Development of New Health and Usage Monitoring System Tools Using a NASA/Army Rotorcraft

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ABSTRACT

An airborne Health and Usage Monitoring System (HUMS) is being developed to acquire rotor and drive train loads in addition to vehicle flight parameter data. Advancements over previous systems include the addition of a partially wireless rotor data system and serially multiplexed smart digital strain sensors. The system has been integrated into the NASA/Army Rotorcraft Aircrew Systems Concept Airborne Laboratory (RASCAL) Sikorsky JUH-60A helicopter. This paper presents the development of a flight loads monitoring system using digital sensor technology, installed on the RASCAL aircraft to demonstrate the functionality of the system. Also presented are pre-flight tests and future research plans for the digital sensor technology.

INTRODUCTION

Health and Usage Monitoring Systems in rotorcraft are becoming increasingly important for safety and to lower the operating cost of the aging fleet of rotorcraft. Helicopters fielded 20 years ago are expected to remain in service for the next couple of decades. Successful airframe designs are going through various system upgrades to incorporate the tremendous advancements made in technology. Such upgrades often result in a substantial increase in gross weight and drag. The resulting airframe operates in a much more severe structural loading condition, which requires close health and usage monitoring to maintain the safety of the rotorcraft.

The emphasis to achieve reduced aircraft operating and service cost and increased safety benefits will continue to grow with both military and commercial operators. This goal could be achieved by monitoring life limited components with direct load measurements as opposed to flight hours expended or regime recognition routines. The conservatism built into the fatigue life estimation of critical components can be reduced by using the actual flight loads, combined with the actual regimes flown by the aircraft are recognized from the flight data. A HUM System capable of recording flight loads along with the appropriate flight parameters can be used to achieve both reduced operation and service cost and improved safety. [1] [2] [3]

HUMS is equally important for ensuring the operational flight safety of experimental helicopters which are used as demonstrators of advanced technology, such as full authority, fly-by-wire/fly-by-light advanced research control systems and carefree maneuvering concepts using active control technology. Advanced technology demonstrators are often aimed at exploiting the complete flight envelope of the rotorcraft and tend to operate close to the edge of the envelope. Under these conditions monitoring the flight loads on critical components is of great importance for flight safety.

Conventional data collection from the rotor hub involves slip rings for data transfer from the rotating system to the fixed system, which have historically been unreliable. Use of wireless Rotor Data Systems (RDS) with digital sensor technology would significantly improve the reliability of rotor state measurement for advanced flight control law applications.[4]

Health and Usage Monitoring Systems in helicopters have attained a level of maturity where their functionality is being expanded to areas such as limit-cueing and carefree maneuvering to enhance situational awareness for the pilot.

The current focus of development for the NASA/Army Rotorcraft Aircrew Systems Concept Airborne Laboratory (RASCAL) Sikorsky JUH-60A helicopter is the testing of an advanced full authority dynamic fly-by-wire flight control system. In order to maximize safety while benefiting from higher performance controls, a load-monitoring, limit-cueing advisory system was proposed. Development of the pilot advisory system will result from data collected, analyzed, and evaluated from initial

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flights by the newly configured RASCAL system. Information generated from the data will be used to develop advisory pilot cue indications that will be integrated into the existing HUMS. The mature system will advise the pilots when the level of loading on structural components resulting in the excess consumption of fatigue life are approached or exceeded.

The RASCAL aircraft also provides a demonstration and evaluation platform to exploit the progress of developing technologies in digital sensors and wireless power and data transfer systems that are needed to produce a practical RDS. The Boeing Company has been developing sub-components for use in production-ready HUMS. Current systems being developed by Boeing are a fully wireless rotor data system, serially multiplexed digital smart sensors, and prototype airborne computers for real-time processing and archiving of acquired data. A diagram of the RASCAL HUMS is illustrated in Figure 1.

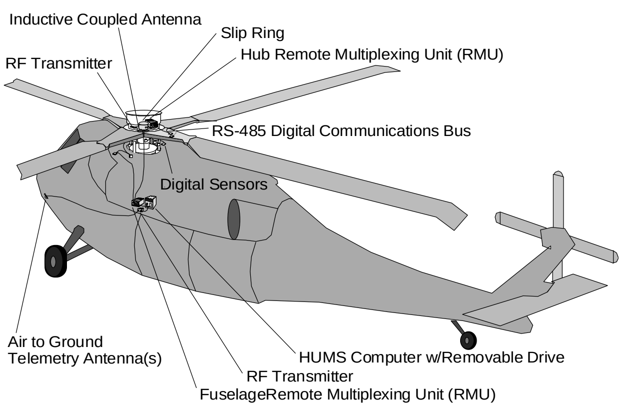

Figure 1 - RASCAL HUMS

Test Aircraft

The test aircraft is the RASCAL shown in Figure 2. RASCAL is a highly instrumented JUH-60A Blackhawk rotorcraft with the entire crew cab area dedicated to research equipment and crew. The aircraft is equipped with a Research Flight Control Computer (RFCC) and high-bandwidth hydraulic actuators operating in parallel with the existing flight control actuators. The primary goal for RASCAL is to develop advanced fly-by-wire flight control laws. The aircraft is instrumented with two MIL-STD-1553 data buses, differential Global Positioning System (GPS) receiver for time and coordinates, a contact slip ring to provide power and collect data from several systems on the rotating frame and a system control computer to act as a bus controller and process HUMS status information. An environmental enclosure mounted on top of the rotor head has space for additional equipment to support the digital sensors and analog signal conditioning.

