Rotating/Nonrotating Interface for Data and Power

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ABSTRACT

Two systems, a roll ring and a rotating transformer, were developed to transmit data (30Mbps) and power (8kW) between the fixed and rotating interface of a helicopter with sufficient accuracy, quantity and reliability to support the new generation of on-rotor controls and sensors. A test stand was developed to evaluate performance and endurance of both units. The roll ring was run for 481 hours at speeds from 400 to 800 RPM with full data and power transfer (623 hours equivalent at 400 RPM). It weighed 20 pounds and met the data and power transfer requirements. The rotating transformer was run for 322 hours at 400 RPM with limited power transfer. It weighed 30 pounds, not including the weight of the drive electronics. It met the data transfer requirements and demonstrated power transfer. No wear or life issues were noted. The roll ring and the transformer represent significant improvements in transfer unit capability and endurance. The roll ring is a more mature technology, while the transformer represents promising non-contacting technology, especially in conjunction with on-blade actuation. Near term, both units should be considered for data transfer or de-ice applications. Long term, the transformer should be considered for on-blade actuation with hub-mounted amplifiers.

INTRODUCTION

Need. The U.S. Army advanced rotorcraft requirements for range, payload, speed, maneuverability/agility and cost cannot be met with current rotor technologies. Similarly, high vibration and noise associated with current rotors are impeding rotorcraft effectiveness in both military and commercial operations. Considering operational aspects, the cost of inspecting and replacing critical structural parts on the rotor is high. On-blade, smart material activated rotor control technologies (SMART) and health and usage monitoring systems (HUMS) for rotor components can overcome these barriers. Power and data transfer for on-rotor controls and sensing are a necessary enabling technology. To date, slip rings have been the primary means of transferring data and power in rotorcraft. However, slip rings suffer from data dropouts and noise and require frequent cleaning and brush replacement. They are not adequate for the new rotor technologies.

Objective. The overall objective of the program was to identify, develop, and validate systems that will transmit data and power between the fixed and rotating interface of a helicopter to support the new generation of on-rotor controls and sensors that are being developed. Such a system must transfer both data and power accurately, reliably, with low maintenance requirements and with fail safety. In order to attain these objectives, full use was made in this program of existing technologies for data and power transfer which might apply to the requirement or which might meet the requirement with further development. Non-contacting means of transfer were emphasized, but also considered were innovative contacting systems that were capable of meeting the reliability and maintainability necessary for flight control system application. Specific objectives and the chosen approach are detailed below.

Approach. Innovative methods of data/power transfer, emphasizing reliability and fail-safety were investigated. Full-scale hardware design, fabrication, and testing of two transfer units was completed. The data/power transfer units were sized to meet and exceed the functional requirements and to be physically compatible with the MD900 SMART (Smart Material Actuated Rotor Technology) rotor. This rotor has piezoelectric, on-blade control and was whirl tested in 2003 using a conventional, contacting slip ring unit, Reference 1. The transfer units developed here have the potential to be used during future flight or wind tunnel testing of the MD900 smart rotor system.

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Initial requirements called for 30 Mbps data transfer from rotor to airframe, 1Mbps from airframe to rotor, and 8 kW power transfer. Requirements were refined and tailored to facilitate testing. Preliminary requirements were defined and scaling was assessed for application of transfer units to an advanced AH-64 and growth CH-47. A feasibility study was conducted considering the following technologies for data and power transfer: rotary transformer, RF, optical (laser), power generation on hub, roll ring, and slip ring. The two most promising data/power transfer units were selected; the non-contacting transformer and the contacting roll ring.

Design, fabrication, and acceptance testing of both MD900-size units were completed at the supplier sites. A test stand and driver electronics for data transfer and roll ring power transfer were designed and fabricated at Boeing. A PC-based data system was assembled for data acquisition and display as well as safety monitoring. Performance and endurance testing while rotating was performed at Boeing Mesa. Data from the tests were analyzed, characteristics of the non-contacting and contacting data/power transfer units were compared, and recommendations for further development were made.

REQUIREMENTS DEFINITION

Recently developments in on-blade control have increased in intensity and seen significant progress. Boeing has been pursuing four variable geometry, active control rotor concepts. These concepts are: 1) On-blade control by trailing edge flaps using piezoelectric actuators, 2) Active integral twist through piezoelectric fibers, 3) steady twist actuation by shape memory alloys (SMA) and 4) High lift through oscillatory blowing using electromechanical actuators.

All of these actuation schemes are based on electrical power. Depending on the specific type of actuator, various types of power conditioning, voltage conversion, amplification and control, and energy storage are required. Some of these tasks are best performed on the rotor, despite the harsh dynamic environment (vibrations, centrifugal forces) and the adverse impact of adding equipment to the hub (weight, drag, signature). Therefore, it is mandatory that a systems approach be taken in developing the power transfer unit for a specific application.

For the current program, the trailing edge flap, driven by piezoelectric actuators is selected as a basis for the power transfer requirements. This concept is well along in its development, with whirl tower testing of the full scale MD900 smart rotor completed in 2003 and flight-testing planned for the near future. Furthermore, a preliminary comparison of the four concepts indicates that power levels for the trailing edge flap were chosen conservative enough, and will be sufficient to drive any of the other three concepts.

Data transfer requirements were initially set at 30Mbps from the rotor to airframe and 1Mbps from the airframe to rotor. The 30Mbps rate was arrived at by transferring 25 data channels each at 2, 5, 10, and 20kHz (100 channels total) with a 32-bit resolution. The 1Mbps rate was determined by the transmit rate of actuator and amplifier control commands to the rotor.

Requirements shown in Table 1 are given for non-contacting and contacting transfer methods. The implied assumption is that the power amplifiers are on the rotor (non-contacting) or in the airframe (contacting). MD900 SMART requirements are representative of the MD900 active flap rotor requirements. The MD900 DPT (Data/Power Transfer) requirements serve as basis for the transfer unit hardware development under the current program. It should be noted that the data transfer rate from the airframe to the rotor was set equal to the data rate from the rotor to the airframe in order to simplify testing. The AH-64 and CH-47 requirements are based on simple scaling and are intended to illustrate requirements for application of the data/power transfer technologies to large aircraft.

FEASIBILITY STUDY

Several basic methods have been proposed to overcome the limitations of slip rings. Proof-of-concept data transfer systems have been developed for rotorcraft using optical (laser), RF (radio frequency), and rotating transformer implementations. Power transfer systems have been developed for spacecraft using rotating transformers and roll rings. A comparison of the available transfer methods is shown in Table 2. For the broad range of available transfer methods and general concepts, numerous suppliers were surveyed.

