Review Paper on Harsh Environmental Structural Health Monitoring

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***Abstract*-Proper maintenance and continuous monitoring are essential for ensuring the safety of the structure. Many types of sensors are developed to monitor the degradations of the structure, especially in a harsh environment, to identify the structural defect at a preliminary stage. To consider the material as a sensor in a harsh environment should have the ability to withstand high temperatures or at a high vibration, electromagnetic interference, high strain, etc. The data acquisition technique and an optimum number of the sensor to get accurate data are a significant factor for SHM, especially at the harsh environment. This review will describe the different types of harsh environments and the suitable and application of reliable, high-efficiency sensors based on the harsh environment.**

***Keywords*- Structural Health Monitoring (SHM), Harsh environment, Optical Fiber Sensor (OFS), Fiber Bragg Grating (FBG),Wireless sensor, Piezoelectric Materials (PZT), silicon carbide (SiC),Genetic Algorithm (GA).**

I.INTRODUCTION

Structural health monitoring (SHM) is necessary for continuous monitoring of the structure to detect cracks or damages. SHM is improving the safety of the structure and reducing human labor, maintenance cost, and downtime. By analyzing the data from the sensors on structures, we can determine the condition of the structure. We can detect the structural damages, allowing us to do the maintenance in advance, and thus we could avoid catastrophic failure of the structure.

Current damage-detection techniques are either visual or in-site experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiograph, Fiber Bragg Grating (FBG), eddy-current methods, or thermal field methods. Three main techniques are used for optical sensing: phase change (fluctuation of the index of refraction), frequency variation, and amplitude changes (known as absorption).

The main component for SHM is consists of data acquisition, power supply, data transmission, data storage and mining, data processing, and data interpretation, as shown in Fig.1. The primary objective of the sensor is to collect data of either acceleration, humidity, deflection, temperature, strain, pressure, or frequency shift of the structural component. The sensor collects one or multiple data from the structure and then transmits the data using the transmitter and receiver to the storage device. Using proper algorithms, we can analyze the data and identify the structural defect.

A Traditional Eddy Current (TEC) and Pulsed Eddy Current (PEC) fusion NDT technique was used to detecting a micro-crack in metals [1]. Many industrial and chemical processes like glass and ceramic production, high-temperature natural gas turbines, and syngas production occur at very high temperatures. For example, the maximum operating temperature for Type K thermocouples (chromel-alumel) is around 1350 ºC. At higher temperatures, exotic platinum- rhodium-based thermocouples such as Type S and Type R (max temperature of 1600 ºC) are used.

However, the sensing elements of these thermocouples are susceptible to chemical attack in corrosive gaseous environments. The fiber optic temperature sensor can measure temperatures from 300 ºC to 1800 ºC in oxidizing and reducing environments. Unlike thermocouples, fiber optic temperature sensors do not depend on the Seebeck effect and have better corrosion resistance.

In some harsh environments like the oil and gas industry, the Optical Fiber Sensor (OFS) is the reliable and best solution for the long-time application. Also, the small size (usually 100-500 microns) of the OFS allows operating on space constraint environments like thin composite structures [2]. Optical fiber is an excellent choice for sensing in a high-temperature environment. Besides optical fiber, ceramics materials, piezoelectric crystals, such as gallium orthophosphate ($GaPO_4$) and the langasite crystal (LGS), can also be used in a harsh environment for sensing applications.

Some harsh environments like the oil and gas industry where at the downhole environmental condition could reach 400°C and have corrosive environments. Most of the sensors used today's reliability decrease by around 225°C. The reliable solution for this high-temperature case is diamond or SiC, or fiber optics. Comparing with SiC, Dimond has stable electrochemistry and excellent corrosion resistance [4-6].