Figure 2 - RASCAL Aircraft

ENABLING TECHNOLOGIES

Structural usage and exceedence monitoring are currently the most important tools for analyzing the health of an aircraft. Sensors mounted directly on the structure provide the most reliable information on structural loading. This data along with time-correlated aircraft parameter data can be fused and used with structural models to determine structural usage and possible damage of an airframe and its life limited critical components.

The current state-of-the-art monitoring system restricts the number of sensors due to the weight and size of signal conditioning and wiring as well as the lack of a practical method for sensing key structural elements located on the rotating assemblies. Current analog systems require expensive and heavy signal conditioning on the rotor and significant power forcing the use of a mechanical contact slip ring. As a result current RDSs exists only for flight testing purpose but are not cost effective or practical for long-term production use.

High-speed data from a rotating platform is typically collected through a contact slip ring, which in the case of the RASCAL aircraft is a customized device with a series of ten platters and six pickups per platter. This allows sixty channels of data, all of which are separate 22 gauge wire leads that must fit within a tight one-inch diameter standpipe. In the past, the slip ring was used to supply power to equipment on the rotating platform and send sensor data down to the fixed platform.

One major disadvantage to the slip ring device itself is the fact that it cannot be disengaged when data is not being collected. With every revolution of the rotor blades the brushes that contact each trace on the platters wear down. After a short period of time, copper dust builds up within the enclosed slip ring, which produces noise and can very likely cause a short between traces. This becomes a high maintenance item that would not be practical for a commercial or military product.

One potential solution is the use of a contactless RF slip ring. However the application of contactless RF slip rings in production rotorcraft is conceivable only if the systems the slip ring services are low power and sensor signals passing through can be multiplexed. Inductive power systems are not efficient and cannot practically produce much electrical power for use on the rotor. However, much can be gained if such a system can be used. Since the moving parts do not contact, there is not any physical wear. Thus maintenance due to physical wear is non-existent. In addition, installation onto various airframes is easier. Most rotorcraft designs contain areas in the hub where such systems are fairly straightforward to implement. In addition, simple interfaces reduce the cost of transmitting many wireless channels. Therefore if the systems can utilize one bus, only two wireless channels are needed: one for up-link and one for down-link.

The digital sensors under development contain on-board signal conditioning and are very small. Such digital sensors can be made low power and permit many sensors to be placed on a single addressable bus for random accessing. Using these attributes, a relatively simple and low-power rotating to non-rotating communication and power interface can be built to service sensors located on the rotating components of a rotorcraft. The main benefit is weight savings and space reduction for both fixed and rotary wing applications. Prospective digital sensor implementations include strain, acceleration, pressure and temperature. The digital bus could also be utilized for sensor nodes (bus mounted systems which have significant local processing) which could include specialized active or passive acoustic interrogation tools, fiber optic systems, acoustic emission systems, etc.

HUMS DEVELOPMENT

The concept of a HUMS on rotorcraft is gaining wider acceptance as HUMS components and installations improve, and safety of flight issues become more complicated. Such complications include new designs, reduced maintenance logistics, and increased usage life demands. To address this need the overall goal of a HUMS is to reduce maintenance cost while increasing safety.

The HUMS on the NASA/Army RASCAL aircraft serves several purposes which include: to provide a platform for testing advanced sensors such as the Sarcos Uni-Axial Strain Transducer (UAST); to integrate a system that monitors component life usage while the aircraft operates at the edges of its intended operational envelope during the course of the advanced fly-by-wire flight control system development; to develop a prototype for future production HUMS units taking advantage of wireless data retrieval; and finally to advance the technology for future real-time pilot cueing of aircraft limitations in various phases of flight.

HUMS INSTALLATION

Installation onto RASCAL

The RASCAL aircraft had an existing RDS that could conceivably be used to transmit strain data from the rotating components to the fuselage storage device. The requirement for a high sampling rate and the “noisy” nature of the slip ring design that is currently installed in the aircraft inspired the development of a wireless RDS.

The data that was previously collected via the 60 channels in the contact slip ring is from a previous Rotor-State measurement system. The rotor loads portion of this system was removed leaving a laser-based approach to measure blade lead-lag, flap and pitch angles. Therefore a portion of the existing environmental housing was available for the new hardware items that were mounted in the rotating platform. The Remote Multiplexing Unit (RMU), transmitter and associated wiring harnesses had a ruggedized enclosure. The typical JUH-60A helicopter operating in the fleet would not likely be equipped with an environmental housing, or a contact slip ring to provide power to the sensors and RMU, so sensors with on-board signal conditioning would be beneficial to promote development of a wireless RF slip ring.