The primary transfer concepts being considered are illustrated in Figure 1. Common elements of the rotor data and power system of interest are: sensors (rotor and actuator), data processing on the rotor and in the airframe, airframe power source (generator), amplifier – high power (conditioning, conversion), amplifier driver (amplification, control, and storage), on-blade actuators, and a controller (airframe based)

Table 1. Transfer Requirements

	MD900 - SMART	MD900 - DPT	AH-64	CH-47
Non-contacting transfer methods with power amplification on rotor:				
data rate from rotor to airframe, Mpbs	5	30	64	64
data rate from airframe to rotor, Mbps	1	30	5	5
power available on airframe	28VDC	115VAC, 400Hz, 3 phase		
power required on rotor - data	28VDC, 5A	28VDC, 5A	28VDC, 10A	28VDC, 15A
- actuation	400VDC, 21A	400VDC, 21A	400VDC, 60A	400VDC, 100A
outer diameter, height of unit, in	OD=5, H=10	OD=5, H=10 or OD=15, H=2	OD=7, H=14 or OD=21, H=3	OD=9, H=18 or OD=27, H=4
inner diameter of unit, in	2.75	2.75	4	5
stationary wire bundle diameter - max, in	1	1	1.5	2
Contacting transfer methods with power amplification in the airframe:				
Data circuits: 5V TTL	14	14	14	14
Power circuits - data: 28VDC	4 at 5A ea	4 at 5A ea	4 at 10A ea	4 at 15A ea
Power circuits - actuation: 1500Vpp	18 at 7.6A ea	18 at 7.6A ea	15 at 20A ea	12 at 40A ea

Table 2. Data and Power Transfer Methods

	Rotating Transformer	Lasers	RF Wireless	Roll Rings	Slip rings	Generators
Pros	EMI resistant Alignment insensitive No contact wear Contaminant resistant Low complexity Maintenance. MTBF **Power transfer**	EMI resistant Alignment insensitive No contact wear	Alignment insensitive No contact wear Contaminant resistant Low complexity Maintenance MTBF	Rolling contact Maintenance MTBF **Power transfer**	**Power transfer**	
Cons	Development risks Weight	Contamination sensitive High complexity **No power xfer**	EMI susceptible **No power xfer (inefficient)**	Alignment sensitive Interharmonic signal noise	Contact wear Signal noise, dropout EMI susceptible Alignment sensitive Maintenance MTBF	Power only **No power when not rotating**

that commands the amplifier driver. The three concepts are:

1. Rotating Transformer. This unit can transfer both data and power using alternating currents. An inverter generates the AC input to the transformer and a rectifier converts its output to DC. Higher frequencies lead to better efficiency, within limits, and smaller size. Using a magnetically coupled core, very high power transfer efficiencies can be achieved. The amplifier driver must be located on the rotor and control signals must be transferred.

2. Optical or RF. Only data can be transferred with this unit. Data must be modulated and demodulated on either side of the interface for bi-directional transfer. Both of these methods are well established. RF methods can be used for power transfer, but are limited by low efficiency, between 10 to 30%. Thus, RF is ruled out for transfer of actuation power. Power can be generated on the hub using an alternator (two required for redundancy). The entire amplifier must be located on the rotor and control signals must be transferred. For pre-flight checks of the actuators (zero RPM built-in testing), a secondary means is used to transfer limited power to the actuators. Alternately, any of the other methods can be used for power transfer.

3. Roll Ring. This unit has the same functionality as slip rings, however a rolling contact is used, resulting in dramatically reduced wear and maintenance. The amplifier driver can be placed in the airframe (a) or on the rotor (b). In case (a), controlled power is transferred bi-directionally and two roll rings (one channel) are required for each independently controlled actuator. In case (b), a single channel transfers power for all actuators. Roll rings require no modulation/demodulation of data or power conversions.

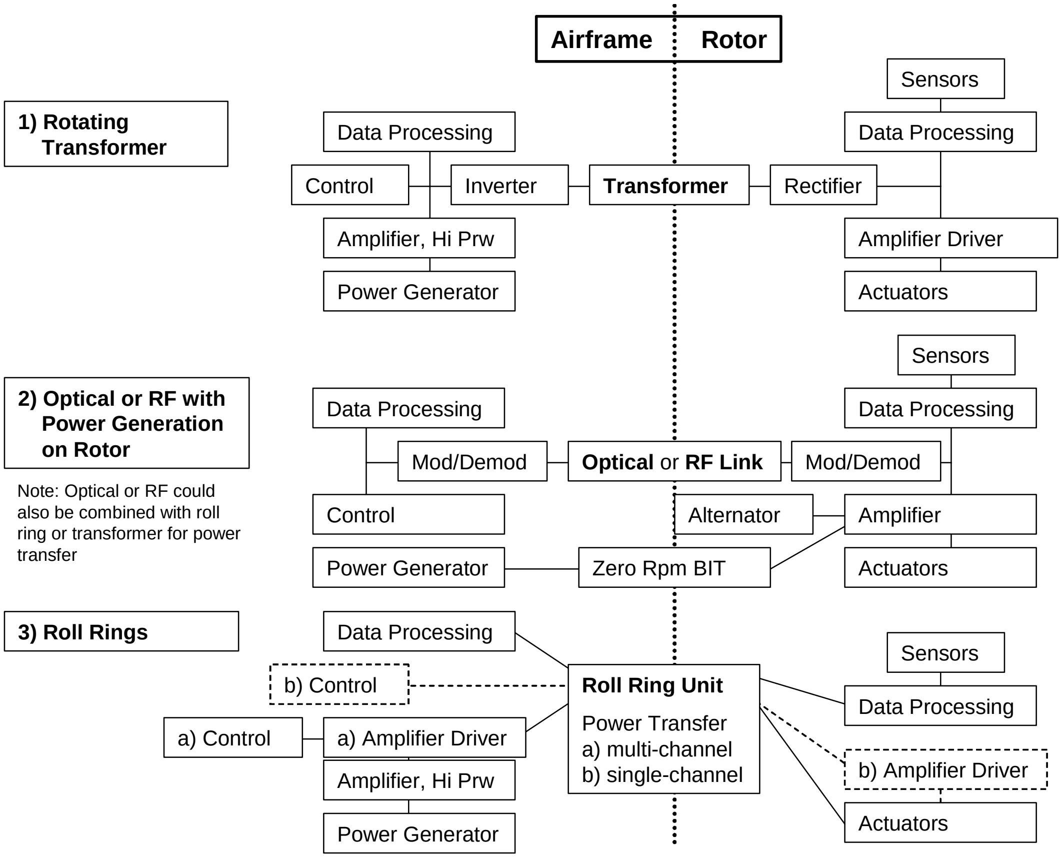


Figure 1. Data/Power Transfer Concepts

Applying system design considerations and trade studies, the technical characteristics, feasibility, and maturity of each concept were established and ranked, Table 3. The rotating transformer by Alpha-Omega and the roll ring by Diamond Antenna were selected as the most promising non-contacting and contacting concept, respectively.

TRANSFER UNIT DEVELOPMENT

Design Requirements

Detailed design requirements and design goals were defined for both the transformer and roll ring. The most important ones are:

1. For bench and flight-testing the transfer unit is intended for installation on top of the rotor hub, with the inner part non-rotating and the outer part rotating. For whirl tower and wind tunnel testing on a test stand (ground test) it is preferable that the transfer unit be installed below the transmission, with the inner part rotating and the outer part non-rotating.
2. The transfer unit shall be designed for the MD900 – DPT requirements, as shown in Table 1. Power required for actuation is 400VDC and 21A if the power amplifiers are located on the rotor, or 18 circuits of 1500VAC peak-to-peak and 7.6A peak if the power amplifiers are located in the airframe.
3. There is a high level of electrical noise on the high power lines. This noise must be isolated from the signal circuits as much as possible.
4. Fail-safety:
    a. Non-contacting: two power transfer channels are required for redundancy, each for 28VDC and 400VDC; a single failure shall not disrupt the data transfer.
    b. Contacting: for redundancy, the unit is required to have spare transfer channels
5. The unit shall be designed considering the following design goals, in order of priority:
    a. Environmental protection from vibration, temperature, humidity, rain, sand, oil, icing, lightning; operation at altitudes up to 10,000ft

