

Aerospace Applications for Surface Acoustic Wave Devices

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ABSTRACT

Surface acoustic wave (SAW) technology can be used to create a variety of different sensors, including strain, chemical, pressure, and temperature. These sensors can be configured to be passive and wireless, which could be useful in aerospace applications. NASA performs tests on the ground, in wind tunnels, and on aircraft during flight and in space. Many of these tests would benefit from the reduction or removal of wires during testing through the use of passive wireless sensors, such as SAW devices. This paper presents a SAW strain sensor for structural health monitoring and other aerospace applications.

Keywords: SAW, sensors, aerospace, surface acoustic wave.

1 BACKGROUND

Strain gages have been used for structural health monitoring applications, such as fatigue, monitoring load conditions, and detecting cracks in airframes [1]. Surface acoustic wave (SAW) strain sensors are being investigated by NASA's Vehicle Systems Safety Technologies (VSST) project for aviation safety applications because they can provide more strain information while adding negligible weight. Passive wireless operation has been demonstrated. SAW devices have also been demonstrated in environments including cryogenic and high temperatures, and are resistant to vibration, radiation, and pressure changes [2].

2 INTRODUCTION TO SAW SENSORS

A SAW device was fabricated on Langasite ($\text{La}_3\text{Ga}_5\text{SiO}_{14}$) (LGS) substrates. The sensor has four orthogonal frequency coded (OFC) reflector banks, which spread the device's response across multiple frequencies. The device has two identical tracks because of fabrication constraints, where each reflector bank is comprised of four gratings (Fig. 1). The gratings in each track reflect a different frequency and are arranged sequentially in ascending order as they are positioned further from the interdigitated transducer (IDT).

The OFC SAW strain sensor and a 350Ω foil strain gauge were bonded onto a stainless steel bar. The bar is 304 stainless steel, 45.75 cm long, 5 cm wide, and 0.635 cm thick. A type K thermocouple was placed in contact with the bar between the SAW sensor and the strain gauge. The bar was configured for cantilever loading.

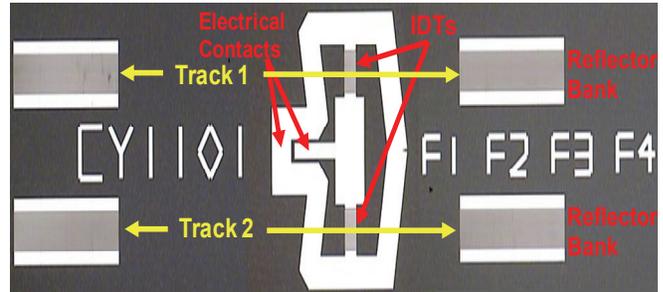


Figure 1. SAW OFC strain sensor. The tracks are shown in yellow and the IDTs, reflector banks, and electrical contacts are all identified in red.

Expansion of a SAW device from tensile strain or an increase in temperature will result in a decrease in the operating frequency and contraction from compressive strain or reduced temperature, will result in an increase in the operating frequency. These changes are due in part to the change in the wavelength and a change in the average propagation velocity of the surface acoustic wave. The velocity changes are due to alterations in stiffness parameters and material density [3].

To demonstrate the change in frequency caused by strain, the SAW was subjected to $7.6 \mu\epsilon$ by placing a 0.5 kg mass on the end of the cantilever bar. The S_{11} data was first taken with a network analyzer for 25 minutes without any strain. Next, the SAW device was strained for 25 minutes and then the strain was removed. The strain application and removal is observed as a 2874.4 Hz shift (red band) and in the contour lines below the plot in Figure 2.

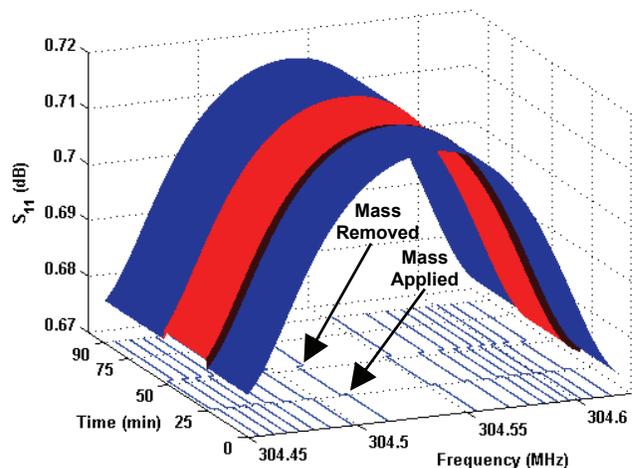


Figure 2. The time and frequency response of a SAW sensor with and without strain from a 0.5 kg mass.

