Wireless Sensor Applications in Extreme Aeronautical Environments

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***Abstract*—NASA aeronautical programs require rigorous ground and flight testing. Many of the testing environments can be extremely harsh. These environments include cryogenic temperatures and high temperatures (greater than 1500°C). Temperature, pressure, vibration, ionizing radiation, and chemical exposure may all be part of the harsh environment found in testing. This paper presents a survey of research opportunities for universities and industry to develop new wireless sensors that address anticipated structural health monitoring (SHM) and testing needs for aeronautical vehicles. Potential applications of passive wireless sensors for ground testing and high altitude aircraft operations are presented. Some of the challenges and issues of the technology are also presented.**

I. Introduction

The environment of aeronautical vehicles is typically harsh, with temperature extremes ranging from cryogenic to above 1500°C. Future hypersonic vehicles, for example, will require high temperature sensors mounted on the structure, as well as cryogenic sensors for monitoring fuel tanks. Sensors are typically located in internal structures with limited access, making the periodic changing of batteries prohibitively costly and time consuming. Furthermore, batteries do not work well at temperature extremes. In contrast to current wireless systems, passive wireless sensor systems do not require batteries. As a result, NASA is investigating the use of passive wireless technology for aeronautical applications. From ground tests to the operation of high altitude long duration aircraft, many applications could benefit from small, passive, wireless sensors that can operate in extremely harsh environments.

II. General Requirements

Aircraft sensing equipment must operate in harsh environments that include temperatures ranging from cryogenic to extremely high temperatures (greater than 1500°C) (Fig. 1). Often, the temperature extremes preclude the use of batteries for sensor applications. Besides temperature extremes, issues of vibration, humidity, and even ionizing radiation must be addressed.

In addition to the listed environmental challenges, the RF environment can also pose a challenge when wireless RF sensors are placed within enclosed metallic structures, such as the interior of wings.

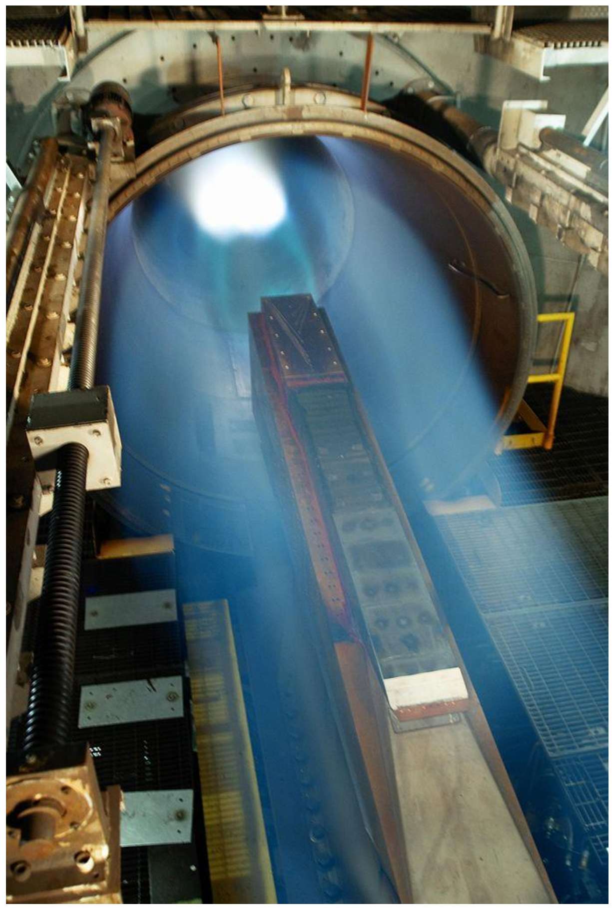

Figure 1. Photograph of the X-51 engine test in the 8 ft high temperature tunnel. The temperature can reach as high as 1927°C, during testing, and the pressure can be as high as 27.5 GPa.