Table 3. Data/Power Transfer Concepts Ranking

		Rotating Transformer		Lasers	RF Wireless	Roll Rings		Sliprings		Generators
		Power	Data	data only	data only	Power	Data	Power	Data	power only
1	EMI resistant	3	3	3	1	1	2	1	1	3
2	low EMI generation	2	3	3	2	3	3	3	3	2
3	Alignment insensitive	3	3	3	3	1	1	1	1	1
4	No contact wear	3	3	3	3	2	2	1	1	1
5	Contaminant resistant	3	3	1	3	1	1	1	1	1
6	Low complexity	2	3	1	3	2	2	2	2	1
7	Maintenance free	3	3	2	3	3	3	1	1	1
8	Long MTBF	3	3	3	3	3	3	1	1	1
9	Power transfer	3				3		3		3
10	Signal quality		3	3	3		2		1	
11	Bandwidth		2	3	1		2		2	
12	Development status	1	1	2	2	2	2	3	3	1
13	Light Weight	1	1	2	2	3	3	3	3	1
14	Small Size	2	2	2	2	3	3	3	3	1
15	Low preduction cost	1.6	2	1	1.4	2	2	3	3	1
16	Scale to large size	2.5	1.5	3	2	2.5	2	1.5	1	2
	TOTAL	33.1	36.5	35	34.4	31.5	33	27.5	27	20
	Normalized Total - Power	1.00				0.95		0.83		0.60
	Normalized Total - Data		1.00	0.96	0.94		0.90		0.74	0.60
	Issues				limited, inefficient power transfer	interharmonic signal noise				no power when not rotating

Notes: 3 = highest ranking (best); 2 = medium; 1 = lowest (worst)
large size = 100kW, 60Mbps

- b. Reliability (4500 hours MTBF – mean time between failures) and maintainability (2250 hours MTBO – mean time between overhaul)
- c. Electromagnetic issues, including observability, vulnerability, compatibility and protection;
- d. Ballistic tolerance – vulnerability, survivability.

6. Mechanical interface requirements are governed by the requirement that both transfer units are drop-in replacements for the MD900 SMART rotor slip ring. Both unit shall meet the following requirements:
   - a. Speed: 400 RPM nominal (100% RPM), 480 RPM maximum
   - b. Maximum envelope: Height should be minimized; goal is 10in, not to exceed 15in
   - c. Outer diameter: OD = 4.950in (OD exclusive of any mounting flange)

Roll Ring

Diamond Antenna's roll rings provide contact between rings in the inner (stationary) and outer rotor through a set of rolling flexures, Figure 2. The rolling contact requires no lubricant, has negligible wear debris, low electrical resistance, noise, and dropouts. Units with high voltage rating (3000V), current transfer (200A), and data rates (150Mbps) are available. Life is primarily limited by fatigue of the flexures. Life tests have demonstrated 350M revs at 3150 RPM without maintenance.

The roll ring was designed and manufactured by Diamond Antenna & Microwave Corp, Lowell Mass., in accordance with the preliminary design layout, interface dimensions, electrical, environment, and vibratory requirements.

The aluminum bodied roll ring assembly overall length is 12.5 inches by 5.75 inches in diameter with a center bore diameter of 2.752 inches. The total weight is 19 lbs (without external wiring).

The roll ring circuits were grouped in three sections to optimize the design and minimize height: high power/high voltage, medium power/low voltage, and low-level data. There are eighteen high power channels. Each operates at -300 to +1200 volts AC with a peak current of 7.6 amps (5.4 amps RMS) and a maximum of 1500 volts difference between them. Three of the channels serve as spares. Each channel has three rings with one flexure per ring. However, during final assembly a flexure was not installed in the middle ring of each high power channel. There are four medium power channels. Each carries 5

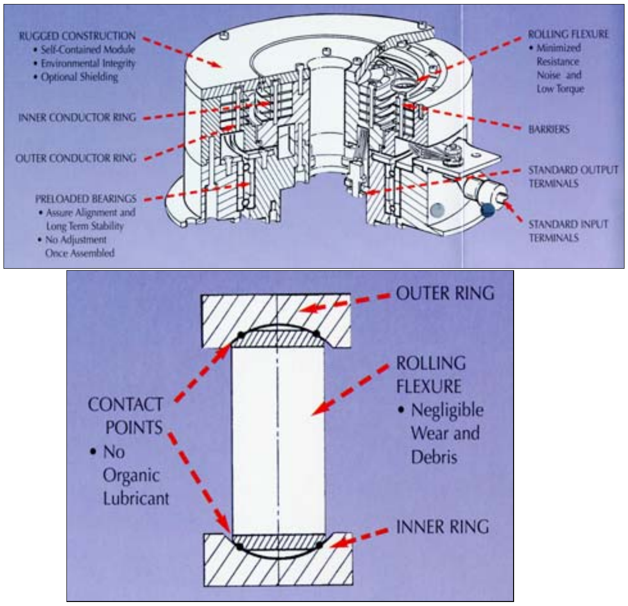


Figure 2. Roll Ring Schematics

amps (10 amps maximum) at 28 volts DC. Two of the channels serve as spares. Each channel has two rings with one flexure per ring. There are fourteen data digital/ground channels. These signals are at TTL (5V) levels. The data rate is 30 MHz. These channels are configured with four two-wire differential signal pairs (RS422 - each with a ground, +signal, and –signal) and two spare channels. The signal channels have two rings and the ground and spare channels have one ring, each with one flexure per ring.

Lead length of the inner body wiring is twenty-one feet of suitable grade and size of wire. Outer body wire terminal blocks are at 4 locations along the body lengthwise. The orientation and distribution of the power (hi & low voltage) and data wires and termination blocks are separated into 4 quadrants at the power side end. The terminals are stud/nut type. Figure 3 shows the roll ring assembly.

The speed capability of the roll ring is up to 900 RPM maximum, where 400 RPM (100%) is nominal. The design calls for a minimum life capability of 4,500 hours at 100% RPM and 75% of max electrical load and a duty cycle of 3 hours continuous at 100% RPM and 100% max electrical load. The roll ring has a temperature operation capability of 20 to 140 degrees Fahrenheit and vibratory capability of +/- 5G at 32.7Hz. Acceptance tests were conducted at the supplier site and demonstrated that the roll ring met the electrical design requirements.

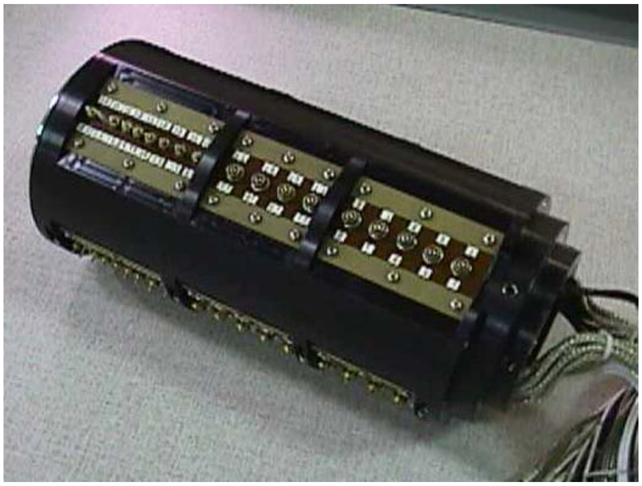


Figure 3. Roll Ring Pototype

Rotating Transformer

Alpha-Omega's magnetically coupled rotating interface (MCRI) couples a high frequency power carrier or a low power very high frequency data carrier. Each interface is composed of two high frequency ferrite cores, one fixed and one rotating. Encoded electrical signals are coupled into the two core sections by fixed windings. There is no physical contact between the two core sections, alleviating all the problems associated with slip rings. Because of the high permeability coupling of the core sections, EMI interference is greatly reduced, unlike RF transmitters. The MCRI is immune to contaminants including oil vapor and EMI interference.

