievable reliability. The bearings are made of consumable electrode-vacuum melted 440 C corrosion-resisting steel to provide maximum fatigue capacity and resistance to atmospherically induced corrosion with a standard available material.

The lubricant consists of a low-vapor-pressure organic liquid with metallo-organic additives. It is applied in a thin film on all bearing surfaces and is impregnated into the ball separator, which is specified with a controlled porosity in order to provide it with lubricant capacity. The lubricant and application method bear the designation Vac Kote by Ball Brothers Research Corporation,[1]

[1]For more information on Vac Kote, see "Lubrication of DC Motors, Slip Rings, Bearings, and Gears for Long-Life Space Applications," by B. J. Perrin and R. W. Mayer, in these *Proceedings*.

who developed the process for use on the Orbiting Solar Observatory (OSO) series of satellites.

Lubricant replenishment is accomplished by oil stored in porous nylon reservoirs located on both sides of each bearing. Oil in the reservoirs outgasses slowly until equilibrium is reached between the oil-coated surfaces of the assembly and the oil vapor in the closed compartment. As an oil molecule is lost by evaporation from any surface, it is replaced by one striking and being captured by the temporarily depleted area. At equilibrium there is a continuous interchange of lubricant molecules between the bearing surfaces, the space around them, and the oil-coated internal walls of the assembly. Oil molecules finding their way through the labyrinth seals are replaced by ones from the reservoirs. The thin lubricant films which this system deploys have been proved capable of lubricating lightly loaded ball bearings at moderate speeds and temperatures by hundreds of space-rated components, many operating for thousands of hours.

2. Overall construction. As seen in Fig. 2, the motor and resolver rotors are mounted on an inner shaft with journals for the bearing inner races. This shaft is titanium to eliminate differential expansion effects on the resolver rotor which could affect its output. The titanium shaft is sleeved with an aluminum tube which is flanged at one end to mount the antenna and which forms the waveguide through the center of the assembly. The toothed wheel, which excites the magnetic pickups, and the rotary RF joint flange complete the shaft assembly. The magnetic pickup exciter wheel and the waveguide flange have integral rings which fit closely in grooves in the housings to form labyrinth seals that retard the escape of lubricant.

The housing is in two parts, both magnesium with Dow 17 surface treatment. Bearing outer ring mounting bores are sleeved with 416 corrosion-resistant steel to provide increased resistance to assembly damage and to reduce differential expansion effects on the bearing fits. An AND10050-2 boss is provided for attachment of a nitrogen purge line for prelaunch operation during periods of high relative humidity, which might cause bearing corrosion.

B. Control System

The control for despinning and stabilizing the antenna with respect to the earth is shown in the functional block diagram of Fig. 3. The IR earth sensor mounted on the spinning portion of the satellite provides the basic pointing reference for the despun antenna. The sensor used in this system operates in the 14- to 16-micron IR band and is free of cloud-induced interference. Such a sensor was manufactured by Lockheed Missiles & Space Company initially for the P-11 Program, the Despun Antenna Test Satellite, and the Intelsat Program. The sensor in use on the present program is a high-reliability version having a calculated mean time to failure of 90 years. The Lockheed sensor provides an earth center reference accurate to within 0.2 deg.