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III. Ground Testing Applications

NASA aeronautical researchers perform tests on components and systems on the ground in conjunction with flight testing. These tests require the placement of a large numbers of sensors on a test article. To date, very few of the sensors are connected wirelessly. Frequently these tests are performed on models and test articles in NASA's wind tunnels. Many of the wind tunnels emulate extreme environments (Fig. 1). The National Transonic Facility wind tunnel uses nitrogen as the gas and operates at temperatures from -157°C to -101°C, and at pressures from 103kPa to 896kPa (Fig. 2). Another transonic tunnel, 0.3 Meter Cryogenic Tunnel, operates down to -195°C. The 8ft High Temperature Tunnel is a hypersonic tunnel that can achieve speeds of Mach 3, 4, 5, and 7. The temperatures range from 482°C to 1927°C, while the pressure ranges from 345kPa to 27,579kPa. The Arc Heated Scramjet Facility can reach temperatures of 2616°C while achieving speeds up to Mach 8. And the 20" Mach 6 Wind Tunnel can operate at pressures up to 13,780kPa. These tunnels use air, nitrogen, CF4, hydrogen combusted air with oxygen, combusted methane/liquid oxygen, and R-134a as the gaseous medium. Wind tunnel tests that routinely operate in extreme temperatures and pressures could benefit from wireless sensors.

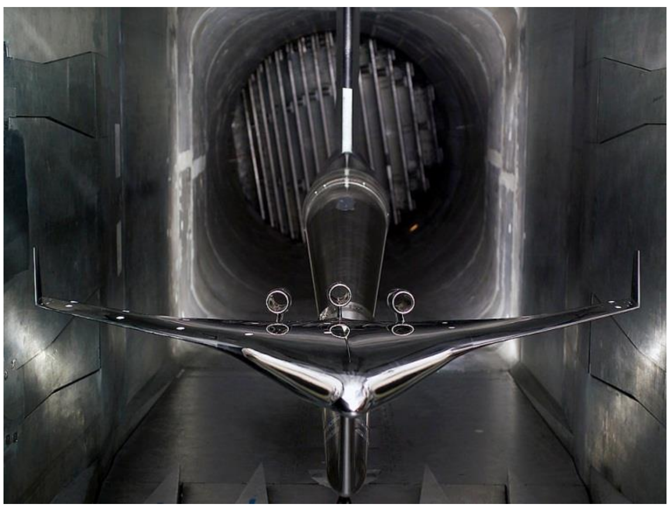

Figure 2. Photograph of the Blended Wing Body model in the test section fo the National Transonic Facilitiy wind tunnel, where temperatures can drop to -157 °C during testing.

Future aircraft will fly at higher altitudes and velocities and therefore will experience more extreme environments than those encountered by today's aircraft. To address these needs, new passive wireless sensor systems will have to be developed that can operate in corresponding environments.

In addition to aeronautics, other disciplines could benefit from passive wireless sensors. At Kennedy Space Center (KSC), wireless sensor networks have been developed for monitoring cryogenic lines and for centering and aligning the space shuttle external tank [1]. On-going work in the Transducers group at KSC integrates wireless communications with sensors and transducers.

At Langley Research Center, researchers have developed and tested a wireless fluid level system that worked while immersed in liquid nitrogen [2]. This device can work in a variety of harsh environments while detecting the level of numerous "fluids" such as liquid nitrogen, transmission fluid, sugar, and even ground corn. While the devices just mentioned do not employ passive wireless technology, they do demonstrate the current trend towards wireless sensing for ground testing.

IV. Aircraft Propulsion Applications

Active wireless sensor systems have been developed for monitoring the health of aircraft engines for commercial, military, and NASA aircraft [3-5], but all of these systems require batteries. NASA would prefer future sensors to be passive. The Army, Air Force, and NASA require high temperature propulsion sensors that can operate in environments of up to 1538°C around the engine and inside the gas path [6]. Both wiring and batteries become an issue in these applications; therefore, high temperature-resistant, passive wireless sensors, like the passive engine-bearing sensor [7], are needed.

