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USING CORROSION HEALTH MONITORING SYSTEMS TO DETECT CORROSION: REAL-TIME MONITORING TO MAINTAIN THE INTEGRITY OF THE STRUCTURE

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Abstract

This study investigates the use of Corrosion Health Monitoring (CHM) systems to detect and manage corrosion in aviation environments, with a specific focus on enclosed areas within aircraft structures. Corrosion poses significant risks to airport facilities and aircraft, and CHM systems offer real-time monitoring and data-driven approaches for proactive corrosion management. Through case studies conducted at two different test sites, the effectiveness of deploying advanced sensors was demonstrated in identifying corrosion-prone areas, optimizing maintenance schedules, and enhancing safety and structural integrity. The study highlights the variability in corrosion rates between open-air and enclosed conditions, emphasizing the need for tailored prevention strategies. It also discusses the challenges of integrating CHM systems into existing maintenance practices and airport infrastructure, addressing issues such as sensor placement, data management, and regulatory compliance, and outlines future directions for R&D in this critical area. By incorporating CHM systems, the aviation industry can transition from reactive to predictive maintenance, improving the reliability and lifespan of assets while reducing costs.

Keywords: corrosion, CHM, SHM, aviation, aircraft, structure integrity.
Article category: research article.

1. INTRODUCTION

Atmospheric corrosion is a pervasive issue affecting various industries, with airports and the aviation sector being particularly vulnerable due to their exposure to harsh environmental conditions. This paper overviews atmospheric corrosion and the factors influencing its occurrence, including the mechanisms behind it, the specific challenges faced by airports and aircraft producers, and the mitigation strategies employed to combat this persistent threat. The goal is to emphasize the importance of proactive corrosion management in ensuring the safety, reliability, and longevity of aviation assets.

Mechanisms of Atmospheric Corrosion

Atmospheric corrosion occurs through electrochemical reactions between metal surfaces and environmental elements. Key factors influencing these reactions include:

- Humidity and Moisture: The presence of water, whether in liquid form or as vapor, facilitates the electrochemical processes that lead to corrosion. High relative humidity levels can accelerate these reactions, while dew, rain, and fog contribute to the persistence of moisture on surfaces.
- Temperature: Elevated temperatures generally increase the rate of corrosion reactions. However, temperature fluctuations can also cause condensation, creating localized areas of high moisture concentration that promote corrosion.
- Pollutants: Industrial pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) react with moisture to form acidic compounds, which can significantly accelerate corrosion. Additionally, chlorides, especially in marine environments, are highly aggressive towards metals.
- Material Composition: Different metals and alloys exhibit varying levels of susceptibility to atmospheric corrosion. Protective coatings and treatments can enhance the resistance of these materials to corrosive processes.

Introduction to CHM Systems

Corrosion Health Monitoring (CHM) systems are advanced technologies and methodologies used to detect, monitor, and assess corrosion in structures and materials, particularly those exposed to harsh environments. These systems leverage various sensors, data acquisition tools, and analytical methods to provide real-time or periodic information about the condition of materials and structures.

Purpose of Corrosion Health Monitoring Systems

Early detection and prevention of corrosion are crucial. CHM systems detect the early stages of corrosion before it leads to significant material degradation. By catching corrosion early, CHM systems help in preventing sudden and catastrophic structural failures. Providing real-time data allows for timely maintenance, which can extend the life of assets.

With accurate corrosion data, maintenance can be performed only when necessary, reducing downtime and maintenance costs. Continuous monitoring ensures that the structural integrity of critical infrastructure is maintained, enhancing overall safety. CHM systems also help ensure compliance with industry safety standards and regulations. Early detection reduces the need for emergency repairs, which are often more costly. Maintenance resources can be better allocated based on actual corrosion data rather than estimated schedules.

CHM systems provide valuable data that can be used for making informed decisions regarding asset management and maintenance. Advanced CHM systems can use collected data for predictive analytics, helping forecast future corrosion trends and potential issues. By implementing CHM systems, industries can significantly enhance the safety, reliability, and longevity of their assets while reducing costs and environmental impact.