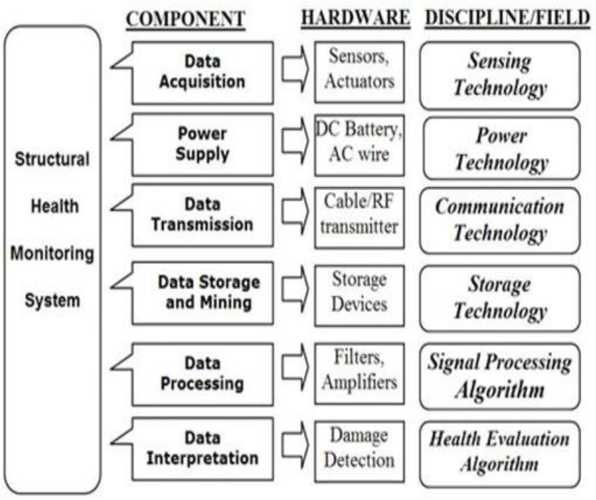


Fig 1. Major Components in structural health monitoring. [3]

The physical properties that make SiC and diamond ideal candidates for harsh environments include a wide bandgap, slow oxidation rates, high hardness, high resistance to chemical etching in acids and bases. Table I summarizes the properties of silicon carbide & diamond.

Table 1. Selected properties SiC, and diamond for harsh environment applications [7-9].

Property	SiC3C	Diamond
Bandgap[eV]	2.3	5.5
Max. operatingtemperature[°C]	900	1100
Heatconductivity[$\frac{W}{cmK}$]	4.9	20
Elastic modulus [GPa]	350	1000
Hardness [$\frac{kg}{mm^2}$]	3300	10000

II. HARSH ENVIRONMENT

The harsh environment means where the surrounding temperature of a structure is very high due to chemical substance or radiation, strong vibration, geothermal drilling or high pressure, etc. The sensor may get damaged in that harsh environmental condition.

III. TECHNOLOGIES FOR HARSH ENVIRONMENT

Many techniques have been used to detect the damage to the structure. For early damage detection where the stiffness change is minimum, a wave propagation-based method is a good option. Since damage decrees the stiffness and therefore changes the natural frequency, by comparing the fundamental frequency of the defect structure with the fundamental baseline frequency, damage can be determined.

IV. WIRELESS SENSORS

Wireless Sensor Network (WSN) can be used in a harsh environment like an offshore platform, tunnel. WSN is cost-effective and also consumes less space compared with the wired sensor [10]. Generally, WSN consists of a micro processing unit, an accelerometer, and a transmitter. In fig.2, WSN can measure the dynamic response generated from vibration.

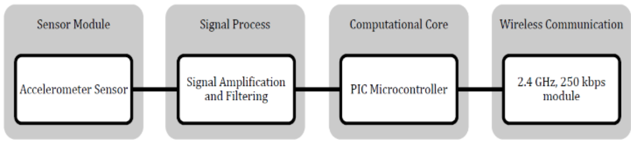


Fig. 2: Wireless Sensor Module. [11]

Radio-Frequency Identification (RFID) sensor is an essential technology in WSN and can play a vital role in a harsh environment. The three main classifications of RFID sensors are active, semi-active and passive types. The battery is an essential part of both active and semi-active wireless sensors. However, a passive RFID sensor does not need a battery, reducing the size and reducing costs. The essential parts for passive RFIS sensors are an RF energy harvester, sensing module, logic circuit, memory, and modulator [12-14].

A frequency selective surface (FSS) is a chipless passive wireless strain and damage detection sensor. Based on the resonance frequency shift, a crack can be identified [15].

