KCF Technologies has developed a novel wireless load sensing technology that can be readily embedded in existing rotorcraft parts located in critical load paths for use in HUMS systems. An H-60 pitch link rod end manufactured by Lord Corporation was chosen as the development platform. The rod end has an existing cavity within the threaded stem where components are embedded. These components consist of a piezoelectric stack for energy harvesting, a magnetostrictive based load sensor, data acquisition hardware, RF transmitter, and all accompanying circuitry. Experimental testing at Lord Corporation demonstrated the system’s ability to harvest energy at representative pitch link loading levels, continuously sample load sensor data at 100 Hz, and wirelessly transmit the data to a nearby location. Flash memory can also be embedded within the rod end to store critical parameters derived from pitch link loading history. When not in service, the part could therefore be interrogated to determine its individual fatigue damage accumulation and remaining service life leading to improved aircraft readiness and reduced maintenance costs. KCF is working directly with partners Lord Corporation, Sikorsky Aircraft, and Goodrich to develop the core technology subject to critical performance and design constraints. KCF is also collaborating with Technical Data Analysis, Inc., to address the essential objectives of tracking each aircraft and its components in near real-time with a system level approach.

INTRODUCTION

Basing rotorcraft component replacement on individual component damage accumulation supports the DoD objectives of improved aircraft readiness and reduced maintenance costs. This concept requires accurate and thorough sensing, automated diagnostics, prognosis models to assess component condition and system integrity, and a data management infrastructure for directing appropriate maintenance activities. In spite of the clear benefits of achieving this transition to component damaged-based replacement, it is difficult due to the large scope of the CBM infrastructure needed and the low tolerance for error in its performance.

Although implementation of the data management system requires a substantial effort to carry out, it has a high likelihood of practically succeeding as a viable commercial and military system. Similarly, the diagnostics and prognostic models can be developed with substantial work but low technical risk. Accurate collection and supply of data to the data processing and management system poses the greatest technical risk since it must be a part of the rotorcraft structure and most approaches will have many potential failure points. In addition, the rotorcraft sensor system weight and robustness must ultimately be compared to simply increasing component size/strength and factors of safety.

The focus of this paper is the high technical risk task of accurately monitoring component damage accumulation. Zakrajsek, et al, indicate that there is a strong case for implementing load monitoring on helicopter rotor assemblies, if sensor system cost can
be reduced and robustness increased\textsuperscript{1}. This paper builds on the substantial amount of work that has already been done in this area. Since the scope of a rotorcraft wide health monitoring system is significantly larger than the project that is the basis for this reporting, a strategic approach was taken to narrow the effort of monitoring the load transferred through uniaxial load members that have rod ends. This work supports the concept that data from a few optimally placed load sensors will enable derivation of a wide range of rotor component loads by using advanced structural models like those being developed by TDA (Technical Data Analysis, Inc.).

Elastomeric rod ends are ideal platforms for load monitoring because they are located on critical load links on main rotor dampers and pitch link assemblies, as pictured in Figure 1. KCF Technologies, Inc. and LORD Corporation have developed a rod end load monitoring system that improves upon work in the area of wireless load monitoring on aircraft by addressing issues related to system level robustness and component level integration. The rod end system is intended to supplement existing HUMS systems by providing real time load data on the rotor assembly. Since the rod end is a common aircraft component, the sensor system is applicable to other locations including landing gear.

OBJECTIVES

The overall goal of this work is to develop fundamental tools for wireless load sensing technology for rotorcraft that can locally harvest energy using embedded components. The primary objectives pursued to reach this goal are the following:

1) Identify appropriate energy harvesting and load sensing methodologies.

2) Develop custom, ultralow power data acquisition and wireless transmission components.

3) Experimentally validate the performance of the embedded components in an H-60 pitch link rod end undergoing representative loading conditions.

BACKGROUND

Rotorcraft Health Monitoring

Energy harvesters and wireless sensors enable complete elimination of liabilities relating to hardwiring of health monitoring sensors. Because batteries require periodic replacement and are sensitive to extreme temperature environments, energy harvesters are an ideal solution for many applications. The combination of wireless data transmission and energy harvesting provides a cost effective and robust approach to implementing sensor systems.