2. IMPACT ON AIRCRAFT AND ON AIRPORT INFRASTRUCTURE

Impact of Aircraft

Selecting optimal locations for sensor placement in the aircraft is an inherently complex and time-consuming task. Sensors need to be installed in areas where corrosion is anticipated to be most severe, ideally based on a comprehensive database detailing observed corrosion hotspots for the specific aircraft type. However, creating such a database requires long-term monitoring and the deployment of the system on already well-documented structures. For instance, the installation of the CHM system on the Mi-24 helicopter used by the Polish Armed Forces (Fig. 1) leverages existing knowledge of the helicopter's structural vulnerabilities, making it easier to strategically place sensors to effectively monitor and mitigate corrosion (Ciężak & Rdzanek, 2020).

Figure 1. CHM system consisting of three autonomic sensors installed on in-service Mi-24

Aircraft are constructed from a variety of materials, including aluminum alloys, steel, and composites, each with differing susceptibilities to corrosion, which have different effects on the fatigue behavior of the structure. Specific corrosion-prone areas include:

- Fuselage Corrosion: Aluminum alloys, commonly used in aircraft fuselages, are prone to pitting and intergranular corrosion, which can lead to structural weaknesses and increased drag, affecting the aircraft's performance and fuel efficiency.
- Wing and Tail Structures: These critical components are exposed to various environmental conditions and are at risk of corrosion, which can compromise their aerodynamic properties and structural integrity.

Corrosion poses severe safety risks to aircraft. Structural failures due to corrosion can lead to catastrophic incidents – such as that of Aloha Airlines Flight 243 (National Transportation Safety Board, 1988). Additionally, corrosion of electrical and hydraulic systems can cause malfunctions that impair the aircraft's operational capabilities. Therefore, rigorous inspection and maintenance protocols are essential to ensure flight safety.

To counteract the effects of atmospheric corrosion, aircraft maintenance involves regular inspections, repairs, and replacements. These activities increase operational cost and require significant resources. While using corrosion-resistant materials and advanced protective coatings can extend the service life of aircraft and improve safety, they also add to costs.

Effective mitigation of atmospheric corrosion involves a combination of material selection, protective measures, and proactive maintenance practices:

- Protective Coatings: Application of corrosion-resistant paints and coatings is a primary defense against atmospheric corrosion. Galvanization, which involves coating steel with a layer of zinc, is particularly effective for protecting steel structures.
- Material Selection: Utilizing alloys with high corrosion resistance and incorporating non-metallic composite materials can significantly reduce the susceptibility of components to corrosion.
- Environmental Control: Managing humidity levels and reducing exposure to corrosive pollutants are crucial steps in minimizing corrosion risks. This can involve the use of dehumidification systems and pollution control measures.
- Regular Inspections and Maintenance: Conducting frequent and thorough inspections allows for early detection of corrosion, enabling timely intervention and repair. Preventive maintenance strategies help address potential issues before they escalate.
- Corrosion Monitoring Systems: Implementing advanced sensors and monitoring systems enables continuous assessment of corrosion levels. These systems provide real-time data, facilitating informed decision-making and prompt corrective actions.

Impact on Airport Infrastructures

Airport infrastructure, primarily made of steel, is highly susceptible to corrosion, which weakens structures and thereby poses significant safety risks. Effective corrosion management is essential to prevent structural failures, accidents, and economic losses. For instance, maintaining the structural integrity of hangars where aircraft are maintained is crucial, as a roof collapse could result in significant damage to the aircraft housed within, leading to multi-million dollar losses for the airport, airlines, and maintenance companies.

Implementing a CHM system can significantly enhance the assurance of structural integrity through the deployment of appropriate sensors. These sensors facilitate continuous monitoring and early detection of potential issues, particularly corrosion, thereby aiding in timely maintenance and prevention of structural failures. For instance, installing an Acuity LS sensor kit on the structural beams of a hangar roof (Fig. 2), where corrosion is most likely to occur (Tzortzinis et al., 2020a), utilizing both painted and bare sensors, allows for a comprehensive assessment of the environmental conditions affecting the structure (Tzortzinis et al., 2020a, 2020b). This configuration enables the evaluation of the current state of the structure and the identification of potential future corrosion-related threats. By monitoring using corrosion sensors both coated and uncoated surfaces, the system can provide valuable data on the onset and progression of corrosion, facilitating proactive maintenance and ensuring structural integrity.