System Overview

A schematic representation of the RASCAL HUMS is illustrated in Figure 3. The Flight Loads Monitoring System (FLMS) consists of three major subsystems. These systems are the RDS pictured in Figure 4, the Fuselage Data System (FDS), and the HUMS computer both pictured in Figure 5. The RDS includes all sensors and signal conditioning located on the rotating portion of the main rotor assembly. The FDS includes sensors and signal conditioning located on the non-rotating portion of the helicopter. The HUMS computer gathers data from both the RDS and FDS, provides some data reduction/analysis, and archives the data on digital storage media.

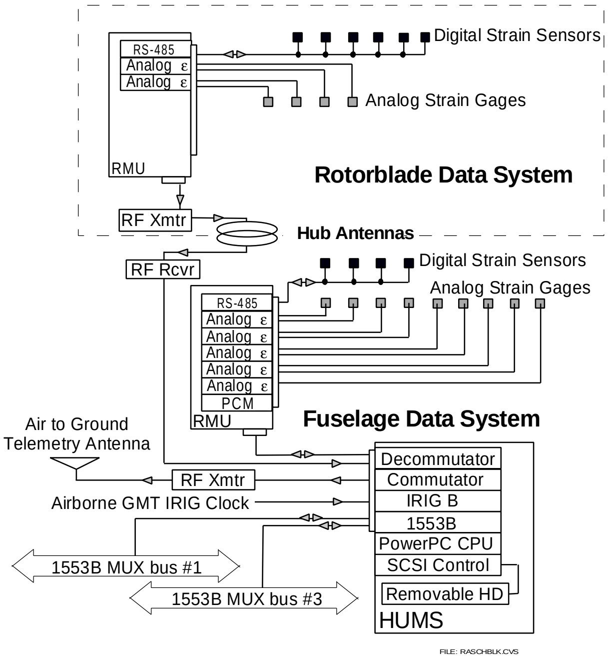

Figure 3 - RASCAL HUMS Block Diagram

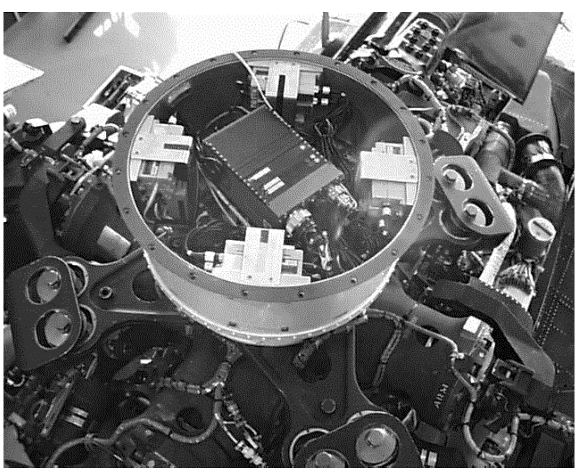

Figure 4 - RDS RMU (center) in Environmental Enclosure

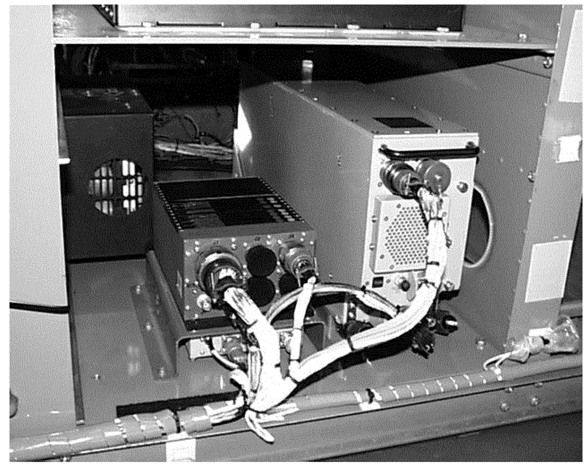

Figure 5 - FDS RMU (left) and HUMS Computer

Rotor Data System / Fuselage Data System

The L3 Communications RMU1000 Remote Multiplexing Units (RMUs) are currently the heart of the RDS and FDS. These field programmable systems gather data from conventional strain gages and addressable RS-485 distributed digital strain sensors. The units are equipped with 16 module slots allowing for expandability above the current configuration. In addition, the RMUs are capable of monitoring other conventional instrumentation sensors such as Resistance Temperature Detectors (RTDs), thermocouples, piezo accelerometers, event counters, synchros, discretes, frequencies, voltages, tachometers, and pressures. The digital sensors are sampled using a microprocessor-based RS-485 module. The module is capable of addressing 256 individual sensors and has a bus bandwidth of one megabit per second.

Sensor signals are gathered from both the rotating and non-rotating portions of the rotorcraft using the RMUs. One RMU is located on the rotating hub and gathers data from a digital strain sensor bus and from several analog strain gages. This RMU sends telemetry data via the wireless RF slip ring to a second RMU located in the fuselage that gathers data from digital and analog sensors located in the fuselage. The second RMU combines all data and passes one PCM stream to the HUMS computer.