Commercial airlines use turbofan engines for routine flights. A schematic of a common turbofan engine is given in Fig. 3 (Upper). This schematic comes from NASA's Glenn Research Center and is available online [8]. These engines run with a combustion station temperature of ~1116°C. High temperature wireless sensors that can operate for long periods are required to optimize the engine parameters for better fuel efficiency.

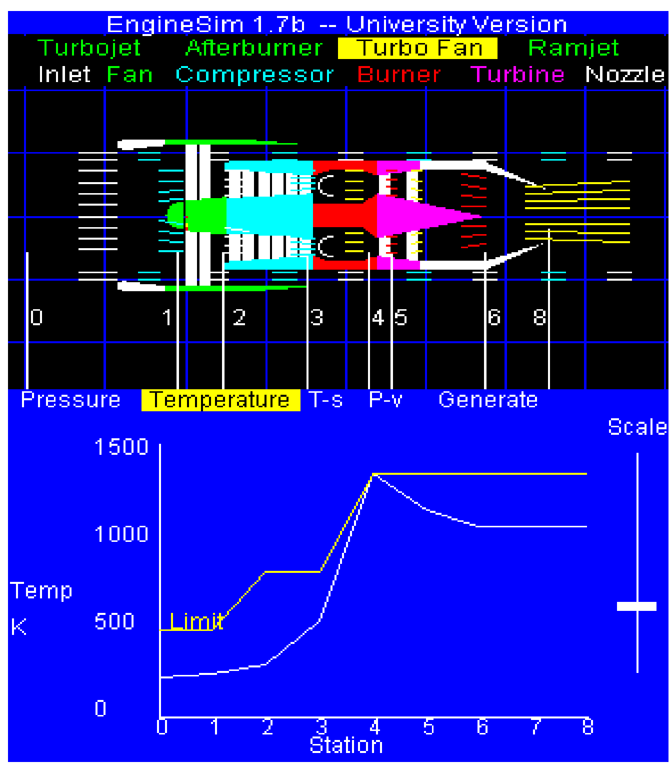

Figure 3. Turbofan temperature profile from EngineSim 1.7b. (Upper) schematic of a common Turbofan engine, showing the numbered temperature stations. (Lower) Temperature profile of the turbofan engine by station number.

High temperature materials are currently being researched for wireless sensor applications. Aluminum nitride is being investigated for high temperature (800°C) operation of temperature compensating sensors [9]. Gallium phosphate (GaPO) has been used as a substrate in the development of a temperature sensor [10]. The sensor is wireless, operates at 433 MHz, and withstands temperatures of 600°C for 192 hours. Sensors made with exotic materials such as Langasite, langatite and langatate have been characterized from -100°C to 900°C [11, 12]. These sensors require metal conductors. Thin films, however, do not behave the same as bulk materials. Therefore research is ongoing on thin film metal characterization for passive wireless sensors [13]. These new materials may enable wireless passive sensors to operate at temperatures higher than 1000°C.

In addition to sensory materials research, radio frequency (RF) transponders are being developed for passive wireless sensor use on turbine blades [14]. The devices have been characterized for operation up to 1100°C.

V. AIRCRAFT STRUCTURAL APPLICATIONS

NASA envisions the addition of structural health monitoring (SHM) sensors to existing aircraft; however, installing wiring for the sensors adds cost and weight to the aircraft. Also, wires are prone to damage such as nicks, breaks, degradation due to wear, excessive heating and arcing. Wiring problems have led to major aircraft accidents and delays of space vehicle launches [15]. In contrast, wireless systems present a desirable option for retrofitting sensors onto existing aircraft for structural health monitoring.

High speeds mean high temperatures from skin friction heating. Sensors for hypersonic (greater than Mach 5) aircraft may experience aerodynamic heating above 1000°C. Hypersonic aircraft based on NASA's HyperX X-43 design (Fig. 4) will fly at Mach 10 and therefore will require sensors that are able to withstand temperatures up to 1282°C [16]. Thus, hypersonic vehicles will need high temperature wireless sensors like those needed for propulsion applications.