An MCRI for data transfer was previously developed and tested, Figure 4. Analog and digital signals were transferred across the interface from standstill to over 800 RPM. Data was transferred at a rate of 1Mbps with this proof-of-concept system. The measured frequency response of the system indicated that a data transfer rate of over 10Mbps could be achieved with the present core materials. Much higher bandwidths are possible with available higher performance ferrites.

An initial study was conducted and confirmed the feasibility of an MCRI for the MD900 requirements. The rotating transformer and drive electronics were then designed and manufactured by Alpha-Omega Power Technologies LC, Albuquerque NM, in accordance with the preliminary design layout, interface dimensions, electrical, environment, and vibratory requirements.

The aluminum bodied transformer assembly overall length is 15.1 inches by 6.125 inches in diameter with a center bore diameter of 2.752 inches. The total weight is 29.6 lbs (without external wiring).

The MCRI has two transformers for redundant, high-voltage power transfer and two transformers for data transfer to/from the rotor. All four transformers are stacked along the length of the unit. The 28V power required for operating data systems on the hub would be derived from the high-voltage power. The cross-section and principal elements of one split core power transformer are shown in Figure 5. The layout of all four transformers is shown in Figure 6. The inner assembly model clearly shows the ferrite cores as well as the secondary power windings (red) and data windings (blue). The outer assembly model shows the primary power windings (green) and data windings (yellow).

Lead length of the inner body wiring is twenty-one feet of suitable grade and size of wire. Outer body wire terminal blocks are at 4 locations along the body lengthwise. The orientation and distribution of the power and data wires and termination blocks are separated into 4 quadrants to minimize any unbalance. The terminals are MHV connectors for power and BNC connectors for data. Figure 7 shows the inner core assembly and windings. Figure 8 shows the MCRI assembly.

The overall layout of four transformers and the electronics required to drive and test the MCRI are shown in Figure 9. The major electronics sections include the power conditioning, high power inverter, and data transceiver as well as the resistive load.

Acceptance testing at the supplier site demonstrated data transfer at up to 20 MHz and power transfer at 1 kW continuously and up to 4kW peak. Power transfer efficiency was measured by comparing the reading of the input AC power meter to the power dissipated across the resistive load. Efficiency was 99% for a single transformer and 86% for two transformers in series, with an accuracy of about +/- 5%. Since efficiencies of greater than 95% are unrealistic, the single transformer efficiency appears high, particularly when compared with 93% as derived from the dual transformer efficiency. Thus, a more realistic value of 93% efficiency is assumed for the single transformer.

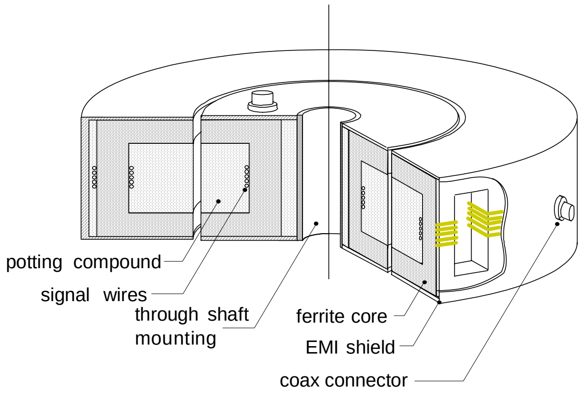


Figure 4. Rotating Transformer Schematic

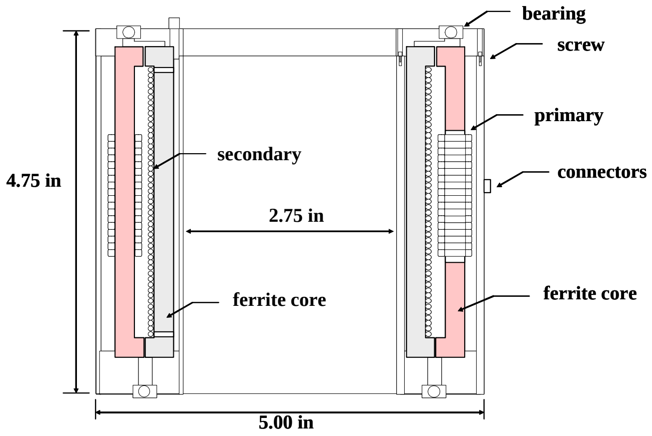
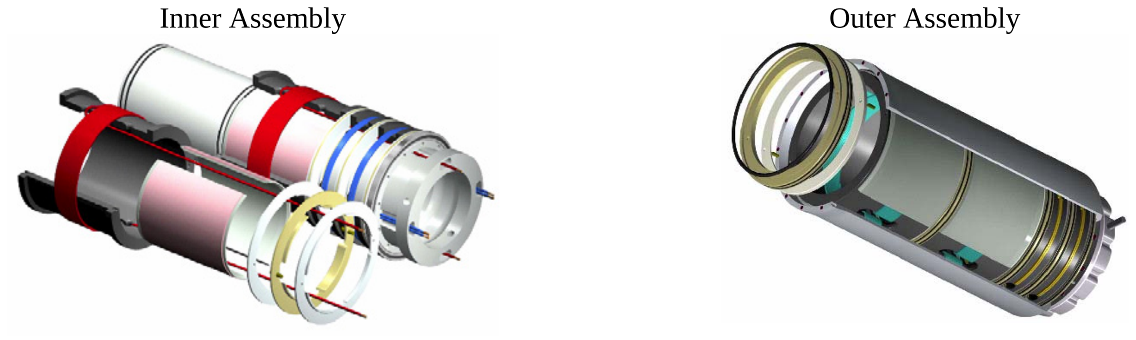