Contactless RF Slip ring

The rotating (RDS) to non-rotating (FDS) wireless communication system consists of a transmitter located in the environmental housing on top of the rotor, contactless RF slip ring antenna located within the rotor hub, and a receiver located in the fuselage.

The RF data transmitter is a L3 Communications T150S-001 S-band transmitter. The transmitter is set up to operate at a carrier frequency of 2250 MHz. This miniature transmitter is located near the RDS and provides a wireless transmission of the PCM data stream from the RDS.

The RF receiver is a Southern California Microwave S-Band Agile Receiver. This Unit locks onto and receives the T-150 transmitter signal consisting of the PCM data stream from the RDS for delivery to the FDS RMU.

The RF antenna was designed and built by L3 Communications. Each sleeve of the antenna contains a loop antenna that was designed to fit around the existing contact slip ring. The mounted antenna is illustrated in Figure 6.

Figure 6 - Wireless Slip ring mounted to underside of the Instrument Platform

Digital Sensor Communications Module

The RMUs are equipped with several MSC1000-001 dual strain gage modules for gathering data from the analog strain gages. In order to gather data from digital sensors, L3 was contracted to modify one of their existing modules. The digital sensor communications module is a modified MSC1000-014 RS-232/422 data decoder. The module is equipped with a microcontroller, EEPROM, and dual ported RAM. L3 modified the module to include an interface compatible with the 1 megabit per second digital sensor bus and wrote software to allow it to communicate with the up to 256 sensor addresses on one bus. It was also capable of running a preprogrammed command/response sequence to all sensors on the bus.

The module has several notable features. The unit is field programmable allowing quick changes to digital sensor configurations. It is capable of synchronizing digital sensor trigger commands with triggers to other analog transducer RMU modules. It also provides power and a synchronous clock output to the sensor bus for use by the sensors.

Digital Sensors

The digital strain sensors used for this program are from Sarcos Research Corporation. These sensors, called Uni-Axial Strain Transducers (UASTs) are fully digital and are shown in Figure 7. A version of their sensor was developed specifically to communicate on the RS-485 bus used on the RASCAL.

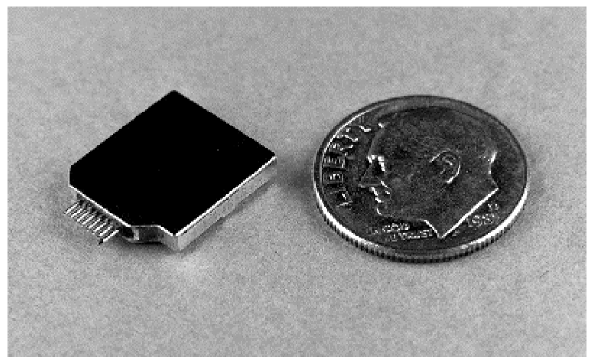

Figure 7 - Sarcos Research UAST

The form-factor of the UAST covers 0.5x0.5 inches, which is a comparable area to that of two average foil strain gages used to measure tension/compression strain. They are packaged in stainless steel or beryllium-copper cases and can be manufactured to meet, or approach, the thermal coefficient of the test specimen by changing the case material. For this test, only the stainless steel and beryllium-copper sensors were used.

Foil strain gage systems have existed for several decades. These transducers are considered mature however several of their attributes are not desirable. Foil strain transducers are not absolute gages and tend to drift over long term operation making it difficult to track static strain loads. In addition, these gages usually have high-cycle fatigue lifetimes that are far less than the expected fatigue life of the part under measure. Industry knowledge about the maintenance of these transducers has indicated that they have a high rate of premature failure.

As a result of these shortcomings and other needs, Sarcos Research Corporation has been developing a radically new method of measuring strain. This device called the UAST, is a fully digital Micro-Electro-Mechanical System (MEMS) transducer. It computes strain by measuring the length between the device's stationary foot and a foot mounted on the device's moveable flexure. The movable flexure foot is attached to an array of electrostatic field emitters within the package. This array is allowed to slide over an array of 64 field detectors on a CMOS IC chip that is mounted to the stationary part of the sensor package. Applying strain to the substrate causes displacement of the emitter array over the detector array. The emitter array is arranged with slightly different spacing to form a vernier scale. The evenly spaced detector array picks up the fluctuations in these fields as the emitter is linearly translated. The values are then digitally signal processed to calculate an absolute translational displacement. The sensor is capable of a measurement range of approximately 11,000 microstrain with a resolution of 2.5 microstrain.[5] [6]

The package was intended to provide a catalyst for testing the electronics within the sensor. During our testing at Boeing it was determined that this package prototype may be suitable for testing in flight. Several additional tests were completed at Boeing to determine the performance of the device during preparation for sensor installation on the RASCAL. These tests had mixed results that were provided back to Sarcos to assist them in improvements that are currently underway as part of a DARPA program. Positive attributes of the sensors included its absolute encoding of strain values even when power has been cycled, good performance under high temperatures, linearity under purely axial loads, internal signal conditioning, non-volatile configuration memory, volatile data buffer memory and addressability. Negative attributes of this version device included non-linear performance when bending loads are applied, non-weather-proof design, small attachment feet requiring ideal adhesive bonds, and the lack of anti-alias filters. The bending problem is solved if a sensor can be bonded to each side of a specimen under measurement and their measurements interrogated together to extract the bending. Excessive bending error occurs on thin substrates, while error due to bending decreases as the substrate gets thicker. The bonding, bending and anti-alias issues are being addressed in Sarcos's current DARPA program. Preliminary designs show promising improvements in all areas.