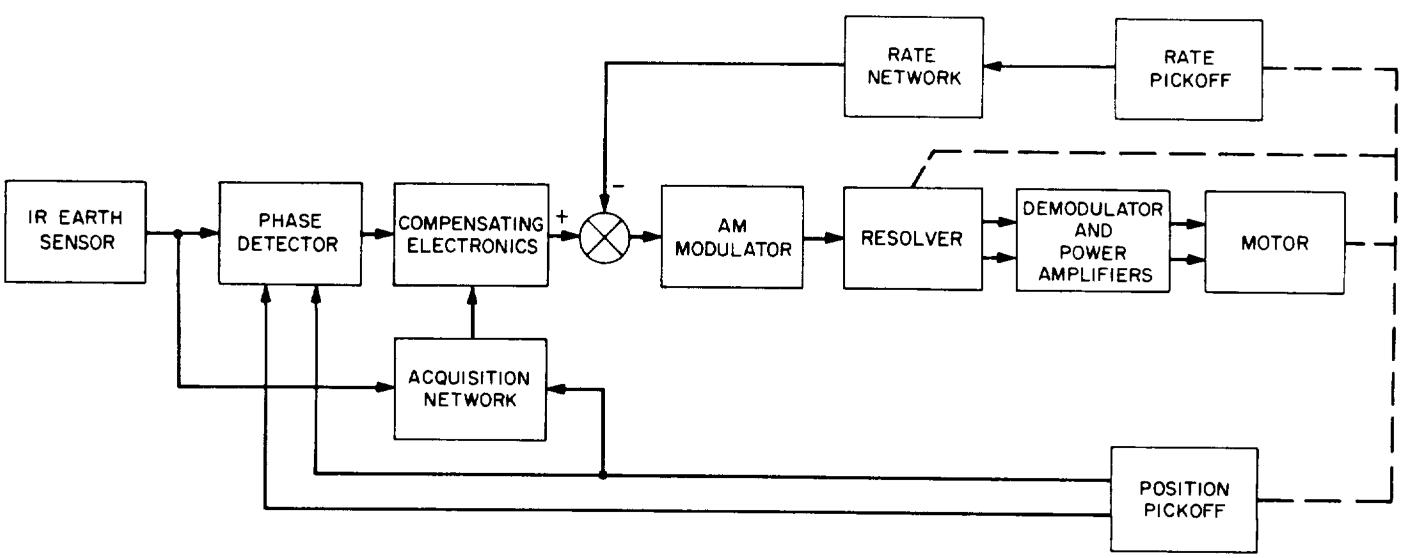

Fig. 3. Despun antenna control loop functional block diagram

Antenna position with respect to the spinning spacecraft is obtained by the use of two magnetic pickups and a steel tooth attached to the drive shaft. Angular rate data are delivered by a third magnetic pickup which is excited by a multiple-toothed steel disc. It was found during development that a high-performance tachometer is necessary to accomplish the pointing accuracy requirement. Two position sensors are used: the signal from the first is used as a prime reference, while the second, mounted 180 deg from the prime, accomplishes sign inversion for the control circuitry. The output of the angular rate magnetic pickup is in the form of a pulse train with a frequency proportional to rotor speed. To avoid the need for a digital frequency lock loop and phase detector, the signal-processing technique converts the pulse train to a speed-proportional signal having a form analogous to the output of a tachometer. Implementation becomes simple in principle and design.

The resolver-commutated synchronous motor affords the system maximum efficiency without the complexity of a special starting circuit and without compromising the long life objectives through the introduction of sliding contacts.

The drive employs a rotary transformer-type resolver which, when properly aligned, acts to commutate the synchronous permanent magnet motor. The resolver has an input winding which is excited at 1000 Hz and two output windings which have an output proportional to the input at the input carrier frequency modulated with a trigonometric function of the angular position of the rotor. The rotor is a variable reluctance element having shorted windings, whose turns and winding distribution are controlled to obtain an optimum modulated wave shape on the output winding and a desired phase relationship between the two windings. The resolver schematic is shown in Fig. 4. The figure also shows the relationship between input and output signals where ϕ is an electrical phase shift between the carrier frequency input and output and θ is the angular position of the rotor.