Figure 4. Artist Conception of X-43A Hypersonic Experimental Vehicle.

The X-51 Waverider is another vehicle that required high temperature sensors. Ground tests of the X-51 engine were conducted in the 8 ft high temperature tunnel at NASA Langley Research Center (Fig. 1). The X-51A Waverider set a hypersonic flight record when it flew at Mach 5 for 200 seconds, beating the X-43 record of 12 seconds. On May 1st 2013, the X-51A broke another world record when it flew for 6 minutes. During this final flight the aircraft achieved Mach 5.1. The nose of the prototype X-51 was expected to reach 1480°C during flight due to skin friction heating (Fig. 5).

Figure 5. The X-51A Waverider Hypersonic Vehicle mounted underneath the wing of a B-52 aircraft.

Many of the aerospace research vehicles such as the Space Shuttle, HyperX, and Helios all contained hydrogen tanks. These vehicles could have benefited from NASA's high temperature chemical sensors which can detect hydrogen [17]. A Surface Acoustic Wave (SAW) hydrogen sensor based on a Langasite substrate and which utilized palladium as the sensing medium has been shown to operate at 250°C [18]. Since SAW technology can be used for hydrogen sensing, all that is needed is the addition of passive wireless capability. SAW devices can be used to detect other chemicals as well. The integrity of wires on board aeronautical vehicles could be determined by monitoring the effluents given off by the wire's insulation [19]. The effluents are generated during aging, over-currents, arcing, and high temperature conditions. SAW chemical sensors could be used to detect effluents and give an indication of wire integrity. SAW technology is very promising for passive wireless operation, but is not the only technology being investigated. Prime Photonics has developed a passive wireless temperature sensor that can operate at 1649°C based on RFID technology. Other technologies include resonant circuits for chemical sensing that can operate at 675°C [20].

At the other temperature extreme, cryogenic liquids are often found in aeronautical vehicles. Hydrogen, liquid oxygen (LOX), Kerosene, and other fuels are often kept at cryogenic temperatures [21]. The external structures of these vehicles may experience extremely low temperatures as well. For these applications, sensors that can operate at low temperatures are required. Cryogenic liquid operation of SAW devices has already been demonstrated [22].

VI. IONIZING RADIATION

High-altitude-sensing applications require sensors that exhibit tolerance to ionizing radiation. Tests conducted on SAW devices demonstrated an inherent radiation tolerance of up to 10 Mrad [23]. The constant size reduction of commercial electronics has led to less radiation tolerance and therefore to more soft errors in standard commercial electronics [24]. In 1993, static RAM memories were inadvertently found to have neutron induced bit errors or Single Event Upsets (SEU) when flown in aircraft at 10km [25]. Also, in 1993 a series of tests on static RAMs demonstrated that they have SEUs due to radiation at 8.8km and at 19.8km. The author uses the data from these flights to predict that Error Correcting Coding (ECC) will be necessary for avionic systems [26]. The author was correct in his prediction, not only are ECCs used in avionics now, they are also available for memory used in consumer computers. The need for radiation tolerant avionics has not diminished, the autopilot memory in a modern commercial airliner was found to have 1 upset every 200 hours [27].

The amount of radiation received varies by altitude, longitude, latitude and the natural solar cycles of the sun. For example, four dosage cases are given in Fig. 6. The radiation dosage versus altitude is plotted for the solar minimum (10/86) and the solar maximum (7/89) for 90 degrees west longitude, and for both 35° and 70° north latitude [28]. Radiation dosages rise with altitude, making spacecraft and high altitude aircraft more susceptible to radiation effects. Since SAW devices are inherently radiation hardened up to 10 MRads, radiation is not a concern.