In such systems, sensors measure various health indicators such as strain, temperature, pressure, and vibration (acceleration). Each sensor node in this case is autonomous and maintenance free in that the energy required to acquire and transmit sensor measurements will be harvested, rather than supplied by a wired power source.

One such existing approach to wirelessly monitor rotor loads has been developed by Microstrain, Inc.\textsuperscript{2,3}. This approach measures rotor loads with a piezoresistive sensor applied to the exterior of the pitch link. Exterior piezoelectric patches provide energy harvesting for load sensing and wireless transmission power requirements. The system was flight tested on a Bell 412 helicopter and was capable of sampling and wirelessly transmitting data at a rate of 64 Hz in flight. Because the load monitoring and energy harvesting components are located on the pitch link’s exterior, however, this system may be readily subject to damaging impacts during helicopter

Figure 1 Potential application of KCF’s embedded load monitoring technology on rotorcraft

KCF is integrating energy harvesting, load sensing, and wireless communication for enabling the rod end’s autonomous and real time load monitoring. The new load sensor addresses the need for low power, EMI robustness, and calibration free sensing. The energy harvester enables battery-free operation of the sensor system with 0.3 inch package size. The wireless RF communication uses recent advances in low-power wireless radio communication. The complete system is self-contained inside the threaded stem of the rod end, rendering a durable and maintenance–free sensor.
operation or routine maintenance. A more robust solution would be to package these components into existing parts in critical load paths. KCF has accomplished this by embedding both harvesting and load sensing components within a pitch link rod end stem. To provide a clear path to commercialization, KCF is collaborating directly with the rod end manufacturer, Lord Corporation, to incorporate the components during the manufacturing process.

**Embedded Component Load Monitoring**

Measuring the structural response of mechanical systems subject to loading provides a fundamental means for characterizing the local response of components or the global inputs to systems or components. For example, strain gauges on helicopter pitch links are used to measure loads being transmitted through the pitch links to the rotor assembly. Alternatively, strain gauges on rotor blades could be used to determine the actual stress state of the blade for estimating its damage accumulation during use.

Use of bondable metal foil strain gauges have been by far the most prominent strain and load measurement technique for the past half century. Foil strain gauges have a network of thin wires embedded in a thin plastic film. When subject to strain, the metal foil stretches, which in turn changes the length to cross-sectional area ratio of the metal wire. The geometric changes of the wire alter the electrical resistance of the gauge. Because the changes in resistance are small, Wheatstone bridge circuits are used to amplify the electrical response.

Their small size, minimal influence on the host structure’s mechanical properties, and ease with which they can be added to a structure have made them useful for many applications particularly in temporary installations or in diagnostic implementations on existing structures. Significant drawbacks of these sensors, which typically do not limit their application in light of other traditional strain measurement technology, include temperature sensitivity, change in performance over time due, and the power electronics needed to operate them. The temperature sensitivity is minimized using low thermal expansion metals alloys such as nickel-copper.

For some applications, the mentioned drawbacks make their use particularly unattractive. For example, strain measurement accuracy on helicopters is critical due to the small safety factors. Changes in the sensitivity over time are unacceptable, especially because these strain gauges are often used for updating component retirement times to reduce operating cost, and a strain gauge that requires frequent calibration would add cost and maintenance. With advances in ultra low power wireless sensors, the power requirements and electronic circuit required for foil gauges are further limiting their applicability for some applications.

Of the alternative and innovative strain sensing technologies, including optical fiber Bragg, piezoresistive, and capacitive, the inverse magnetostrictive sensors are the most promising for discrete low power sensor nodes. Fiber Bragg sensors are particularly well suited for applications where large power electronics are acceptable, cost is not a concern, and many measurement locations along a single fiber are needed. Piezoresisitive sensors suffer from strong temperature sensitivity, and capacitive sensors typically require complicated power electronics and signal processing.

The strain sensor developed by KCF utilizes the inverse magnetostrictive effect. This effect characterizes the change of domain magnetization when a stress is applied to a material, which is also known as the Villari effect. On a micro scale, application of a magnetic field causes boundaries between the domains to shift and the material’s dimensions to change. A Hall effect sensor is used to measure changes in the magnetic permeability of the magnetostrictive material. The sensor voltage output can then be calibrated to actual load levels. The advantages of this approach include very low power requirements and the ability to put the sensor in sleep mode when data is not acquired.