Figure 2. Example location of corrosion sensors on the hangar structure

Airport infrastructure includes comprises numerous metal structures, including hangars, control towers, bridges, and support frameworks. Steel is commonly used in these structures, maing them particularly vulnerable to atmospheric corrosion, which can lead to compromised structural integrity either in bare metal or in embedded steel in concrete. The corrosion in the former cause the reduction of load-bearing capacity; in the latter, the corrosion products generate spalling and weakening of the concrete, compromising the stability of the structure.

Corrosion-induced degradation of airport infrastructure poses significant safety risks. Structural failures can lead to accidents and operational disruptions, endangering lives and causing substantial economic losses. (Herzberg et al., 2019; United States

Government Accountability Office, 2019). Ensuring the integrity of these structures through effective corrosion management is therefore mandatory, requiring frequent (the frequency of building inspections depends on the building regulations in a given country) inspections and maintenance activities, driving up operational costs. Preventive measures such as protective coatings and cathodic protection also contribute to the financial burden. Moreover, maintenance operations often lead to downtime and disruptions, affecting airport efficiency and reliability (Rakas et al., 2018).

Atmospheric corrosion is a pervasive and persistent challenge for the aviation industry, affecting both airport infrastructure and aircraft. The impacts of corrosion are far-reaching, encompassing structural integrity, safety, and operational efficiency. Through a combination of advanced materials, protective coatings, environmental controls, and proactive maintenance, the aviation industry can effectively manage and mitigate the risks associated with atmospheric corrosion. In particular, continued research and innovation in corrosion monitoring and prevention can be fundamental to learn how safeguarding the longevity and reliability of aviation assets.

3. CASE STUDIES

To test the effectiveness of the CHM systems, two different locations in Italy were selected as corrosion test sites: the CNR-ICMATE facilities in Padua and Bonassola (MARECO Laboratory), shown in Fig. 3.

Figure 3. Two atmospheric corrosion test sites in Italy
(CNR-ICMATE laboratories in Padua and Bonassola)

The test site in Bonassola, a small village on the Ligurian coast of the Mediterranean Sea, is a sea-exposed site at MARECO, the CNR-ICMATE polythematic marine laboratory (Fig. 4). Here, a stand with sensors is placed on the balcony above a laboratory set inside a cave. During fall 2023, a severe storm induced particularly high surf, with waves causing intense washing of the Acuity LS position. In Padua the corrosion test site is located in an industrial zone, in the immediate vicinity of the highway (city bypass) and two large railway reloading facilities (Fig. 5). It is one of the most industrialized regions of northern Italy. These locations provide data from environments where aircraft and potential airport installations are most exposed to rapid corrosion.

Figure 4. View of the corrosion test station in Bonassola

Figure 5. View of the corrosion test station in Padua (Google view)

Sensors at both corrosion test sites were positioned similarly: one sensor was installed in an open-air environment, while the other was positioned inside an aircraft wingtip (simulating the microclimatic conditions within a confined space). An autonomous sensor array with an independent power supply, the Acuity LS (Fig. 6) from Luna Labs, was selected for this study (Friedersdorf et al., 2019). This choice was primarily influenced by the prior successful implementation of these sensors by AFIT in a flying helicopter in recent years, demonstrating their reliability and suitability for similar applications.

