Honeywell International has developed and flight-tested a Corrosion and Corrosivity Monitoring System (C2MS). The C2MS detects galvanic corrosion in the main gearbox feet fasteners of helicopters. In addition, it monitors the environmental conditions inside the main floorboard compartment to determine the need for structural maintenance. The C2MS sensor on a main gearbox feet fastener sends a small electrical signal through the fastener and housing to measure the conductivity of the assembly. The measured conductivity value is used to determine if galvanic corrosion is present in the fastener assembly. The floorboard compartment sensors use a surrogate metal coupon to measure the corrosivity of the environment. The information from this sensor is used to recommend an extension to the calendar-based maintenance schedule. Fleet-wide information can be gathered by the system. The C2MS uses two Data Collection Units (DCUs) to store the corrosion data: one for the main gearbox feet fasteners and one for the main floorboard compartment. The DCU design addresses the issues of long battery life for the C2MS (greater than 2 years) and compactness. The data from the DCUs is collected by a personal digital assistant and downloaded to a personal computer where the corrosion algorithms reside. The personal computer display provides the location(s) of galvanic corrosion in the main gearbox feet fasteners as well as the recommended date for floorboard compartment maintenance. This paper discusses the methodology used to develop the C2MS software and hardware, presents the principles of the galvanic corrosion detection algorithm, and gives the laboratory and flight test results that document system performance in detecting galvanic corrosion (detection and false alarm rate). The paper also discusses the benefits of environmental sensors for providing a maintenance scheduling date.

Keywords: Corrosion, galvanic corrosion, corrosivity, condition-based maintenance, low power, sensor system

1. INTRODUCTION

Maritime aircraft operate in a particularly hostile, corrosive environment. Salt is always present on ship deck and can be encountered at altitudes up to 1500 feet above sea level. Since aircraft materials are primarily chosen for their lightness and strength, they are prone to corrosion. In addition, fastener assemblies in the aircraft require steel bolts for strength that are screwed into lightweight magnesium casing. This use of dissimilar metals in the main gearbox fastener assembly is a prescription for galvanic corrosion. Galvanic corrosion can cause rapid damage to flight-critical structures, which has a detrimental effect on safety and operational capability. To minimize the effects of corrosion, maintenance personnel must regularly schedule expensive and time-consuming inspections. Currently, maintenance uses visual inspections, man-in-the-loop inspections with various types of non-destructive evaluation (NDE) equipment, and regularly scheduled strip and search inspections. Clearly, an autonomous corrosion monitoring system is needed to reduce man loading and provide reliable early warning corrosion information suitable for condition-based corrosion maintenance.
Honeywell International (United States) partnering with Avonwood Developments LTD (United Kingdom) has developed and flight tested a Corrosion and Corrosivity Monitoring System (C2MS). The C2MS continuously monitors two corrosion prone areas in helicopters: the fastener assembly for the main gearbox housing, and the main floorboard compartment. The C2MS provides the only in situ galvanic corrosion detection system that we are aware of that can continuously monitor the main gearbox fastener assembly. The C2MS uses corrosive environment sensors (CES) in the floorboard compartment to provide a more accurate estimation of the date to inspect the compartment than that obtained from a calendar-based maintenance system.

2. SYSTEM OVERVIEW

The C2MS constantly monitors critical equipment and corrosion prone areas in helicopters to provide information for condition-based maintenance. The C2MS performs two corrosion sensing functions. It detects galvanic corrosion in the main gearbox feet fasteners and monitors environmental conditions inside the main floorboard compartment of helicopters to determine the need for structural maintenance. Early detection of galvanic corrosion in the main gearbox feet fasteners ensures flight safety and mission readiness while eliminating unnecessary fastener inspections. The C2MS sensors on the main gearbox feet fastener send a small electrical signal through the fastener and housing to measure the conductivity of the assembly. The conductivity information is used to determine whether galvanic corrosion is present in the fastener assembly. The floorboard compartment sensors use a surrogate metal coupon for the measurement of the corrosivity of the environment. Maintenance intervals can typically be extended by measuring the actual corrosivity of the environment rather than using worst-case-based calendar inspections. Figure 1 shows an overview of the C2MS.