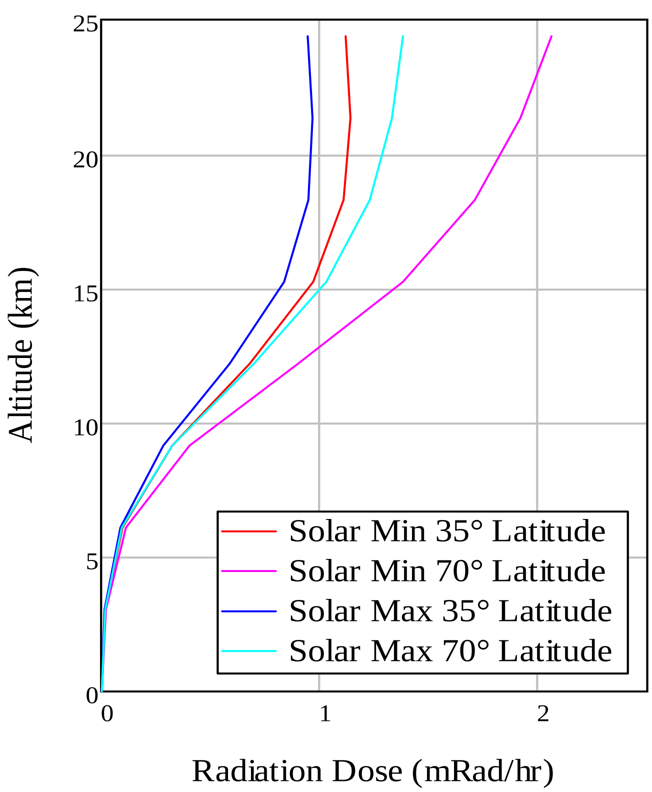

Figure 6. Radiation dosage versus altitude for the Solar minimum (10/86) and the Solar maximum (7/89) for 90 degrees west longitude from [28].

Micro-Electro-Mechanical Systems (MEMS) are also inherently radiation tolerant and may be used to develop sensors for extreme environments. Radiation-tolerant electronics are very expensive compared to commercial electronics. Therefore, inherently radiation tolerant technologies are better candidates for sensors in high altitude and space applications than devices made from conventional electronics.

VII. CHALLENGES AND ISSUES OF WIRELESS SENSING FOR AERONAUTICAL VEHICLES

One of the main challenges for wireless sensors is power [29]. Often batteries cannot be used due to inaccessible locations or exposure to large temperature extremes. Energy harvesting systems that rely on batteries for energy storage are eliminated for the same reasons. Thus, passive wireless sensing systems that do not include batteries should be developed.

Pressure variations from vacuum to high pressures should not be an issue for solid state devices such as MEMS, ICs or SAW devices. For most cases, corona discharge and arcing at low pressures should not pose a problem when the voltages are low. However, an issue may arise when devices are miniaturized and the spacing between charged components is reduced, allowing corona discharge and arcing to occur at lower voltages. Devices must be designed with Paschen's law in mind to avoid arcing and corona discharge when the pressure drops.

Vibration is an issue for all aircraft. Component failures from the high levels of shock and vibration during operation are not uncommon. Monitoring of dynamic loading during flight is important for SHM and fatigue life analysis [30]. Structural health monitoring using conventional sensors (such as strain gauges) has been difficult during flight due to the dynamics of aircraft loading and the random vibrations that are generated. Strain is often measured on research aircraft like those found at NASA's Dryden Research Center (Fig. 7).

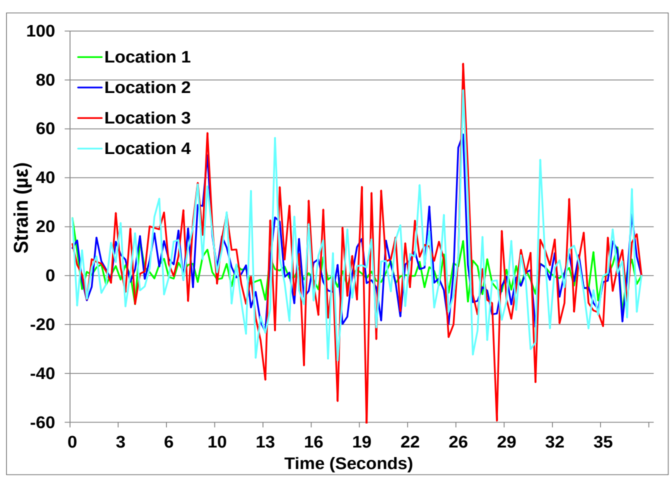

Figure 7. Strain sensor vibrational noise from four locations on the wing leading edge during takeoff.