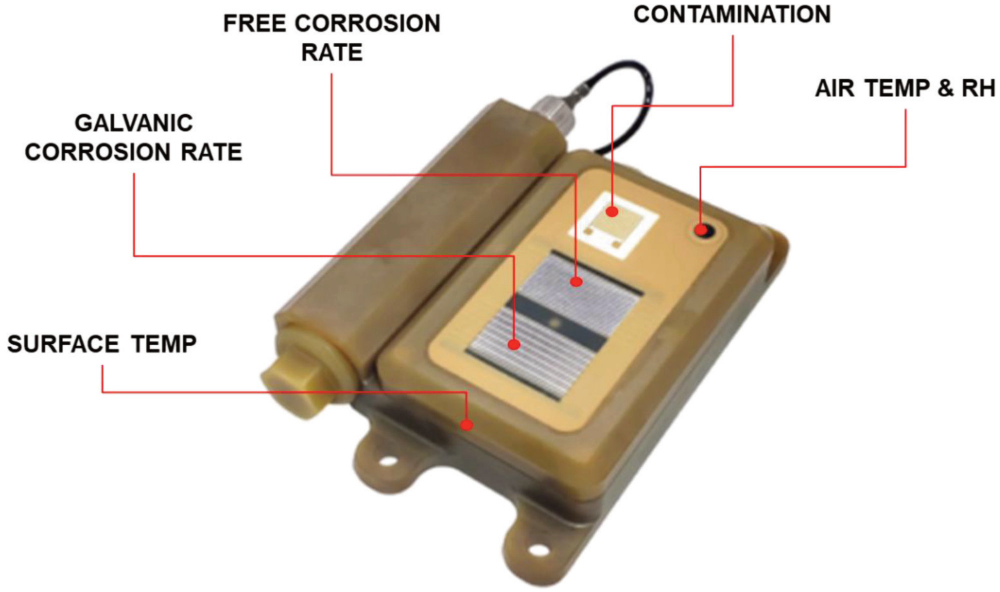

Figure 6. Acuity LS sensor system

Comprehensive measurements were taken for all parameters (presented in Table 1) every 30 minutes.

Table 1. Recording elements and registered parameters

Recording elements	**Registered parameters**
Air temperature (Ta)	-40ºC – +85ºC (±0.3%)
Relative humidity (RH)	0% – 100% (±2%)
Conductivity due to pollutants	micro-Siemens, µS
Free corrosion	Free corrosion current, µA Cumulative free corrosion, µC
Galvanic corrosion	Galvanic corrosion current, µA Cumulative galvanic corrosion, µC
Surface temperature (Ts)	-40ºC – +85ºC (±0.3%)

Acuity LS sensors output a conductivity measure in µS, due to pollutants such as SO_2 and NO_x, which can form acids in the presence of moisture, as well as C particles and chlorides. The free and galvanic corrosion outputs are measured in µA, the cumulative corrosion in µC, which is proportional to the mass loss rate of the sensor alloy in g/(m^2*year). These units are consistent with ISO 9223 standards for classifying, determining, and estimating the corrosivity of atmospheres. Corrosion rate measurements are performed using laminated wafers produced from metals and engineering alloys. For testing, the sensors used the following metal combinations:

- for free corrosion measurements – aluminum 7075-T6;
- for galvanic corrosion measurements – a compilation of aluminum 7075-T6 and stainless steel A286.

Interestingly, after just 3 months, significant differences in the corrosivity of atmospheres were observed between the two corrosion test sites. Moreover, within the same site, the tests reveal appreciable differences in corrosivity between atmospheric corrosion (outside) and that observed inside a closed space (microclimate), shown in Figs. 7 and 8.