HUMS Computer Hardware

The HUMS Computer is located within the fuselage. Its function is to gather data from inputs, format and process the data, and then output and/or store the data internally.

The HUMS computer features state of the art Commercial Off The Shelf (COTS) ruggedized hardware. The MIL-SPEC Single Board Computer (SBC) board features a DY-4 Power PC 603 processor with an Ultra SCSI bus and a 10 base T Ethernet port. It also contains mezzanine interfaces, which allowed the addition of two dual-redundant MIL-STD-1553 busses. A Berg 4422-V64 "Do-All" decommutator/simulator board handles the Pulse Code Modulated (PCM) data streams. This board contains a 5 Mbit/s PCM decommutator with bit-synchronizer input as well as a 5 Mbit/s simulator (commutator) PCM output. The card is equipped with an IRIG-B time code signal input, which is used as the time-stamp for incoming data. The computer enclosure is a ruggedized VME-based convection-cooled ATR chassis. The enclosure slides into a bay-mounted ARINC-style shock tray to provide shock and vibration isolation. Power, signal, and data connections as well as the removable half-height securable hard drive are accessible on the enclosure's front panel. Configuration files for the incoming and outgoing data streams can be stored within the HUMS computer on the removable drive cartridge. The HUMS Operational Flight Program (OFP) is stored on resident flash EPROM.

Data is streamed into the enclosure through the decommutator module with bit synchronization, and time-stamped using the IRIG-B daughter card. The two dual-redundant MIL-STD-1553B ports permit bus monitoring of two 1553 buses. One 1553 bus permits control and status words to be available on the pilots Multi-Purpose Display for HUMS status and control. Data stored on the Iomega® Jaz® drive is formatted as FAT-16 compatible for playback through an Intel® based machine running Windows® or a compatible UNIX machine. Data can also be streamed through the commutator (commonly called a simulator) through a transmitter and antenna system on the rotorcraft via wireless telemetry to a ground based station.

HUMS Computer Software

The software developed was designed to provide field-configurable real-time data acquisition, processing, telemetry, and on-board storage. It is based on a real-time operating system called VxWorks® created by WindRiver®. The real-time software insures precise data acquisition and storage without potential data dropouts experienced with other conventional operating systems.

The HUMS software provides the capability to add and remove software components, with minimal impact to existing platform software. Software components consist of general-purpose software modules that are designed to operate on a collection of data. Components may include math libraries, statistical algorithms or data analysis software.

The software architecture includes facilities to easily import, schedule and remove software components on any HUMS implementation while minimizing impacts to the current OFP. Furthermore, the requirements placed on the designers of these components are kept to a minimum. This allows for a wide variety of third party software to be used across a wide range of HUMS implementations.

The HUMS architecture framework consists of a collection of C++ classes and class associations. All of the framework classes are platform independent – there is no operating system or hardware specific software within the framework classes. The OFP for a particular HUMS platform is implemented through classes that inherit functionality from the framework.

All data input and output streams are configurable through a set of configuration lookup files. These files define how the hardware parses the data from the incoming streams, how it is time stamped, what data passes through data analysis and reduction, and what data (including the new analyzed data) is passed out to storage, telemetry or pilot cue. The RDS and FDS PCM configuration files are compatible with the configuration file used by L3 Communications such that it may be used to identically configure the L3 Remote Multiplexing Units with a matching PCM stream.

HUMS Sensor Installation

Rotorcraft components in the rotor system and the upper control system operate in a high fatigue environment. In monitoring these critical components it is possible to calculate the fatigue-life usage and determine if the aircraft needs more or less frequent maintenance. For the JUH-60A, Sikorsky Aircraft Company identified candidate components for monitoring and specified the load limiting values and damage tracking in various flight modes.

A list of the components selected for instrumentation is shown in Table 1. The list is divided evenly between parts that are found on the rotating and fixed frames of the aircraft.

Two sets of sensors were placed on the components in Table 1. The primary strain gages are standard single element foil strain gages arranged in Wheatstone bridge configurations. A secondary set of digital strain gages was used in a proof-of-concept application of the digital bus, harness and sensors together. In the process several issues were raised regarding the suitability of digital sensors in their current configuration. Installation of the digital sensors is illustrated in Figure 8 and Figure 9 respectively.