Figure 5. Rotating Transformer Element Cross-section – Power Transfer


Inner Assembly

Outer Assembly

Figure 6. Model of Transformer Inner and Outer Assembly

Figure 7. Transformer Inner Core

Figure 8. Transformer Assembly

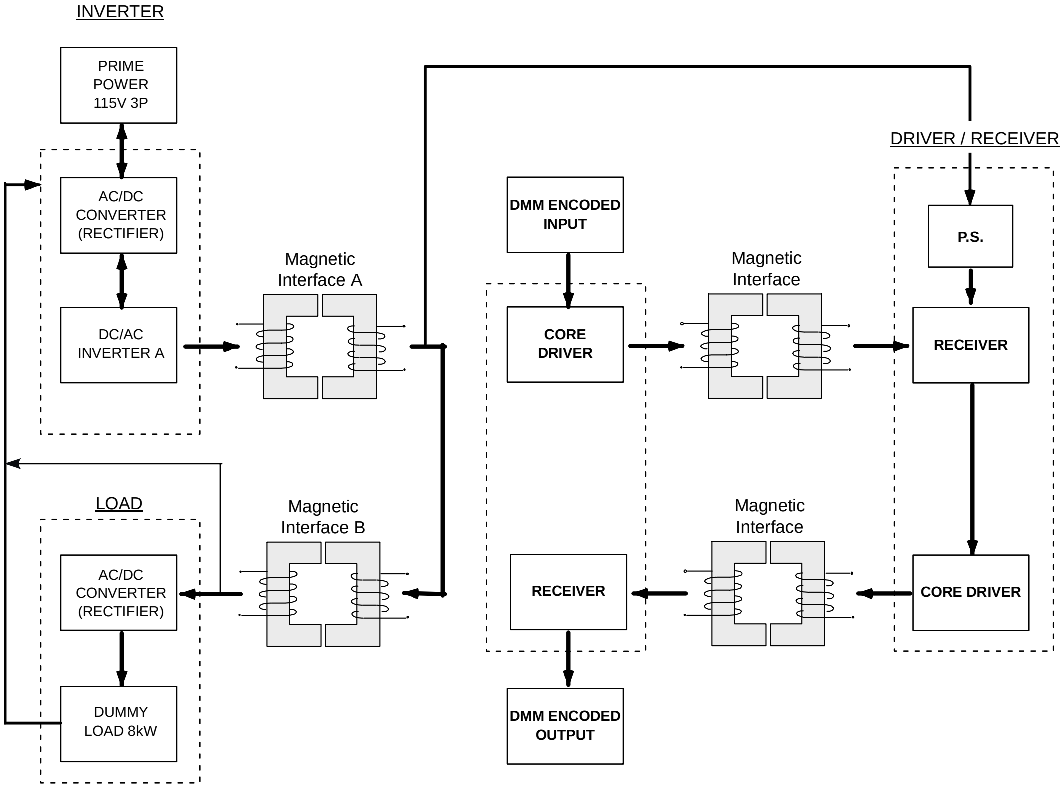


Figure 9. Transformer Configuration and Layout for System Demonstration

Design Summary

A summary of requirements and design data for the slip ring, roll ring, and transformer are shown in Table 4. Comparison of transfer unit outer diameter shows only small differences. Compared to the slip ring overall height, the roll ring height is 22% greater and the transformer height is 32% greater. Similarly the roll ring weight is 67% greater and the transformer weight is 150% greater. It also should be noted that the transformer weight does not include the weight of the required drive electronics. However, the drive electronics could be an integral part of the amplifiers required for on-blade control.

Table 4. Requirements and Design Data Comparison

	Requirements		Design Data		
	MD900 - SMART contacting	**MD900 - DPT** contacting/non-cont	**Slip Ring** contacting	**Roll Ring** contacting	**Transformer** non-contacting
data rate from rotor to airframe, Mbps	5	30	5	30	30
data rate from airframe to rotor, Mbps	0	30	5	30	30
data circuits; 5V TTL	14	14 / 4	14	14	4
data transfer protocol			RS-422	LVDS	LVDS
power available on airframe	28VDC	115VAC, 400Hz, 3P	n/a	n/a	115VAC, 400Hz, 3P
power circuits - data; 28VDC, 5A	4	4 / -	4	4	derived
power circuits - actuation } 1500Vpp, 7.6Apk	12	18	12	18	
- amplifier non-rotating } 500Vpp, 7.6Apk	6		6		
power circuits - actuation; amplifier rotating		400VDC, 21A			1600VAC, 9A (4)
outer diameter of unit, in	5	5 (15 alt)	5.25	5.75	6.125
overall diameter of unit, in			6.375	5.75	8.00
overall height of unit, in	10	10 (2 alt)	11.4	12.5	15.1
inner diameter of unit, in	2.75	2.75	2.75	2.75	2.75
stationary wire bundle diameter - max, in	1	1			
weight of unit, excl ext wiring			12	20	30
Power - actuation			#16 AWG Shielded	#16 AWG Shielded	#14 AWG
Power - data			#16 AWG Hookup	#16 AWG Hookup	n/a
data - basic			#22 AWG Tw/Sh/Pr	#22 AWG Minicoax	#24AWG
lead sequence (S - signal, G - ground)			GSS	SSG	n/a
data - spares			#22 AWG Hookup	#22 AWG Hookup	n/a

TRANSFER UNIT TESTING

Test Setup

The test setup schematic in Figure 10 shows an axial data/power transfer unit, with the inner element (non-rotating) supported by a stationary standpipe and mounted to a base. The outer element (rotating) is mounted to a hub plate, which is driven by a 1 HP, 220-volt AC motor via a pulley/belt system. By changing pulley size, both the nominal MD900 and lower rotor speeds for larger rotors can be attained. Using a variable speed motor allows appropriate overspeeds in order to accumulate a large number of rotor revolutions, i.e. simulated operating hours, in a shorter time. Motor speed is controlled manually by a rheostat. The mechanical setup is essentially the same for the roll ring and transformer.

Power supplies, electronics, electrical loads, and sensors specific to the roll ring or transformer are used to test the power transfer. Power is sent up through the transfer unit and back down using the second, redundant channel and into an electrical load. This load consists primarily of resistors and capacitors to simulate the reactive load of a piezoelectric actuator. Voltage and current of the input and output power are sensed, converted to digital format, and processed in the PC-based data system.

Special purpose electronics are used to generate, send, receive, and check a data signal stream to test the data transfer. The data signal is sent up and back down through the bi-directional data transfer section. The input and output data streams are compared to determine the error rate of the data transfer section, which is recorded in the PC-based data system.

The PC-based system continually acquires and displays all data, including test stand, motor, ambient, and data and power transfer data. Safety checks, implemented in software, trigger automated shutdown and allow for 24-hour operation of the test.

All electronics and sensors are remotely located in the fixed system, with the exception of a data receiver/driver unit for the transformer.

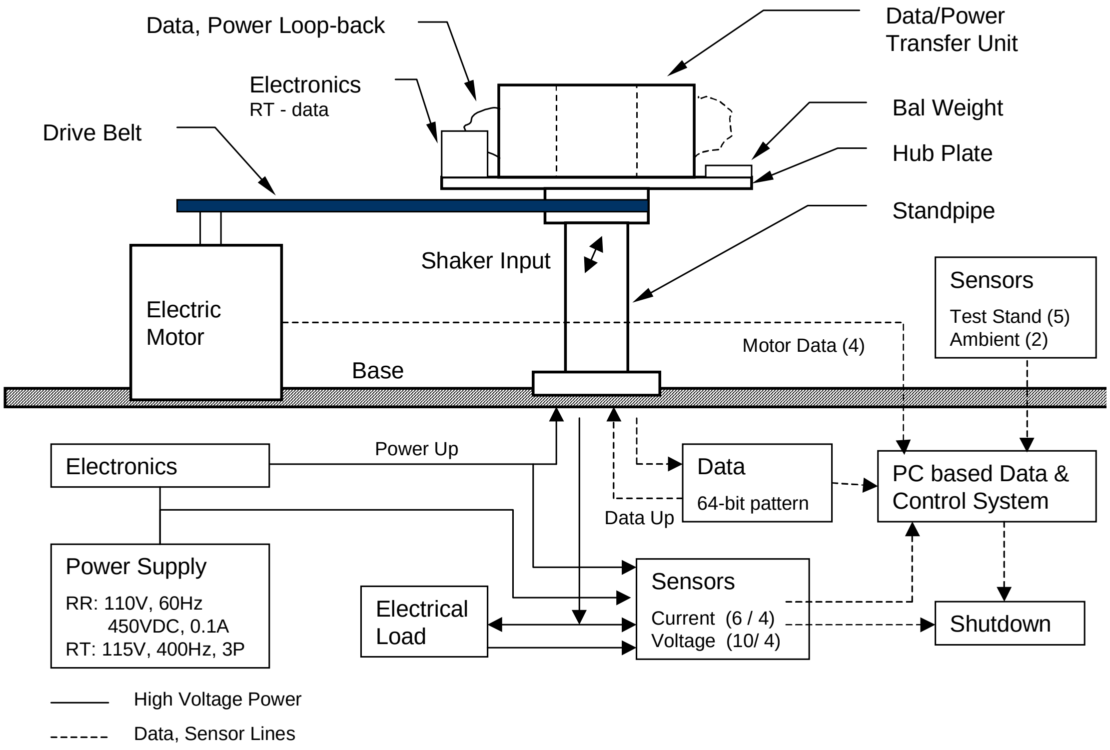


Figure 10. Data/Power Transfer Unit Test Setup

Test Objectives

Performance testing establishes the quality and efficiency of the data and power transfer under normal operating conditions. Initially, the transfer unit is evaluated without rotation. This is followed by a rap test to obtain the fundamental modes of the unit/test stand. Next the unit is spun-up and balanced as required, up to the maximum allowable rotor speed. No data/power transfer is applied. After clearing the data/power transfer and rotation envelope separately, baseline performance of the unit is established at nominal rotor speed and at the maximum test rotor speed.