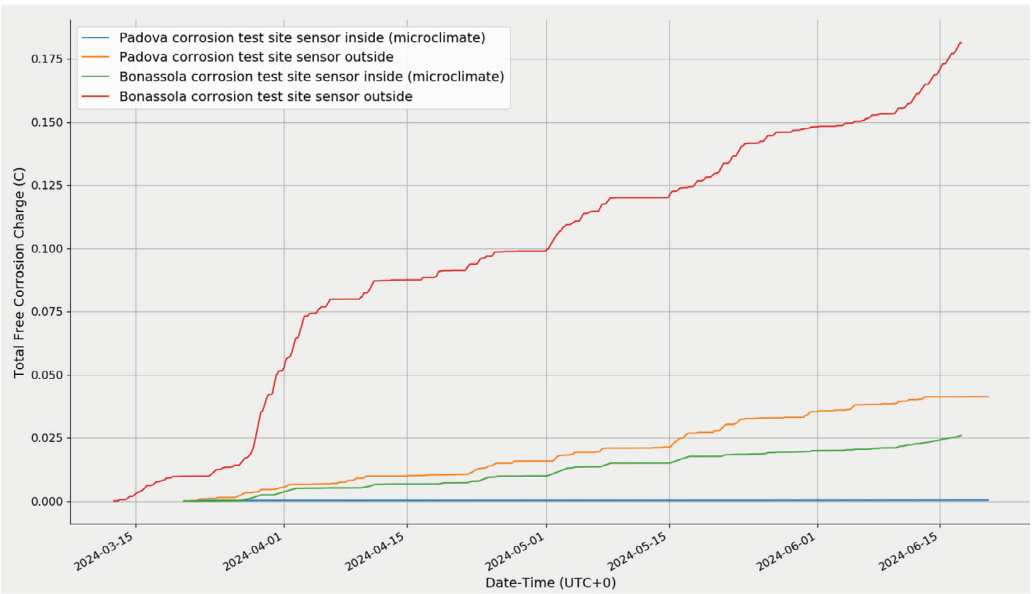

Figure 7. Total Free Corrosion Charge

The microclimate within enclosed sections of aircraft wings involves specific environmental conditions present inside these structures, such as temperature, humidity, and the presence of chemicals or microorganisms. In aircraft wings composed of either metal or composite materials, temperature variations are significant and influenced by external conditions. At high altitudes, the external temperature can plummet to approximately -60°C, which directly impacts the internal temperature of the wings. Generally, the humidity within the wings is low, owing to the hermetic seal and the inherently low humidity of high-altitude air. Nevertheless, moisture ingress can occur through leaks or condensation, potentially leading to the corrosion of metallic components.

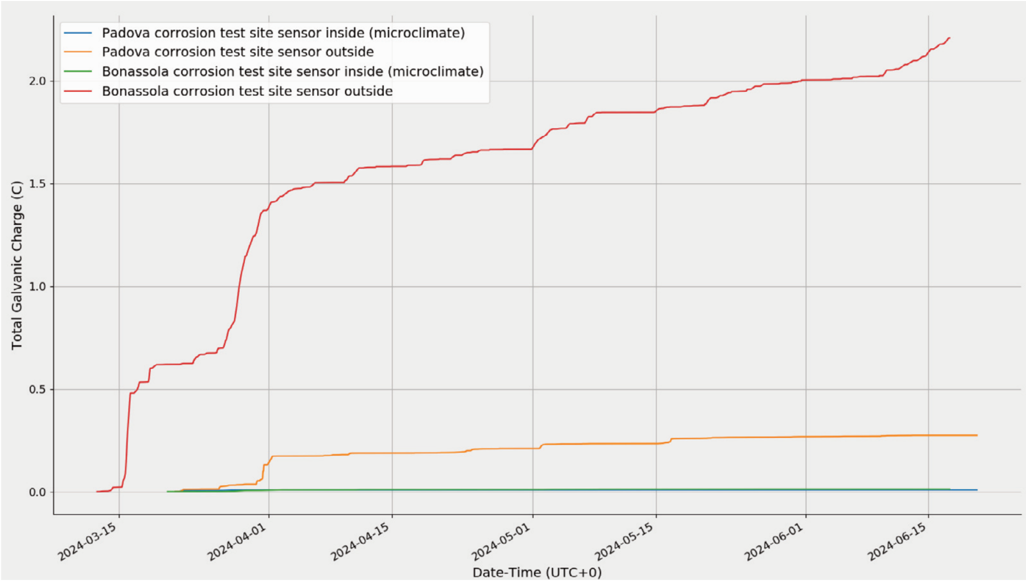

Figure 8. Total Galvanic Corrosion Charge

Figure 9 presents the chloride ingress into the internal structure of the wing, as evidenced by a delay of approximately 4 to 10 hours between the increase in conductance signals detected by the exterior and interior sensors. This delay indicates the time required for chloride ions to permeate from the wing's surface to its internal regions.