To further characterize the strain response of the SAW sensor, multiple experiments were performed using the bar. The load was both increased from 0 kg to 1.0 kg in 0.1 kg steps and decreased from 1.0 kg to 0 kg in 0.1 kg steps at room temperature. The results are given in Fig. 3. The SAW strain measurements are in good agreement with the strain gauge while the temperature is held constant.

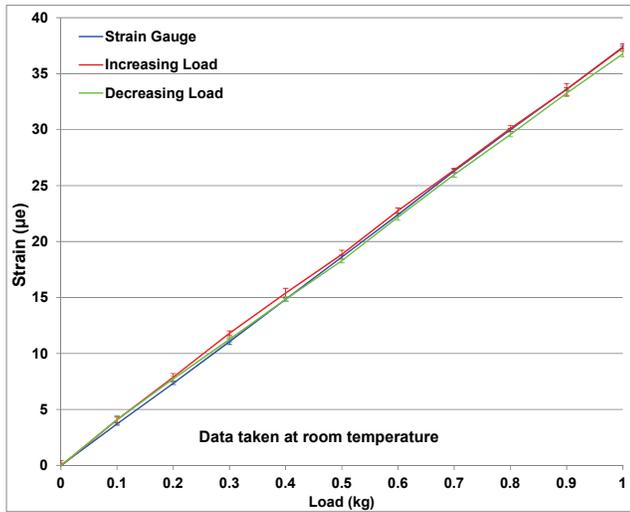


Figure 3. SAW strain sensor versus strain gauge. Error bars indicate one standard deviation.

The frequency shift from a SAW device can be used for many different sensors. A SAW device can act as a fastener failure sensor by monitoring the strain on a vibrating panel with multiple loading conditions [4]. The results with and without a bolt removed are given in Fig. 4.

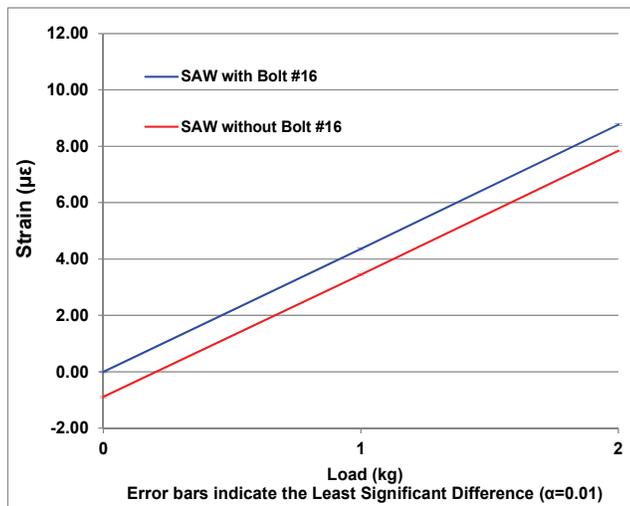


Figure 4. SAW sensor with loading (0kg, 1kg, and 2kg) and all the bolts tightened. A single bolt has been removed.

3 AEROSPACE APPLICATIONS

NASA's aerospace projects have many applications that could benefit from passive wireless sensor networks. For these applications, the sensors are typically located in internal structures with limited access, making the periodic changing of batteries prohibitively costly and time consuming. Batteries do not work well in temperature extremes. For example, NASA wind tunnel testing can be completed in very harsh environments. The temperature can vary from -195°C to 2616°C depending on the tunnel and the test being performed (Fig. 5).

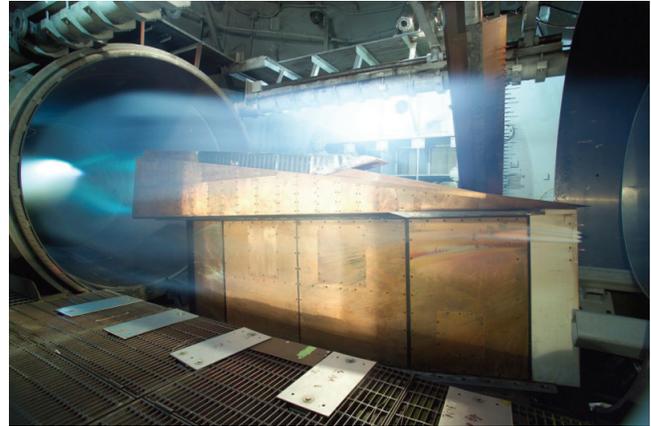


Figure 5. X-51 engine test in 8-foot high temperature tunnel. Testing can reach 1927°C .