![Figure 1: Overview of C2MS operation](image)

The C2MS consists of two data collection units (DCUs), a personal digital assistant (PDA), and corrosion analysis and display software that run on a PC. Each DCU is composed of corrosion sensors and electronics for autonomously collecting and storing corrosion data. The PDA is used to gather corrosion data from the DCUs and transfer the data to a PC for analysis, display, and archiving. Figure 2 shows the DCU and attached sensors. Each DCU is configured for either galvanic corrosion detection (eight sensors) or corrosion environment sensing (three sensors).
3. CORROSION SENSOR METHODOLOGY

The C2MS is a battery operated sensor system that detects galvanic corrosion in the main gearbox feet fasteners and constantly monitors the corrosive environment inside the floorboard compartment. The galvanic corrosion sensor (smart bolt cap or smart washer) and the CES perform their sensor functions independently. The galvanic corrosion sensor has a mission life greater than four years and the CES has a mission life of from two to four years, depending on the environment inside the floorboard compartment. The smart bolt cap and smart washer sensor follow the same principle of operation for detecting galvanic corrosion; however, they are attached in a different manner in the fastener assembly. The operation of the smart bolt cap and CES are discussed in the following subsections.

3.1 Smart bolt cap sensor

Galvanic corrosion occurs when two dissimilar metals are in direct contact with each other and moisture is present. In a helicopter, the magnesium transmission case is bolted to the helicopter with a steel bolt and nut. When galvanic corrosion occurs, the magnesium case becomes the anode and the steel bolt the cathode with magnesium the sacrificial metal in the galvanic corrosion cell.

Because galvanic corrosion can be very aggressive and must be avoided, a standard protective system prevents direct contact between the dissimilar metals and prevents moisture penetration between the metals. The system includes protective paint on the magnesium case, protective coating (e.g., cadmium on the steel bolt and nut), and a protective sealant on and around the exposed bolt head. The paint helps prevent electrical contact between the bolt head and the magnesium case. The cadmium coating helps reduce galvanic action.

The smart bolt cap sensor has a metal sensing ring that is periodically energized by the C2MS battery. Under normal conditions, when the fastener's protective system is intact and no galvanic corrosion is present, the sensing ring is electrically insulated from the metal structure. In this case, no current can flow from the battery through the conductive ring to chassis ground. This condition results in a measured resistance value along this path of several hundred mega ohms. If a failure occurs in the protective system, i.e., the sealant and protective coating have broken down, and moisture has penetrated into the assembly initiating galvanic corrosion, then there must be a conductive path from the battery, through the sensing ring to chassis ground. This condition results in a measured resistance value of several hundred kilo ohms. This drop in resistive value indicates galvanic corrosion. Note that moisture must penetrate the assembly to create a conductive path to ground and thus make the low resistance measurement possible. However, moisture in the assembly can come and go relatively quickly depending upon environmental conditions. C2MS deals easily with this situation by measuring the resistance value several times a day, then latching to a galvanic corrosion DETECT whenever the resistive change is measured. (In actuality, multiple resistive measurements and a
voting scheme are used during a single interrogation cycle.) Once a DETECT is declared it remains on until reset.

The smart bolt cap and smart washer sensor are patented in both the United States and the United Kingdom.

3.2 Corrosive environment sensor
Removing the helicopter floorboards and performing compartment maintenance requires considerable labor (man loading) and causes significant down time, affecting mission readiness. Floorboard compartment maintenance is typically performed on a calendar-based schedule. Note that floorboard compartment sealants and coatings are frequently upgraded, which tends to lengthen the schedule. While extending the time between maintenance cycles is, in general, good, it also increases the risk that the floorboard compartment will experience excessive damage before maintenance is performed. The CES is designed to reduce the man loading requirements and overall maintenance costs by providing a condition-based maintenance schedule for floorboard removal. While mission readiness and other requirements do not afford the luxury of maintaining each helicopter at the optimum time, it is conjectured that fleet-wide condition information can be used to provide the optimum low-cost maintenance solution for the fleet.