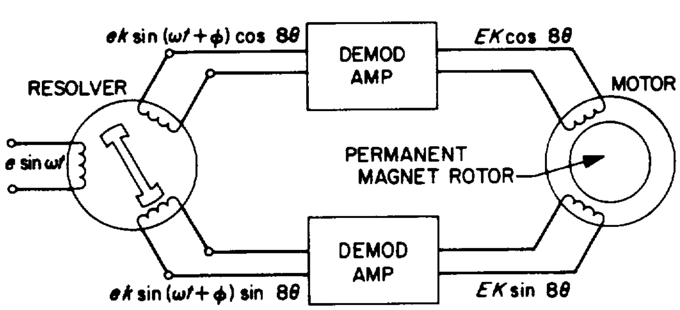

Fig. 4. Motor-resolver block diagram

The acquisition network consists of a speed differential circuit. The earth sensor output triggers a monostable to generate a speed-dependent signal as described above for the rate network. This signal is compared with the output of a similar tachometer circuit operated by the position feedback magnetic pickup. The output error is proportional to the speed differential, after filtering, and is fed to the compensating electronics.

III. Test Results

Performance data available at the time of publication reflect results of two successful breadboard systems and one model constructed of flight quality components in flight model configuration. The data represent the cumulative effort of approximately 10 months of intensive design, simulation, test, evaluation, and redesign.

The power required to operate the mechanically despun antenna is described in two respects, starting transients and tracking. The maximum power input during the starting is limited by the dc-dc converter and is no greater than 7.5 W lasting no more than 10 s. The running or tracking power varies with bearing drag and speed of rotation. The bearing drag varies inversely with temperature and is practically independent of speed in the range of 76 to 105 rpm. A plot of total power versus temperature is shown in Fig. 5. The power includes the requirements for (1) a shunt regulator to reduce bus current ripple to 15 mA peak to peak, (2) the dc-dc converter losses, and (3) the control power for the motor

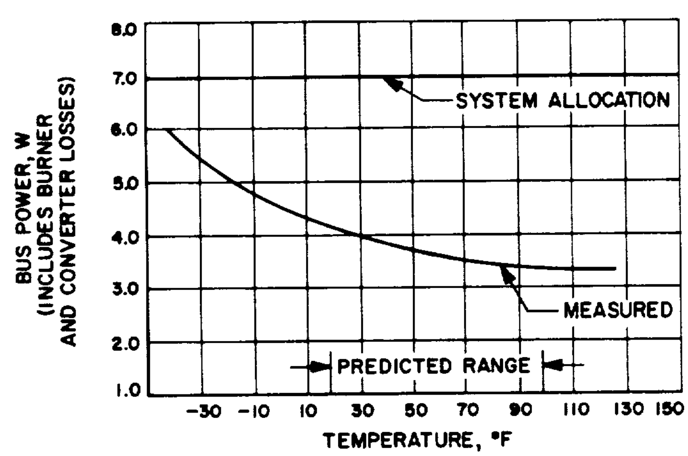

Fig. 5. Bus power vs temperature

drive assembly. The design margins in Fig. 5 result from specifying a 30°F temperature range in excess of the predicted limits. The control circuitry can drive the motor at 180% of the most severe drag torque predicted.

The tracking error varies with speed. Slower speeds result in a greater sensitivity to tachometer errors caused by runout. Electronic drift errors also increase, although slightly. Temperature-induced drift errors are of second-order consequence, with the test data reflecting the jitter error caused by resolver-motor nonconformity and mechanical runout. The results of measurements made on the development model are shown in Fig. 6. In order to demonstrate the context of information shown in Fig. 6, a sample of the acquisition transient is included. The acquisition transient shows the time (≈90 s) from turn-on to tracking at the ±0.5-deg level. The 0.5-deg allocation is from a total system requirement of ±1 deg and is proportioned between mechanical alignment (±0.1 deg), earth sensor errors (±0.2 deg) and the despun antenna control.