In the current work, KCF has seamlessly embedded this sensor in a pitch link rod end’s interior so that information recorded about the rod end’s health remains with the rod end. In this case, removing the rod end from its assembly will not disassociate the health data from the rod end. This is important for air and land vehicle components that are periodically removed and may remain in storage for a period of time. Since retrieval of health data from the sensor depends on the operation of the energy harvesting power supply, the power harvester must be subject to its intended environment. When a component with an embedded sensor and power harvester is in storage or removed from its assembly, the energy harvester is likely to be completely inert and it would not be possible to extract health data from the component. This is an issue because one of the main purposes of embedded health sensors is to evaluate if a component can be returned to service. KCF is currently developing technologies that will allow for local interrogation of uninstalled components that rely on embedded energy harvesters for power. Current designs consist of connectionless interrogation wands that can quickly provide wireless power and communicate with the component to assess its health when not in use.
Energy Harvesting

To harvest energy from a host object’s mechanical strain, piezoelectric transducers are directly attached or embedded in the host component, where the piezoelectric material strains with the host component. This strain on the piezoelectric element in turn induces charge at its electrodes. The charge is then extracted by the circuit so that it can be delivered to the health monitoring device.

This strain-based harvester is implemented by placing the piezoelectric material in the load path. Since the electric field generated in the piezoelectric material is proportional to the strain, the voltage at the electrodes is minimized by using thin layers of material. In this configuration, the $d_{33}$ piezoelectric constant defines the relationship between strain and electric field. To increase the power output of the harvester while still minimizing voltage, the piezoelectric material is layered to form a piezoelectric stack. The piezoelectric element is coupled mechanically to the host structure by placing it under a preload using the host structure’s surrounding structure. In this way, the element is in parallel with the primary stiffness of the host structure.

Energy is harvested from the electromechanical transducer using a circuit that consists of a diode bridge, a DC-DC converter, energy storage element, and voltage regulator. Input voltage protection and overvoltage protection for the storage element are also included in the circuit. The bridge provides rectification of the voltage waveform from the energy harvester transducer. The uni-polar rectified waveform is fed into an input capacitor that acts as a voltage filter so that a steady DC voltage is available for the DC-DC converter. The DC-DC converter optimally transfers energy from the input capacitor(s) which are at variable voltages to a much larger sized energy storage element that is typically used within a narrow voltage range. The energy storage element provides an energy reservoir so that the load can draw power that is much higher than that supplied by the harvester for short durations. This is needed because the electrical load is generally determined by its specific application and it is often much higher than that which is available directly from the energy transducer.

Infrastructure for Dynamic Component Life Tracking

For effective component tracking and life assessment, it is imperative that up-to-date history and remaining life of components be readily available through a sophisticated system architecture that smoothly integrates all pertinent data management systems. KCF is collaborating with technology partner TDA to address the essential objectives of tracking each aircraft and its components in near real-time with a system level approach, gathering complete component usage history and thereby accurately predicting the life of each component, and subsequently eliminating penalties imposed due to unknown usage histories. KCF’s sensor development supplements this system with accurate and near real-time load data on the rotor assembly.

TDA envisions one comprehensive and integrated dynamic component tracking system. This vision brings together rotorcraft data in one open architecture framework to provide near real-time component health and fatigue life expended (FLE) values. The fleet management tool envisioned in this framework will promote the development of safety strategies through asset management via prognostics, scheduling fleet maintenance actions, and future acquisitions.

TECHNOLOGY DEVELOPMENT

Load Monitoring H-60 Rod End with Embedded Components

An elastomeric H-60 pitch link rod end was chosen as the development platform for KCF’s rotorcraft load monitoring technology. The rod end, pictured in Figure 2, was provided by the Lord Corporation. As indicated in the figure, the energy harvester, load sensor, data acquisition circuit board, harvester circuit board, and RF communication circuit board are all embedded within an existing cavity that is approximately three quarters of an inch in diameter and four inches deep. The loads applied to the rod end in flight cause dynamic straining of the part, which in turn cause straining of the piezoelectric harvesting element. The dynamic voltage created in the piezoelectric element is collected by the harvester circuit. The harvested power is then delivered to the load sensor and the data acquisition and RF communication boards. The magnitude of the dynamic flight loads is sufficient to power all of the embedded electrical components and RF communication devices.
Magnetostrictive Load Sensor