The CES uses a metal "coupon" to constantly measure the corrosive environment inside the floorboard compartment. The CES does not detect or determine the location of metal corrosion in the compartment's structure. This means the CES scheduling methodology is completely inferential, i.e., the worse the environment in the compartment over the longer period of time, the more need there is to perform maintenance. We have selected stainless steel as the coupon material rather than the metal used in the floorboard compartment. This enables a higher sensitivity measurement of the environment inside the compartment than that obtained using aluminum which is more resistant to corrosion. With the stainless steel coupons our algorithm uses the principles of electrical resistance NDE (resistance increases as metal thickness decreases) to continuously estimate the corrosion rate and the cumulative metal loss of the coupon. The cumulative metal loss for the stainless steel coupon is compared against the cumulative metal loss expected from ISO9223 corrosivity categories C1-C5 for stainless steel. A proprietary algorithm is then used to estimate the expansion or contraction from the calendar based maintenance date. The CES also contains a temperature and humidity sensor that can be used to calculate the Time of Wetness (TOW) inside the compartment. Our original intent was to use TOW as collaborative information with the electrical resistance sensor. However, we have yet to see any real advantage from these additional sensors and our plan is to eliminate the temperature and humidity sensors from future C2MS units.

The approach used for the CES is patent pending in the U.S. and a foreign patent application has also been filed.

4. FLIGHT TEST SYSTEM

4.1 System hardware
The system hardware consists of Data Collection Units (DCUs) and a set of attached sensors. Two DCUs are required to instrument a helicopter, one configured with corrosive environment sensors and one configured with galvanic corrosion sensors. Figure 3 shows a DCU with all three corrosive environment sensors and Figure 4 shows a DCU with all eight smart bolt cap sensors.

The other form of the galvanic corrosion sensor is for helicopters with washers in the fastener assembly. For this case, a smart washer sensing ring is attached to the outer rim of the Equipment Manufacturer (OEM) washer. Figure 5 shows a smart washer sensor.
The DCU power is enabled using a reed switch, which consists of two ferromagnetic reeds, hermetically sealed in a gas filled capsule. When these reeds are introduced to a magnetic field, they assume opposite polarities and attract each other closing the contacts. When the magnetic field is reduced beyond the spring force of the reeds, the contacts spring open. The magnetic field is supplied by an internal magnet that slides into place during the installation process.

The DCU electronics are sealed in an aluminum enclosure with a silicone elastomer to reduce corrosion and vibration concerns. EMI radiation from the hardware was mitigated by careful use of components with low radiation properties. The grounded aluminum enclosure also shields against EMI transmission both to and from the helicopter.

Vibration testing was performed on the hardware using a sinusoidal vibration with broadband background superimposed. Four different frequencies corresponding approximately to the fundamental, blade passage and 1st and 2nd harmonics were tested ($f_1$, $f_2$, $f_3$, and $f_4$). Each axis was tested at these frequencies for a period of 1 hour for a total of 12 hours testing. Figure 6 shows the typical vibration exposure for the helicopter. Shock testing was done using the shock response spectra shown in Figure 7.
Temperature testing was performed by ramping from room temperature to -40°C where it remained for 4 hours to stabilize the temperature. It then maintained operation for 30 minutes. Next, the temperature was ramped to 32°C and operation was maintained for 30 minutes. The temperature was ramped to 60°C where it remained for two hours to stabilize the temperature. It then maintained operation for 1 hour. Finally, the temperature was ramped back to room temperature and the cycle was repeated 10 times.

The DCU communicates to a PDA with a wired serial link. The two DCUs are bussed together using a shielded twisted pair cable with a connector installed for a single point data download to the PDA. No specific time is set for system download; however, data should be collected as often as practicable. The sooner the conditions for galvanic corrosion are detected, the quicker a maintenance check can be performed. At the time of download, all data collected since the previous download is transmitted.