Other aerospace applications with extremely harsh environments include propulsion systems testing with temperatures up to 1538°C , hypersonic vehicles, which experience skin friction heating up to 1282°C , and composite overwrapped pressure vessels (COPV), which operate in cryogenic temperatures down to -195°C . Despite challenging harsh environments, new technologies, such as SAW, microelectromechanical systems (MEMS), and radio frequency identification (RFID), may provide the sensor solutions that will address NASA's passive wireless sensor needs.

Another wireless application is the new launch escape system for manned rockets that NASA has developed. The Max Launch Abort System (MLAS) is comprised of four solid rocket motors attached underneath the manned capsule and inside of a protective composite fairing (Fig. 6). The MLAS was launched on July 8, 2009, from Wallops Island in Virginia. The main objective of the launch was to test the aerodynamics for a stable trajectory during an unpowered portion of the flight. To monitor the capsule during flight, 176 sensors were flown. These sensors included 87 pressure sensors, 52 strain gauges, 23 accelerometers, 13 thermistors, and one microphone. A passive wireless implementation could have reduced the wiring weight of this suite of sensors.



Figure 6. (a) NASA's Max Launch Abort System (MLAS) rocket and (b) MLAS during launch from Wallops Island Facility.

Although not passive, RFID sensor tags were used as part of the Smart and Intelligent Sensor Project (SiSP) for the MLAS [5]. Although the tags were not flown, they were part of a payload demonstration project that included a suite of new smart sensor and wireless technologies that were evaluated for flight readiness. The use of the tags for ground support equipment and comparisons with the flight payload measurements will aid in increasing the technology readiness level and the likelihood of future flight opportunities for RFID sensors. While this example was for ground-based testing, the Orion crew module could benefit from wireless sensors if they were flight qualified.

The European Space Agency (ESA) [6], the Indian Space Agency [7], the National Natural Science Foundation of China [8], and NASA [9] are all investigating wireless sensor systems for operation on the lunar surface. In addition, NASA is developing wireless sensor networks that can perform integrated system health monitoring of

spacecraft and health monitoring of astronauts [10]. Italian [11] and British [12] researchers are evaluating wireless sensor network operation for Mars exploration. The vision for extraplanetary exploration relies on wireless communications and wireless sensor networks. The systems being evaluated must connect landers and habitats to astronauts, sensorcraft, sensor probes, and robotic and manned rovers.

Future space habitats may be inflatable rather than rigid structures (Fig. 7). These structures require wireless sensors that can be embedded in the layers of material that comprise the shell. Shape, strain, humidity, chemical, pressure, and temperature sensors are required. The sensors cannot use batteries because they may be embedded, and they may experience extreme temperatures. The folding process eliminates the use of wires as well; therefore, passive wireless sensors are needed for this application. Students at the University of Maine have begun to investigate wireless sensors for detection of impacts on inflatable structures for space [13]. NASA is currently planning to attach an inflatable module to the International Space Station in 2015.

On Oct. 28, 2009, NASA launched the ARES 1-X rocket (Fig. 8), equipped with over 906 sensors on board as part of the Development Flight Instrumentation (DFI) system [14]. The sensors measured aerodynamic pressure and temperature at the nose of the rocket and contributed to measurements of vehicle acceleration and angle of attack. Six-hundred-and-eighty-nine of the 906 sensors were low data rate sensors; 112 temperature sensors, 98 strain gauges, 108 accelerometers, and 371 pressure sensors. Passive wireless sensors could reduce the cabling weight for these measurements. SpaceX and Orbital Sciences Corporation have both won NASA contracts to develop new commercial rockets that can carry supplies to the International Space Station (ISS). These new rockets will have the same requirements for low mass, low power, and passive wireless sensors.



Figure 7. Prototype inflatable lunar habitat.



Figure 8. ARES I-X rocket on Launch Pad 39B at NASA's Kennedy Space Center.

4 CONCLUSIONS

From the ground to space, NASA has applications that require passive wireless sensor technologies. NASA sensor systems often only require basic sensors (e.g., shape, strain, pressure, acceleration, and temperature), which 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, and ionizing radiation. However, despite the issues and challenges, new technologies, such as SAW, MEMS, and RFID, are leading to the development of robust passive wireless sensor systems that may one day operate in extreme environments found in aerospace applications.

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