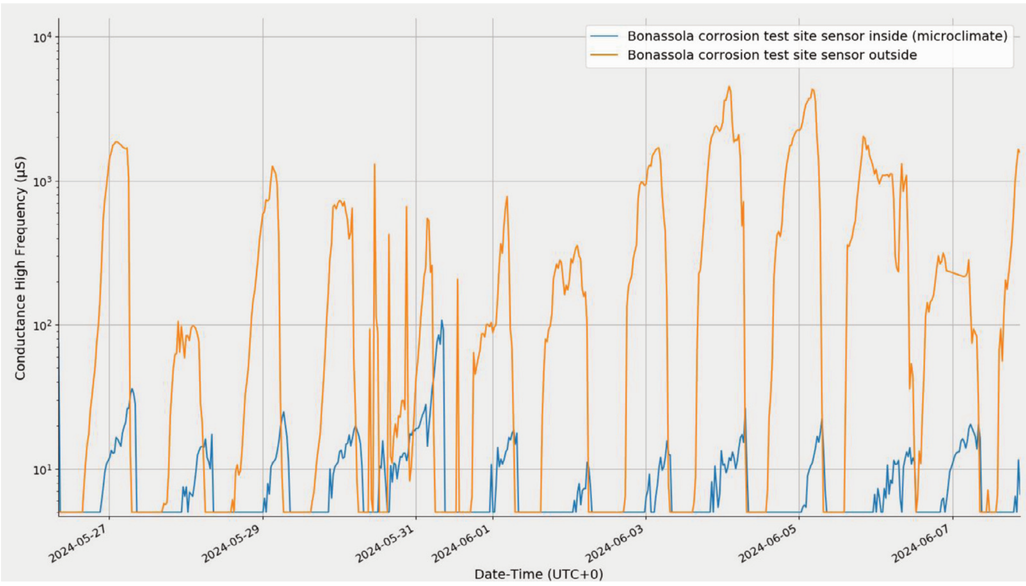

Figure 9. Conductance High Frequency

It is important to note that there may be various chemical substances inside the wings, such as lubricants, fuel (in the case of wings acting as fuel tanks), anti-corrosion agents and sealing materials. Although their presence and condition may influence the microclimate, they were excluded from this study in order to simplify the diagnostic models. Another aspect deliberately not included in the research is the measurement of the amount of air exchange, which may also affect moisture condensation and the accumulation of gases or chemical vapors. This decision was necessary to focus on the main microclimate conditions that would allow for determining climate corrosivity in accordance with the ISO 9223 standard.

This case study demonstrates the importance of environmental conditions in corrosion testing and the need for location-specific considerations when assessing material durability. The significant differences in corrosion rates seen between Padua and Bonassola underscore the role of sea water, particularly the high levels of chloride deposition recorded near the seaside. These results highlight the need for targeted protective measures and maintenance inspection based on data obtained during sensor measurements in environments with a) high chloride levels, b) common atmospheric pollutants, or c) both high chloride levels and atmospheric pollutants, the latter combination requiring intensive and targeted efforts to ensure the longevity of metallic structures and components.

Benefits of Using CHM Systems

Condition Health Monitoring (CHM) systems provide a comprehensive approach to ensuring the safety, efficiency, and reliability of aircraft operations. The integration of these systems into aviation practices offers numerous benefits that significantly enhance both the operational aspects and overall safety protocols. This section focuses on the primary advantages of CHM systems, including enhanced safety, cost efficiency, and data-driven decision-making.

Traditional maintenance methods often rely on scheduled inspections and reactive repairs, leading to higher costs, unexpected downtimes, and over-maintenance of systems that may not yet require attention. In contrast, CHM systems enable real-time monitoring and predictive analysis, allowing for targeted, condition-based interventions. This reduces unnecessary maintenance actions, minimizes unscheduled downtime, and extends component lifetimes by addressing issues before they escalate. Presenting comparative data clearly demonstrates the cost-effectiveness, efficiency, and reliability improvements that can be achieved with a CHM system, making a strong case for its implementation.

Enhanced Safety

CHM systems excel in the early detection of corrosion, fatigue, and other structural issues that can compromise the integrity of an aircraft (Li et al., 2021). By continuously monitoring the health of an aircraft's structure, these systems can identify potential problems before they escalate into serious failures. Timely intervention facilitated by CHM systems can not only prevents catastrophic incidents (Wright et al., 2019) but also extend the lifespan of aircraft components. With the detailed and real-time data provided by CHM systems, airport operations and flight safety protocols can be significantly enhanced. Continuous monitoring allows for proactive measures to be implemented, ensuring that all aircraft are in optimal condition before takeoff. This level of monitoring and maintenance reduces the likelihood of in-flight failures and enhances the overall safety of both passengers and crew.