Acceptance testing of the transfer unit establishes its electrical properties versus the requirements. Acceptance tests are performed at the beginning and at the end of the test sequence for each unit.

The endurance test verifies reliable electrical and mechanical operation and assesses wear characteristics over an extended period of operation. For this test the unit is spun continuously (24 hours per day). The endurance test is accelerated by increasing rotor speed and power levels to the maximum values within safety limits. The test is run for several weeks to accumulate a large number of revolutions.

During the endurance test, both the data and power streams are run at their nominal values of 30 Mbps and 8 kW. The transfer is bi-directional for both data and power. Data are recorded and signal transfer reliability is evaluated by analyzing for noise, distortions and dropouts, as well as power transfer efficiency. Wear characteristics of electrical contacts (if any), seals, and bearings are inspected and documented.

TEST RESULTS

The data/power transfer units were extensively tested to establish their performance and assess their durability. Basic acceptance testing was conducted by the suppliers. Performance and durability testing when rotating was conducted at the Boeing structures lab in Mesa.

Roll Ring

The roll ring installation on the test stand, standpipe, motor, and drive belt are shown in Figure 11. The drive and sensor electronics are mounted in a 19-inch rack. They consist of the motor control, the power transfer test electronics/loads for the two out-of-phase sections of the roll ring, the data transfer test electronics, and the safety shut down.

After installing the roll ring a rap test was conducted to determine the stand frequencies and establish rotor speed ranges to be avoided during testing. The rap test showed two lateral modes at 7.5 and 16.9Hz and a longitudinal mode at 20.2Hz for the basic configuration. Therefore, 450 RPM was passed through quickly when increasing rotor speed. The two higher modes are above the maximum speed of 900 RPM. Rotor speed envelope expansion up to 900 RPM showed minimal vibrations. As expected, due to symmetry, no mass balancing of the roll ring was required. The electrical setup for data and power transfer was verified for data rates up to 34 MHz and full power transfer at about 8 kW.

The roll ring was run for 481 hours at rotor speeds of 400, 500, 600, 700 and 800 RPM. Based on cycle counting this corresponds to 623 equivalent hours at 400 RPM nominal speed. Initially a rotor speed of 800 RPM was used. Due to test stand bearing thermal issues, the speed was reduced and final runs were made at 400 RPM. For all runs a data rate of 30 MHz and full power transfer of -300 to +1200 V and 7.3 A was used. During the entire test only minimal changes in data transfer error and power transfer characteristics were observed. Periodic tests of leakage current and ring resistance for ring pairs also showed only minimal changes. However, several pairs of rings developed an open circuit condition during the testing. In those cases the pair was bypassed and testing was continued. After completion of the test runs, it was confirmed that rings 4, 5, 6, and 23 had an open circuit condition.

The data error as function of transfer rate is shown in Figure 12. Date error is expressed in terms of frequency shift between the input and output signal. Values up to 2-4% are acceptable, depending on the level of error correction. The data shown here were taken at the beginning and end of the endurance test, during runs 3 and 33 respectively. Results show that data error was not affected by the presence of full power transfer. Rotor speed added substantial error. This was found to be a result of electrical noise from the motor controller. Errors are increased around 8 MHz due to the motor controller and around 26 MHz due to line reflections. Data error changed only minimally over the entire test period. Differences for the two cases with rotation (400 RPM) may be due to changes that were made in the motor controller. In general, data transfer accuracy is excellent up to 22 MHz. At the nominal 30 MHz rate the data error is about 2%.

Sixteen electrical parameters were monitored to evaluate the power transfer characteristics. These included the high voltage leakage current, peak contact current, power source voltage (min and max), ring voltage (peak and average), average load current and peak load voltage. The load voltage versus run time is shown in Figure 13 as a representative indication of power transfer characteristics. Except for two instances when the test setup was altered, only minimal change is seen over the entire test period.

The roll ring met the electrical as well as data and power transfer requirements. It performed well during the endurance tests, except that four out of 36 rings developed an open circuit condition. A post test tear down, inspection, and failure analysis was performed by the supplier to identify the cause of the open circuits. The rings and flexures of all the undamaged channels were in excellent shape. Two channels were found to have open circuits in the wiring. This can be eliminated by providing additional strain relief combined with in-process inspection of the wiring. The other two channels, in two separate events, may have experienced arcing to adjacent channels with a resulting failure of the flexures. In one event, the test equipment was also damaged and may have caused the failure. This problem can be addressed by radially extending the insulators between circuits, thus reducing the possibility of arcing and preventing the cascading effect from failed flexures. This feature has since been incorporated into later roll ring designs. It is recommended that the effectiveness of the design changes is confirmed through testing.