4.2 Sensor locations
The DCUs are mounted in locations that are convenient for the sensors. Since no access to the DCU is required for operation or data download, they do not need to be easily accessible. The corrosive environment sensors are located under the floorboards and are secured to the helicopter skin with epoxy. The galvanic corrosion sensor takes on two forms: the smart bolt cap sensor and the smart washer sensor. The smart bolt cap sensor is used when no washer is present in the fastener assembly. It attaches to a recess in the bolt head by tightening a nut on the sensor. The smart washer sensor replaces the OEM washer in the assembly and is shown in Figure 11.
5. FLIGHT TEST RESULTS

Corrosion algorithms and display software reside on the PC to which the corrosion data is downloaded. The C2MS display screen is shown in Figure 12. In the middle left portion of the screen the helicopter Tail Number is selected. Information in the top portion of the screen indicates whether galvanic corrosion has been detected in any of the eight gearbox feet fasteners in the helicopter. For the case shown, all eight gearbox fastener assemblies are green, indicating that galvanic corrosion is not present. If galvanic corrosion is detected, one or more of the green-filled circles will turn red. The information in the center of the screen indicates the recommended extension or contraction in the calendar-based maintenance schedule. Here, the recommended extension is 12 weeks, our current maximum extension time. The calculated date for the inspection is also shown in the middle of the figure. The button (Floorboard Compartment Environment) on the middle right of the screen can be used to call another screen that displays detailed information on the environment measured inside the floorboard compartment.

During an 18-month flight test in the United Kingdom using three helicopters, two galvanic corrosion detections occurred. The two galvanic corrosion detections were verified by manual inspection of the fastener assemblies. There were no false alarms over the 18-month test period in the United Kingdom. During two flight tests in the United States, one of 13-month duration and the second of 14-month duration, no galvanic corrosion detections occurred. A third flight test of 16 months in the United States had two galvanic corrosion detections. The first detection was recorded but not inspected. When the inspection was performed two months later another detection was recorded. The inspection verified a break in the sealant along with the presence of moisture. As expected, there were no false alarms during the tests in the United States.

During a 14-month and a 16-month helicopter test in the United States, the CES reported unusually low levels of environmental corrosivity inside the floorboard compartment and recommended the maximum extension time of three months before maintenance is performed. For the 16-month test the floorboards were removed at the end of the test; however, for the 14-month test the floorboards were removed to perform maintenance after 10 months. In both cases, the maintenance team reported that the floorboards were "clean" and maintenance was unnecessary. Checks with the flight data logs indicated that both helicopters had only a few hours flying time over salt water and were basically in a low salt environment over their entire test periods further verifying the CES recommendations.

The C2MS does not currently provide a summary display of fleet-wide corrosion conditions as shown in Figure 13. However, we anticipate adding this feature to future versions of the C2MS.
6. CONCLUSIONS

The C2MS detects galvanic corrosion in fastener assemblies and monitors hard-to-reach areas to determine whether corrosion maintenance is needed. While the C2MS was developed for and is being tested on rotary aircraft, the technology is directly applicable to several other platforms including fixed wing aircraft and ships. We are not aware of any other sensor that can unobtrusively monitor fastener assemblies for galvanic corrosion. In addition, because of the simplicity of the principle used in the detecting galvanic (measuring a large decrease in resistance), the system is virtually false-alarm proof.

The goal of the CES is to provide better information in scheduling maintenance than can be obtained using a calendar-based maintenance system. Scheduling is accomplished using onboard sensors to measure corrosive activity. This approach provides the maintenance engineer with "a pair of eyes" in difficult locations that should be a valuable tool in scheduling maintenance.

Testing of the C2MS through this date has produced outstanding results; however, more testing is required to form a statistically significant data base to further evaluate system performance. Another difficulty facing the C2MS is one that faces all condition-based maintenance systems—lack of documented corrosion maintenance costs to establish and prove a value proposition for the maintenance system. We can only hope that in the future studies will document maintenance costs and provide a rationale for condition-based maintenance systems.
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