Table 1. Monitored Components

Aircraft Frame	Component	Material
Rotating	MR PUSHROD	Titanium-6Al-4V
Rotating	MR SHAFT EXTENDER	Titanium-6Al-4V
Rotating	MR BLADE CUFF EDGEWISE BENDING	Titanium-6Al-4V
Rotating	MR BLADE CUFF FLATWISE BENDING	Titanium-6Al-4V
Fixed	RIGHT TIEROD	Aluminum 7075-T73
Fixed	FORWARD STATIONARY SWASHPLATE LINK	Steel 4340, 180KSI
Fixed	AFT STATIONARY SWASHPLATE LINK	Steel 4340, 180KSI
Fixed	LAT. STAT. SWASHPLATE LINK, TENSILE LOAD	Steel 4340, 180KSI
Fixed	LAT. STAT. SWASHPLATE LINK, SCISSORS LOAD	Steel 4340, 180KSI
Fixed	LEFT TIEROD	Aluminum 7075-T73

For strain measurement of tension and compression on flat-surfaced common metals the digital strain gage is clearly superior. Only one sensor is required to measure tension or compression in any one axis, whereas a complete Wheatstone bridge is necessary for foil gages. The absence of a conditioning card is advantageous for reducing the complexity and cost of additional equipment. With higher production runs, the cost of the digital sensors can expect to be lowered to acceptable levels for commercial applications.

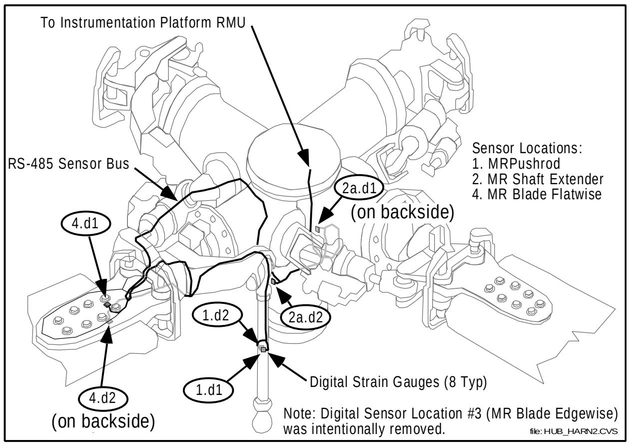

Figure 8 - RDS Sensor Installation

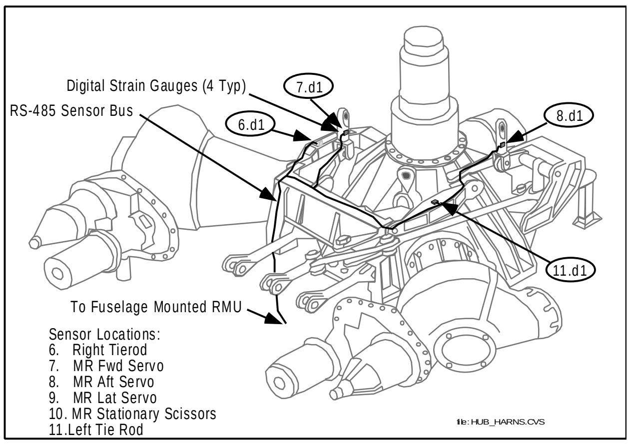

Figure 9 - FDS Sensor Installation

Harness Issues

Some of the design attributes of this system were positive and will be reused in future sensor designs. Data communication to the sensors was done using RS-485 transceivers. The differential transceivers within the Sarcos UAST were added to talk a simple half-duplex protocol for communication of commands and data. The RS-485 hardware has proved to be robust and capable of tolerating most EMI/RFI environments. Also a 5 volt power regulator was added to insure 5 volts at each transducer. This proved effective due to voltage drops along the bus and will be necessary in future designs.

However, during the design certain shortcuts had to be made in order to maintain schedule. As a result, the design of some of the hardware interfaces to the harness were less than ideal. The cost of hybridization is expensive and the Sarcos UAST is a hybrid. As a result, the clock and the program line were implemented as a single-ended signal and thus susceptible to common-mode noise problems. This implementation worked on the RASCAL due to the expected flight plans in low RF environments and lack of EMI and RFI equipment on-board. However this approach is not an acceptable solution for military environments or long bus lengths. In fact, the program line required capacitors both at the far end of the bus and at the mid-point to insure that the total electrical noise was below a logic 0 (0.9 vdc).

Other bus construction issues surfaced during installation. The sensors were built with integrated Omnetics Nano-Series connectors. These connectors are surprisingly robust but due to their extremely small size require a small gauge conductor. These 32 gauge conductors were vulnerable to damage making construction of the harness tedious. The sensor bond was also at risk every time the connector was inserted or removed because the connector was located on the sensor. These issues will be addressed when the system is redesigned for next generation digital sensors.