Cost Efficiency

CHM systems also bring substantial cost-saving benefits by optimizing maintenance processes and reducing unexpected expenditures. Traditional maintenance schedules are often based on fixed intervals or flying hours, which may not accurately reflect the actual condition of the aircraft. CHM systems enable maintenance schedules to be optimized based on real-time data, ensuring that maintenance is performed precisely when needed. The Royal Netherlands Air Force (RNLAF) were the first to demonstrate the necessity for changes in the maintenance system for NH90 helicopters, supported by research conducted by the Netherlands Aerospace Center (NLR) (Hoen-Velterop, 2017). This approach not only ensures better aircraft performance but also prevents unnecessary maintenance actions, thus saving time and resources. By identifying potential issues early, CHM systems reduce the incidence of unexpected downtimes and costly repairs. Aircraft can be maintained in a more predictable manner, avoiding the high costs associated with emergency repairs and unplanned grounding of aircraft. This predictive maintenance approach ensures higher fleet availability and better allocation of maintenance resources.

Data-Driven Decision-Making

The implementation of CHM systems revolutionizes maintenance planning and risk management through the utilization of advanced data analytics. CHM systems generate vast amounts of data related to the health and performance of aircraft components. By leveraging data analytics, operators can gain deep insights into patterns and trends that were previously undetectable. This data-driven approach allows for more informed maintenance planning, risk assessment, and decision-making processes. Operators can prioritize maintenance activities based on the criticality of the issues, optimize resource allocation, and enhance overall operational efficiency.

In summary, the benefits of implementing CHM systems in aviation are manifold: from enhancing safety through early detection of potential issues, to improving cost efficiency by optimizing maintenance schedules, to enabling data-driven decision-making. As a transformative advancement in the field of aircraft maintenance and operations, CHM systems are set to play a crucial role in shaping a safer, more efficient, and more reliable future for air travel.

4. CHALLENGES AND LIMITATIONS FOR CORROSION HEALTH MONITORING (CHM) SYSTEMS

Integrating Corrosion Health Monitoring (CHM) systems with existing aircraft systems and infrastructure poses several technical challenges that must be carefully addressed to ensure seamless operation and effective corrosion management. This section explores these challenges in detail.

Challenges for Corrosion Health Monitoring Systems

One of the primary technical challenges is integrating CHM systems with the diverse and complex array of existing aircraft systems. Aircraft are equipped with numerous electronic, mechanical, and structural components, each designed to meet stringent performance and safety standards. CHM sensors must be compatible with these systems without causing interference or compromising their functionality. The integration process often requires interfacing with aircraft avionics and data communication networks to transmit corrosion data for real-time monitoring and analysis. Ensuring compatibility and adherence to avionics protocols and standards is critical for maintaining system integrity and reliability. Compatibility issues can arise due to differences in data formats, communication protocols, and bandwidth limitations.

Determining the optimal locations for corrosion sensors within the aircraft structure is crucial for effective monitoring. Sensors must be strategically placed to monitor critical areas prone to corrosion, such as joints, fasteners, and hidden compartments. The minimum number of sensors required to effectively cover essential areas of the helicopter has been identified as three (Ciężak & Rdzanek, 2020). However, access constraints, structural design limitations, and aerodynamic considerations can complicate sensor placement and installation. Maintaining sensor accuracy and reliability over time requires periodic calibration and maintenance. Integrating calibration routines into existing maintenance schedules and procedures is essential to ensure consistent sensor performance. Challenges may arise from the need for specialized equipment, trained personnel, and adherence to strict calibration protocols.

Corrosion monitoring sensors generate large volumes of data that must be efficiently managed, processed, and analyzed. Integrating corrosion data with existing maintenance management systems (MRO software) and aircraft health monitoring platforms requires robust data integration capabilities. Real-time data processing and analysis are necessary to derive actionable insights and facilitate timely maintenance decisions. Protecting corrosion data from unauthorized access, cyber threats, and ensuring compliance with aviation industry regulations (e.g., GDPR, FAA regulations) present significant challenges. Implementing stringent data security measures, encryption protocols, and access controls is essential to safeguard sensitive corrosion-related information.

Sensor installation, calibration, and testing may necessitate aircraft downtime, potentially disrupting flight schedules and operational efficiency. Minimizing these disruptions requires careful planning and coordination with airline operations. Operational protocols must ensure that CHM activities do not compromise flight safety or regulatory compliance. The initial investment and ongoing operational costs associated with CHM system integration can be substantial (Cusati et al., 2021). Balancing these costs against the potential benefits, such as extended aircraft lifespan and reduced maintenance expenses, is crucial for justifying the implementation of CHM technologies.