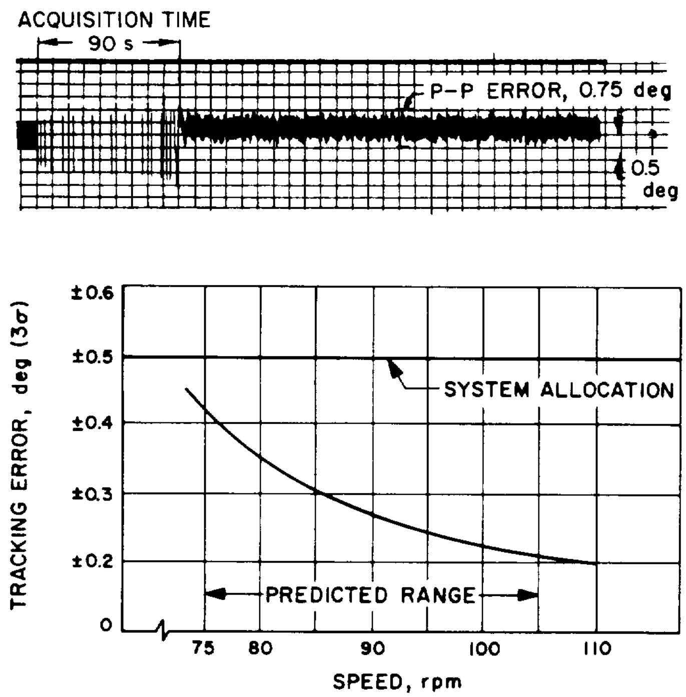

Fig. 6. Acquisition and tracking performance

IV. Summary and Conclusions

A despin drive making use of what is believed to be a unique application of a resolver-commutated synchronous motor to a speed servomechanism has been described. The total system is simple, has a minimum of moving surfaces in contact with each other, and consequently has a high reliability for the long space mission it is designed for. All these characteristics make the drive well suited to its intended mission as well as to others that may arise in the future.

Salient conclusions drawn from this design experience are:

(1) A resolver-commutated synchronous motor is practicable for high-precision orientation requirements.

(2) Sliding electrical contact surfaces can be avoided, enhancing confidence in a long mission lifetime objective.

(3) The system weight and electrical power requirements are extremely attractive, particularly when compared with other schemes.

(4) The system can be readily adapted to related despin applications.

Discussion

H. Smallen: Why was not beryllium used instead of magnesium for the housing of the drive assembly (Fig. 2)?

Beryllium has physical and mechanical properties which enhance its use for bearing housings for aerospace applications. These include:

(1) Coefficient of expansion comparable to steel bearings and races.
(2) High stiffness.
(3) Light weight.
(4) High-precision elastic limit.
(5) High damping capacity.
(6) Better corrosion resistance than magnesium (does not require protective coating as does magnesium).
(7) High thermal conductivity.
(8) High specific heat.

The use of magnesium for the drive assembly housing necessitated the use of a titanium shaft to eliminate differential expansion effects on the resolver rotor. This, along with an aluminum tube, complicated the device. In spite of the high beryllium cost compared to that of magnesium, it is believed that a better and less expensive drive assembly would have resulted.

VHPB (vacuum hot-press block beryllium) would be the logical choice. This material is easy to machine and many intricate housings have been fabricated for space applications.

Table D-1 compares beryllium and titanium for bearing housing application.

D. D. Phinney: Beryllium has excellent characteristics for use as a structural material in despin drives. Our investigations show, however, that the cost differential is significant and cannot be justified in all instances. Titanium and magnesium were used in the subject drive instead of beryllium because of lower cost and better availability, at a penalty of a few ounces of weight. When all requirements were considered, no significant design simplification appeared possible by using beryllium that would offset its high cost. Use of magnesium for the housing, on the other hand, simplified handling procedures, since magnesium is not notch sensitive while beryllium requires any surface scratches to be etched out to prevent cracks.

Table D-1. Physical and structural property comparisons for beryllium and magnesium

Alloy	Density, lb/in.^{3}	Young's modulus, 10^6 psi	Typical tensile strength, ksi		Thermal conductivity, Btu ft/h ft^2 °F	Specific heat, Btu/lb/°F	Thermal expansion, 10^{-6} in./in./°F
			F_{tu}	F_{ty}			
VHPB beryllium	0.067	42–44	50	40	110	0.40	6.2
Magnesium	0.066	6.4	36	29	35	0.25	13.5

F_{tu} ultimate tensile strength.
F_{ty} tensile yield strength.