The magnetostrictive load sensor currently in development at KCF consists primarily of a magnetostrictive material, a Hall effect sensor, and permanent magnets located at either end of the magnetostrictive material. A change in stress to the load sensor results in a change in the magnetic permeability of the magnetostrictive material. This change in permeability alters the amount of magnetic flux that is passing perpendicularly through the Hall effect sensor. This change in magnetic flux corresponds to a change in the Hall voltage output, which can then be calibrated to the load. The Hall effect sensor is ultra low power and compact, with a geometry of 2.0 x 3.0 x 0.75 mm, and is capable of being put into sleep mode when not being interrogated.

Energy Harvesting

The embedded energy harvesting element consists of a piezoelectric stack element that generates a voltage in proportion to the level of strain it undergoes. The piezoelectric stack within the rod end is capable of providing in excess of 5 mW of power while the rod end is subject to representative pitch link loading.

A comparison of the harvester power generation and the power used by the sensor for various operation modes is plotted in Figure 4. The power generation depends directly on the magnitude of load applied to the rod end, and the power consumed is approximately proportional to the data sampling rate.

Data Acquisition and Wireless Transmission

An ultra low power microprocessor is employed to sample the load sensor data. The microprocessor has a 12 bit A/D for high resolution conversions, a DMA engine for efficient and power sensitive transferring of data, multiple timers for synchronization, and large amounts of on-board RAM for larger transfers of data packets. The data acquisition code is interrupt driven to take advantage of the different low power modes of the processor. The RF link has over the air data rates of up to 2Mbits/sec, which halves the duty cycle over traditional 1Mbits/sec RF radio. This in turn reduces the number of over the air data packet collisions that could occur. The radio also has the capability of auto-acknowledging receptions of data packets, up to three times, without any microprocessor involvement. Flash memory components ranging from 4 – 128 Mb can also be added to store sensor history and rainflow counting.

Standard IEEE 802.15.4 protocols such as Bluetooth® and Zigbee® are designed for specific applications that are different enough from rotorcraft low power sensor applications that a proprietary RF communication is required. The wireless solution presented herein addresses the need for a lower payload overhead and high data transmission rate while maintaining a high level of robustness. In addition, KCF’s wireless communication system will comply with the US government’s FIPS 140 security standard.

Antenna design is a critical feature for highly reliable data transmission and in terms of optimal mechanical packaging. A few antenna designs were evaluated for application to the rod end sensor. Patch style antennas provided a balance between size and attenuation. Chip antennas for direct implementation on a PCB and helical whip antennas were also characterized. A summary of preliminary antenna testing is shown in Figure 6.
Experimental Demonstration under Representative Loading

An experimental demonstration of the wireless load monitoring technology was conducted at the Lord Corporation. The test setup is pictured in Figure 6. It was demonstrated that the wireless sensor system reports the uni-axial rod end load time history in near real time. The system consists of the piezoelectric stack energy harvester, a 2.4 GHz wireless RF link, and the magnetostrictive strain sensor to measure and report the component load. Proper operation of all three subsystems and their interoperability was tested.

The demonstration showed that for nine of twelve typical loading conditions, the harvester provided sufficient power to sample and transmit load data wirelessly at a continuous rate of 100 Hz. Proper operation of the wireless RF link was confirmed by the receipt of full and coherent data sets. The strain sensor operation was confirmed by registration of the rod end’s static and dynamic load levels. In Figure 7 and Figure 8, force time histories are plotted as measured by a calibrated load cell and KCF’s embedded load cell for both sinusoidal and triangular force inputs. It was observed that the two load cells agreed well over a range of loading conditions.

On-going development work includes strain sensor signal conditioning, increased strain sensor sensitivity, data acquisition synchronization, storage of data locally at the rod end, energy transmission to the component when it is not loaded, wireless security, improved energy harvester performance, and calibration modes of operation.

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Figure 6: Experimental testing of rod end with embedded components at Lord Corporation for varying loading conditions at 4.3 Hz.

Figure 7: Force time history of Lord load cell and KCF’s embedded load cell for a sinusoidal force input at 4.3 Hz.

Figure 8: Force time history of Lord load cell and KCF’s embedded load cell for a triangular force input at 5 Hz.

American Helicopter Society International, Inc.
REFERENCES