Limitations of Corrosion Health Monitoring Systems

Corrosion Health Monitoring (CHM) systems represent a specialized subset of Condition Health Monitoring (CHM) tailored to detecting and managing corrosion in aircraft structures. While these systems offer promising solutions to mitigate corrosion-related risks, they have a number of limitations that warrant consideration in their implementation and development.

Corrosion sensors need to operate reliably in the diverse and often harsh environments encountered by aircraft, including varying temperatures, humidity levels, and exposure to corrosive agents. Ensuring consistent and accurate detection across these conditions remains a significant technical challenge. Sensors must withstand environmental stresses while maintaining precise measurements to effectively monitor the progression of corrosion.

The ability of sensors to detect early-stage corrosion, particularly in hidden or hard-to-access areas of aircraft structures, poses a considerable challenge. Achieving sufficient sensitivity without false positives or negatives requires advanced sensor technologies and calibration methodologies. Furthermore, the range and coverage of sensors must be optimized to ensure comprehensive monitoring of critical areas prone to corrosion.

Interpreting corrosion data accurately to assess structural integrity and predict future corrosion behavior requires robust diagnostic algorithms and models. Variability in sensor readings, environmental factors, and complex corrosion mechanisms can complicate the reliability of corrosion assessments. Ensuring the consistency and reliability of diagnostic outputs is critical to preventing unnecessary maintenance interventions or overlooking potential risks.

Establishing industry-wide standards and regulatory frameworks for corrosion monitoring technologies is crucial for ensuring their reliability, interoperability, and compliance with aviation safety regulations. Achieving certification for new CHM technologies involves rigorous testing and validation processes to demonstrate their effectiveness and safety in diverse operational conditions.

While CHM systems do not directly quantify structural fatigue; the data acquired from these systems provide valuable insights that facilitate the assessment and prediction of fatigue-related deterioration in structural components. By continuously monitoring corrosion-related parameters, CHM systems contribute to the development of predictive models for structural fatigue, enabling more accurate prognostics and maintenance strategies aimed at enhancing the longevity and safety of the structure.

Based on the analysis presented in the preceding section, the characteristics of Condition-based Health Monitoring (CHM) systems can be delineated in terms of their respective advantages and disadvantages, as outlined below.

Based on the preceding analysis, the characteristics of CHM systems can be summarized in terms of their respective advantages and disadvantages, as summarized in the following graphic:

Advantages of CHM

- Early detection of corrosion
- Proactive maintenance scheduling
- Early detection of corrosion
- Reduced maintenance costs
- Increased aircraft lifespan
- Enhanced safety
- Help in determining the fatigue of the structure

Disadvantages of CHM

- High initial investment and ongoing costs
- Challenging integration with existing systems
- Complex data management and analysis
- Sensor reliability and accuracy issues
- Potential for false positives/negatives
- Disruptions to aircraft operations for installation
- Lack of industry standards

CONCLUSIONS

This exploration of Condition Health Monitoring (CHM) systems has underscored their significant role in monitoring atmospheric corrosion and ensuring the structural integrity of aircraft. CHM systems provide a multi-faceted approach to enhancing aviation safety, optimizing maintenance procedures, and enabling data-driven decision-making.

The experimental campaign carried out at two different sites (Padua and Bonassola) using Acuity LS sensors demonstrated the capability of real-time corrosion monitoring. These results illustrate how CHM systems, when applied to aircraft, can support diagnostic and prognostic activity which leads to improved prevention of structural failures and ensure the safety of both passengers and crew. Furthermore, CHM systems enable a shift from reactive to proactive maintenance strategies, significantly lowering maintenance costs and enhancing the overall efficiency of airport operations.

The transformative impact of CHM systems on aviation safety and maintenance is profound. By leveraging advanced data analytics, these systems provide valuable insights that inform better maintenance planning and risk assessment. This leads to more informed decision-making, optimized resource allocation, and ultimately, a more reliable and efficient aviation industry.

Moving forward, it is crucial to encourage the further adoption and research of CHM systems. The benefits discussed herein highlight the significant advancements in safety, efficiency, and cost-effectiveness that these systems bring to aviation. However, realizing the full potential of CHM systems will require ongoing research and development to refine their capabilities and expand their applications.

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