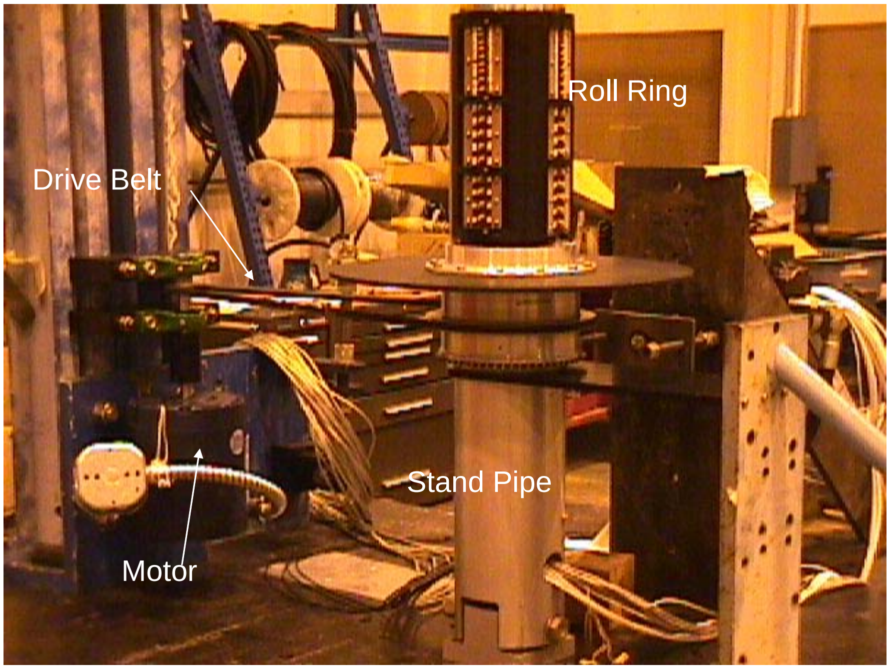


Figure 11. Roll Ring Installation on the Test Stand

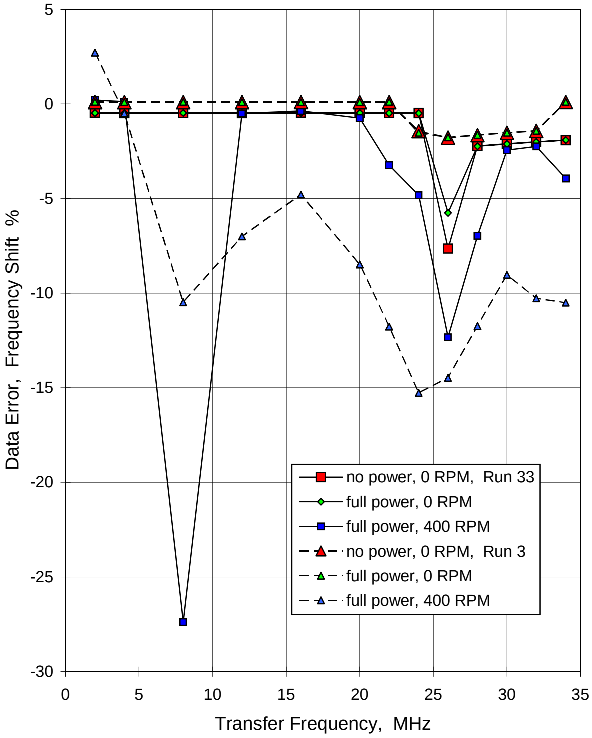


Figure 12. Roll Ring Data Error Versus Transfer Frequency

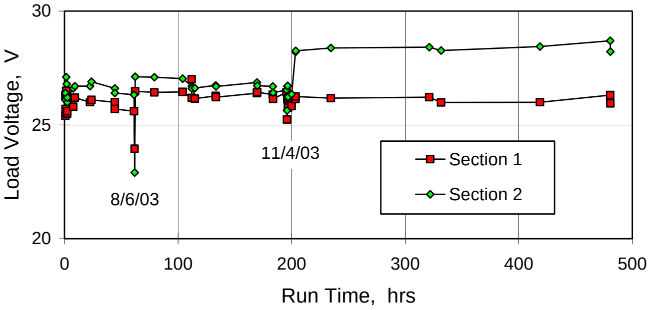


Figure 13. Roll Ring Load Voltage Versus Run Time

Transformer

The transformer installation on the test stand, standpipe, belt, idler, and cooling fan are shown in Figure 14. Also shown are the data transceiver, battery pack, and balance weights, all mounted on the rotating hub plate. A circuit board is mounted on the non-rotating side of the transformer for processing of thermistor readings from the inner and outer transformer cores. The same motor drive, data monitor, and safety circuit as for the roll ring test are used. The transformer power conditioning, inverter, and diagnostics electronics chassis are mounted in a 19-inch rack. A resistor bank is used as load impedance.

After installing the transformer, the rotor speed envelope was cleared up to 700 RPM. A total balance weight of 213 grams was added to balance the unit to 0.15 inch/sec at 700 RPM. The electrical setup was verified for data rates up to 34 MHz and power transfer levels up to 1 kW.

The transformer was run for 322 hours at a rotor speed of 400 RPM. Power transfer was limited to 1 kW. During the endurance runs, no data was transferred while rotating due to limitations of the battery pack required to power the transceiver. The temperature of the outer core (rotating) could only be measured at zero rotor speed. During the entire test only minimal changes in data transfer error and power transfer characteristics were observed. No wear or life issues were noted.

The data transfer error as function of transfer rate is show in Figure 15. Date error is expressed in terms of frequency shift between the input and output signal. Values up to 2-4% are acceptable, depending on the level of error correction. The data shown here were taken at the beginning and end of the endurance test, during runs 5 and 17 respectively. Data error changed only minimally over the entire test period. Results show that bi-directional data transfer meets the requirements only at 2, 4, and 12 MHz. At all other frequencies, line reflections introduce significant error. Further improvements and tuning of transceiver electronics would be required to achieve acceptable bi-directional data transfer.

Detailed oscilloscope traces of input and output data signals for 12, 20, and30 MHz are recorded for the non-rotating case. Results show that power transfer levels (0 and 300 volts on the load corresponding to 0 and 1 kW power transfer) do not affect data transfer. Only at the 12 MHz rate are the output traces for bi-directional transfer of acceptable quality. When switching to uni-directional data transfer, i.e. reading the data signal on the rotating side after transfer through a single transformer, output signals for all transfer rates from 2 to 34 MHz were of acceptable quality. The result for the uni-directional transfer at 30 MHz shows that the transformer meets the data transfer requirements.

Six electrical parameters were monitored to evaluate the power transfer characteristics. These included the inverter voltage, primary current, secondary voltage and current, and the load voltage and current. The load voltage versus run time is shown in Figure 16 as a representative indication of power transfer characteristics. Results show that only minimal change is seen over the entire test period. Detailed performance measurements could not be made, since the driver electronics were damaged during setup.

Temperatures of the power transformer inner and outer core were monitored during testing using two thermistors. It should be noted that the outer core temperature could only be recorded at zero rotor speed. Both readings were unreliable at times, however, enough data was obtained to assess the thermal environment in the cores. When transferring power at the 1 kW level (corresponding to 300V on the load), the inner core reached a maximum temperature of 143 and 120 deg F without and with the external cooling fan, respectively. Temperature levels in the outer core were comparable.

The transformer met the data transfer requirements when operated in the uni-directional mode. This mode is representative of the actual intended application. Power transfer was limited to about 1 kW continuous and 4 kW peak due to electrical and thermal constraints. The transformer windings required more insulation to eliminate arcing under high voltage. As a result the heat shields could not be fitted, thus reducing thermal conduction within the unit. No potting was applied in order to allow disassembly and inspection of this prototype unit.

It is recommended that the power transfer levels of the transformer be increased by improving wiring insulation and thermal management. Better thermal transfer from the cores to the outer housing can be achieved through potting with available thermally conductive epoxies. A more robust inverter design and improved tuning of the data transceiver are desirable. Electronics to provide 28V power on the rotating side must be added. Finally, the weight of the transfer unit should be minimized and the weight and volume of the drive electronics should be