Typical small aircraft can experience vibrational noise in the range of ±60 με peak-to-peak, while the aircraft experiences up to 1000 με loads during flight. These strain measurements are similar in magnitude to those taken on other research aircraft [31, 32]. Aircraft such as the P3 experience ±0.6g of vibrational noise during flight [33]. The data in Fig. 7 is from four strain sensors mounted on the wing leading edge during takeoff. The raw sensor data was filtered with a two point moving average. The moving average was subtracted from the original data leaving the vibrational noise only. The structural noise, which is mostly due to vibrations of the aircraft, is -60 με to +85 με. Although SAW sensors are able to filter out this noise from strain measurements, many other types of sensors such as conventional strain gauges cannot.

RF communication issues pose a significant challenge to implementing SAW systems successfully. Modulation methods must be chosen to allow large numbers of devices to communicate without interference. The bandwidth must be utilized carefully to enable high data rates, while adhering to FCC limitations. Encoding schemes must be developed to allow for efficient operation in noisy environments. The devices must be small which means higher frequencies and therefore smaller antenna sizes. Higher frequencies enable higher data rates; however, the range will begin to decrease when the frequency reaches 10 GHz. Higher frequency devices may also mean that the fabrication feature sizes must shrink, which may lead to manufacturing issues. Also, the frequency of operation must follow FCC guidelines. Electromagnetic interference poses a problem for all wireless systems. All wireless electronics must be designed to pass tests for both electromagnetic compatibility and interference [34].

Certification of wireless sensor networks for flight is another issue that must be addressed. This includes the allocation of frequencies for wireless sensing on aircraft, along with the determination of RF power levels, and FAA acceptance for aircraft use. There is a concern that wireless devices within the cabin may interfere with aircraft antennas located outside the cabin [35]. Personal electronic devices and cell phones have been tested to determine the effects that wireless devices may have on the aircraft avionics. Active RFID tags have been tested for compliance with RTCA/DO160 aircraft emission limits [36]. The tags exceeded the thresholds, but further investigations are needed before the effects from the interference can be understood. The interference from passive tags was not considered a concern, however, because the study focused on RFID tags contained in cargo pallets without an interrogator. Unfortunately, passive SAW sensors would require an active interrogator within the aircraft structure. Because SAW sensors will share the same frequency bands with RFID tags, and some of the same RF modulation techniques, they may exceed the emission thresholds as well. Before any wireless sensor system can be certified for use on aircraft, it will have to be tested.

VIII. CONCLUSIONS

From the ground up to the edge of space NASA has applications that require passive wireless sensor technologies in extreme aeronautical environments. NASA sensor systems (which include: acceleration, temperature, pressure, strain, shape, chemical, acoustic emission, ultrasonics, imaging, eddy current, thermography, and terahertz waves) could benefit from becoming passive and wireless. However, each of these applications has its own requirements and issues. Extreme environments offer many challenges that must be addressed; such as temperature, pressure, vibration, ionizing radiation, and certifications. Yet despite the issues and challenges, new technologies such as MEMS, SAW, and RFID are developing robust passive wireless sensor systems that may one day operate in extreme environments.

The need for passive wireless SAW sensors has been identified, but NASA does not possess all of the necessary resources to develop them. Thus, NASA encourages partnerships, including those with universities and industry, to aid in the development of the wireless passive sensors for the extreme environments found in aeronautical applications.

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