Gage Mounting Issues

The issues experienced with the installation of the UAST strain gages are primarily related to the packaging of the gage. Mounting to a curved surface presents a problem due to the rigid casing of the UAST. A thin bond line is required due to a design thickness based on a finite element analysis of bond line stresses that are evolved at substrate strain levels of plus or minus 5000 micro-strain. In addition, some of the designated components are composed of titanium or exotic alloys and in some cases special protective coatings like Zinc Chromate. A few even have had special lubricants used during manufacturing which make it difficult for the sensors to adhere. Further, as a shot peened, critical aircraft component, surface abrasion is not allowed, making cleaning difficult and does not give the adhesive a rough surface to adhere to.

The UAST uses (0.060" square) attachment feet to establish a discrete gage length (approx. 0.467") over which displacements will be measured and strain inferred. Each foot sets the belly of the UAST package 0.015" above the gaging area. A 5-mil standoff nub on each foot of the device is used to create a 5-mil bond line. Thinner bond lines would have less creep such as used with strain gages. Strain gages are bonded with something closer to a 0.1 or 0.2 mil thick bond line. This is not a problem with strain gages since the gages themselves are stretching and shrinking. However, the UAST's feet, which are essentially rigid, might fail prematurely at moderate strain levels with a thin bond line.

Since the UAST gage is not conformal to the specimen surface, it doesn't take a large external force to knock off the gage. A light bump from a mechanics wrench with a force as little as 5 pounds can easily exceed any loads normally seen at the bond-line. Unlike foil gages that have a large surface area and low profile the UAST gage has a high center of gravity. Any external load that is applied to the gage creates a large moment that is experienced at the bond-line. Therefore, for protection from the elements as well as inadvertently bumping a sensor, environmental covers are placed over each UAST. These covers are machined aluminum caps that cover the UAST entirely but do not touch the sensor itself.

Bonding Procedure

The recommended adhesive for installation of the UAST sensors is Micro-Measurement's AE-10 which is a two-component, 100% solids epoxy system. This adhesive has a medium viscosity and results in highly elastic (non-viscous) bonds. Unfortunately, it doesn’t cure quickly yet the surface preparation requires swift treatment making installation of numerous sensors at one time difficult. Elevating the temperature does speed up the curing process as seen in Figure 10, yet it is necessary to take precautions to protect the surrounding sensors and test specimen itself. Another option is to use AE-15 which is recommended for more critical applications where zero drift and hysteresis must be minimized, but extended cure times and adhesive run-off makes AE-15 a less likely candidate. Elevated post-cures for both types are recommended for maximum stability and both are highly resistant to moisture and most chemicals once cured.

Measurements Group, Vishay, the manufacturer of AE-10 an AE-15 recommend that the adhesive be free of moisture and contaminants[7]. Through numerous bonding trials in the laboratory and on the aircraft, several adhesive related issues arose when bonding to exotic materials, specifically titanium alloys. Sensors were coming off after relatively low proof loads were applied. The reasons for why certain sensors failed to properly adhere are still unknown, but some clues lie in the components that did not fail.

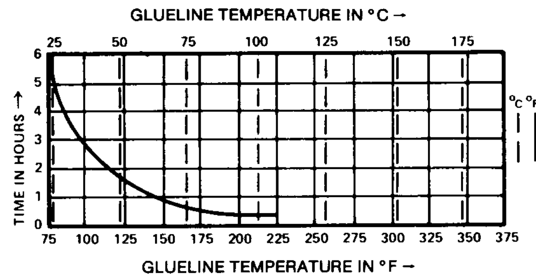

Figure 10 - Adhesive Cure Time[8]

The most difficult component turned out to be the main rotor blade cuff. This part is a machined titanium alloy with both concave and convex curves and a smooth, apparently finely shot-peened surface. Time also has an effect on the bond, as it was found that proof loads within 24 hour of curing passed with more than ample margin, yet a week later would result in a bond failure.

A proof load procedure was devised to apply at least two times and up to three times the maximum load the sensor would experience on any given component. Care was taken to not impart an impact or tangential component of force on the gage when performing the proof load. Sensors on the leading and trailing edges of the main Rotor Blade did not survive these tests and primary strain readings are left to the foil sensors mounted in the same location.

FLIGHT TEST RESULTS

Flight tests are anticipated during second quarter 1999. It is anticipated that test data from these tests will be presented at the American Helicopter Society, Forum 55 in Montreal.

FUTURE RESEARCH PLANS

Digital MEMS Strain Transducers

The current digital strain gage prototype developed by Sarcos Research is 0.5 x 0.5 x 0.1 inches. New gages under development will be as much as 30% smaller in area and have at least one more axis of measurement. Additional advancements in electronics will include anti-alias filters, faster electronics, improved processing, and optional internal fatigue calculations. Advancements in package designs will promote improved bonds, easier installation, a weather tight enclosure; and less sensitivity to bending. These improvements will be completed by mid 2001 through a program funded by

DARPA. It is anticipated that devices from this program will be installed on the RASCAL for testing.