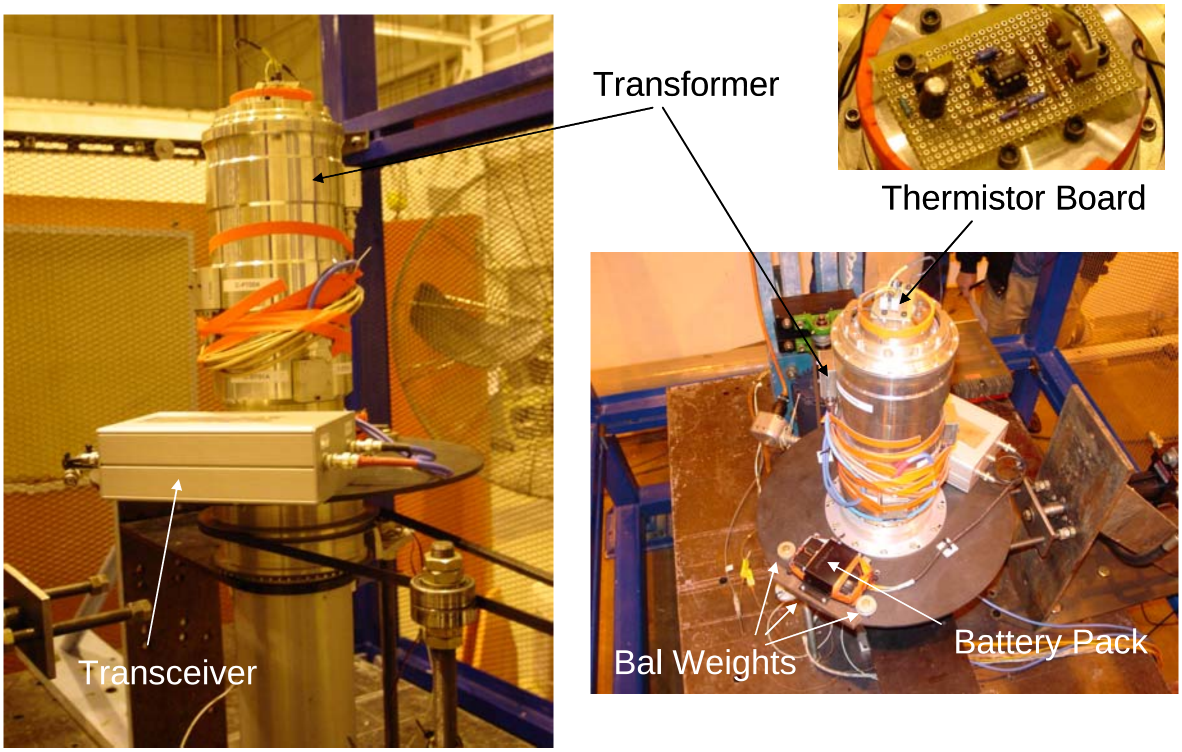


Figure 14. Transformer Installation on Test Stand

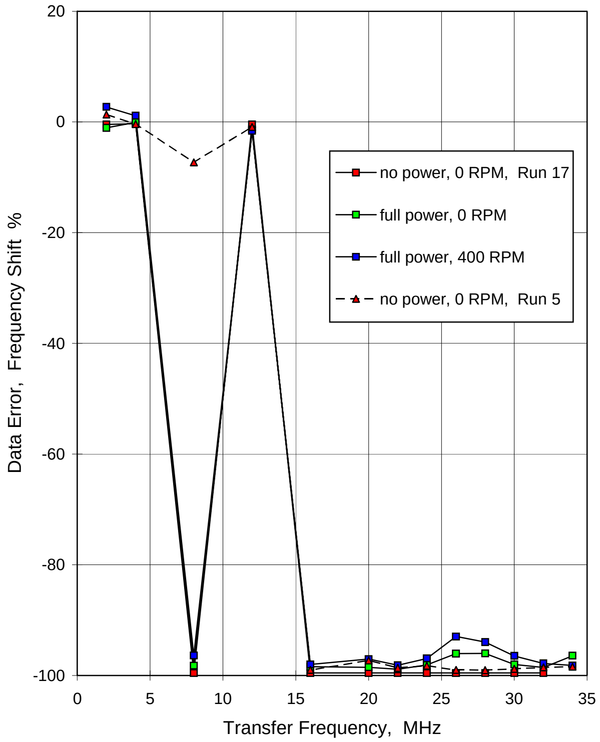


Figure 15. Transformer Data Error Versus Transfer Frequency, Bi-directional

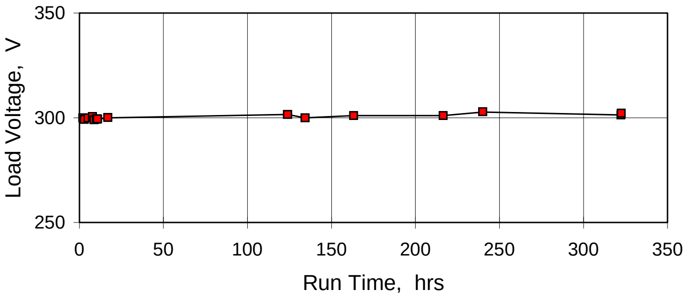


Figure 16. Transformer Load Voltage Versus Run Time

reduced. The test hardware was not optimized for weight and size. It appears that a much more compact size and lower weight can be achieved by incorporating the power transformers into the design of the amplifiers for on-blade control. The data transmission modules could be incorporated in the interface design to increase performance and reduce size.

SUMMARY

The Boeing Company, Mesa Arizona, and two subcontractors developed two systems that transmit data and power between the fixed and rotating interface of a helicopter with sufficient accuracy, quantity and reliability to support the new generation of on-rotor controls and sensors. Requirements called for 30Mbps data transfer and 8 kW power transfer. Diamond Antenna fabricated a roll ring (contacting) and Alpha-Omega developed a rotating transformer (non-contacting). The two data/power transfer units were extensively tested to establish their performance and assess their durability. Basic performance testing was conducted by the suppliers. Performance and durability testing when rotating was conducted at the Boeing Structures Lab in Mesa. To this end, a unique test stand was designed and fabricated for rotational testing of the transfer units. Power, data, and sensor electronics were developed to test the units under realistic loading conditions and evaluate the transfer characteristics.

The roll ring met the data (30 MHz) and power (8 kW) transfer requirements during 623 equivalent hours of testing. Four circuits went open during the endurance test, however, design and fabrication changes have been identified to correct the underlying causes. The transformer met the data transfer requirements (30 MHz) and limited power (1 kW) transfer requirements during 322 hours of testing. Potting with available thermally conductive epoxies would raise power levels substantially. Both units showed no significant change in transfer characteristics and performance, such as data error, power level, data and power noise levels, power transfer efficiency, and dropouts. No problems with wear of seals or bearings was noted.

Specific conclusions are:

1. The roll ring was run for 481 hours at speeds from 400 to 800 RPM with full data and power transfer. Equivalent run time at the nominal 400 RPM would be 623 hours.
2. The roll ring unit weighed 20 pounds and met the electrical as well as data and power transfer requirements. Only minimal changes in data and power transfer characteristics were observed during the testing. Four circuits went open during the endurance test, however, design and fabrication changes have been identified to correct the underlying causes.
3. The rotating transformer was run for 322 hours at 400 RPM with power transfer at 1 kW. Data transfer when rotating was limited to a few hours since batteries were used to power the rotating transceiver.
4. The rotating transformer weighed 30 pounds, not including the weight of the drive electronics.
5. Data transfer requirements were met for the uni-directional case, i.e. single transformer.
6. Power transfer at 1 kW continuous and 4 kW peak was demonstrated. Power levels were limited due to thermal and arcing constraints unique to the test unit. Potting with available thermally conductive epoxies would raise power levels substantially. Power transfer efficiency for a single transformer was approximately 93%.
7. Only minimal changes in data transfer and power transfer characteristics were observed during transformer testing. No wear or life issues were noted.

The roll ring and the rotating transformer represent significant improvements in transfer unit capability and endurance. For comparison, a conventional slipring with identical capabilities weighed 11 pounds. It would require cleaning after 50 to 100 hours and rebuilding after several hundred hours.

Both technologies successfully accomplished data and power transfer in one unit. The roll ring weighs less than the transformer, is more mature technology, and requires no electronics. Testing should be conducted to confirm effectiveness of proposed design changes. The transformer represents promising non-contacting technology, especially in conjunction with on-blade actuation. More development is needed to improve its performance and reduce overall weight. Near term, both units should be considered for data transfer or de-ice applications. Long term, the transformer should be considered for on-blade actuation with hub-mounted amplifiers.

ACKNOWLEDGEMENTS

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