Other Digital Sensor Technologies

Other digital bus compatible devices are under development. These devices may contain an interface to off the shelf transducers (such as a strain gage, accelerometer, pressure sensor, RTD, etc.) or an embedded transducer as illustrated in Figure 11. The devices will contain conditioning electronics, processing electronics, RAM (data buffering), non-volatile memory (on-board calibration information), and bus interface electronics. Conditioning electronics could include a precision excitation source, variable gain, variable anti-alias filtering, and perhaps temperature feedback permitting temperature correction if necessary. Current ASIC fabrication technology permits such a device to be very small including the embedded transducer. Initial prototypes for these devices are expected to be 1.0 x 0.5 x 0.1 inches or smaller.

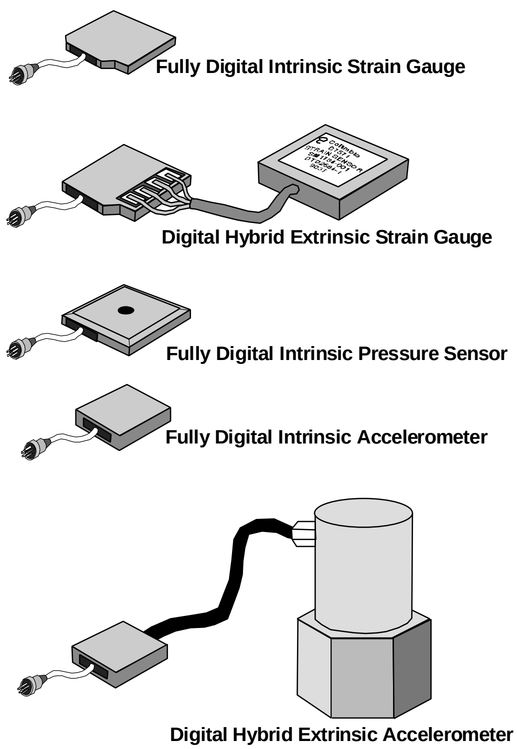

Figure 11 - Digital Network Sensors

Contactless RF Slip Ring

The use of a contactless RF slip ring could eliminate the need for a contact slip ring for data and power transfer, which is typically used in flight test operations but unreliable for long term use. The development of addressable digital bus mounted sensors eliminates power hungry conditioning electronics. These reductions in power draw on the rotorcraft make completely wireless power and data solutions achievable for rotating systems.

The anticipated system will provide a wireless repeater implementation of the smart bus protocol by converting the sensor bus implementation to an inductively coupled wireless link and then back to the sensor bus. The system will also include an inductive power system. This system will provide power up to the RDS for driving the sensor electronics and other low power systems.

Future RASCAL Demonstrations

Several improvements are anticipated with the HUMS implemented on the RASCAL rotorcraft over the next couple of years. Lessons learned from the current installation have created new designs currently being built that will substantially improve the performance of the sensors and systems. These improvements are intended to create a system that could be implemented onto production aircraft. Such improvements should significantly reduce the number of components within the system, reduce its power requirements, and dramatically decrease the cost.

The current plans are to install the new sensors and the wireless slip ring described earlier onto the rotorcraft in year 2000 through 2001. These improvements will complete the aerospace industry investment to drive the technology in this direction.

This technology development effort is anticipated to provide manufacturers of sensors and systems several new technologies for implementation into new or existing designs. Available for use will be an open-architecture communication protocol, designs of the communication device developed by Boeing or purchasable communication ASICS, bus design specifications and design application notes. End user applications anticipated include the intended aerospace applications, industrial control, automotive applications, and smart building systems (HVAC, lighting, etc).

CONCLUDING REMARKS

The HUMS system discussed in this paper has been completely installed and integrated into the RASCAL UH-60 rotorcraft. Successful operation of all of the components has been confirmed and data has been collected during preliminary ground runs. In the effort to advance HUMS development for rotorcraft, this configuration takes us one step closer to an affordable production unit using smart sensors and wireless data transfer.

Bonding issues still need to be addressed for long term use of the UAST sensors or their derivatives for an effective application, but the technology is available and capable. As this system matures, the harnesses will become smaller and the bus design more efficient. For RASCAL, flight loads monitoring will be an integral part of monitoring the resulting effects of a high-bandwidth flight control computer, maintaining safe operation while expanding the envelope of the aircraft.

Data collected by HUMS will be important in future flight cueing and carefree maneuvering projects. Digital data collected from both rotor and fuselage systems provide high bandwidth data to develop predictive algorithms to enhance situational awareness for the flight crew and provide the capability to fully utilize the complete operational flight envelop of the rotorcraft.

Wireless rotor data system using digital sensor technology provides a significant improvement in the reliability of rotor state measurements. Rotor state feed back used in rotorcraft flight control law development has been show to increase the bandwidth of control system. The RASCAL aircraft, which is primarily an advanced research flight controls development platform, could potentially benefit from the digital rotor data system to provide reliable rotor state feedback for the flight control system.

Structural Usage Monitoring System (SUMS), the structural subset of HUMS, using regime recognition to improve safety and realize cost savings for fielded rotorcraft is gaining acceptance. SUMS with direct rotor loads measurement using the digital sensor technology could provide reliable data to allow the transition of life limited component retirements from a conservative fixed flight hour based to an actual usage based system, which would meet both cost saving and safety enhancement goals.

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