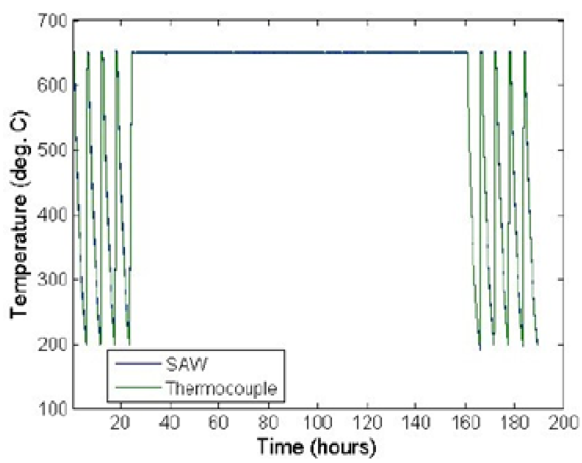
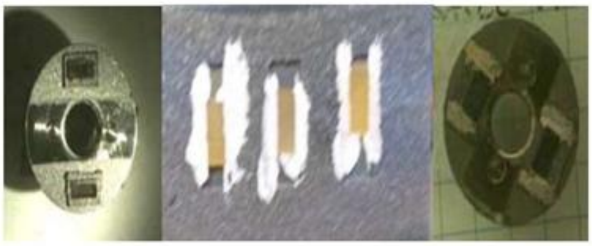


Fig 3. Temperature measured by a K-type thermocouple and the wireless LGS SAW sensor. [21]

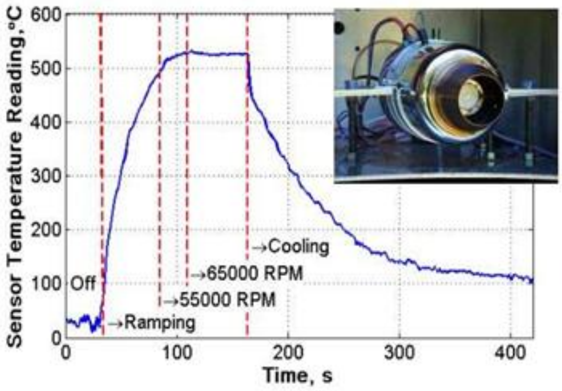
Ceramic tape is considered an excellent choice for the manufacturing of pressure sensors for high temperatures.

A passive wireless resonant telemetry is widely used in sensor technology to detect pressure [16-18].

Pressure can be converted into a frequency shift output which can be identified remotely [19]. In wireless sensing, acoustic wave technology can be used in a harsh environment. In figure 3, at 650 ^{0} C, the LGS SAW sensor is very accurate for a long time compared to k type thermocouple.



(a) Wireless sensor packaging turbine engine.



(b) Exhaust temperature of the turbine

Fig 4. Wireless passive LGS SAW sensor a) packaging b) for measuring the temperature of the exhaust section of the integrally bladed rotor (IBR) of a JetCat turbine engine. [20]

To measure the temperature of the exhaust section of the JetCat turbine engines, LGS SAW sensors were assembled to Inconel disks (Fig 4a). Fig 4b shows the JetCat turbine's temperature data, which were measured wirelessly.

V. SEMICONDUCTOR MATERIAL AT HIGH TEMPERATURE

Due to the high melting temperature, silicon carbide (SiC) is used in harsh environmental sensing applications. SiC contains chemical stability along with attractive mechanical and electrical stability [21-25]. Silicon carbide (SiC) has a wide bandgap (2.0 eV ≲Eg≲ 7.0 eV) and high electron saturation drift velocity. Silicon carbide (SiC) is the first substitute for Si for the harsh structural environment. SiC contains higher stiffness and fracture strength [26] plus a better capacity to resist wear, oxidation, and corrosion [27] than silicon.

This unique feature of SiC in a harsh environment made it a suitable sensor for monitoring the structural health of the aerospace system. Dopes SiC piezoresistive sensor can withstand 800 ^{0} C.

3C-SiC deposited on Silicon-on- insulator (SOI) wafers used as a pressure sensor and can operate up to 350 ^{0} C [28-30]. The 6 H- SiC pressure sensors can operate up to 600 ^{0} C [31]. In figure 5, SiC MESFET has been used to make a SiC pressure sensor telemetry circuit that can withstand 400 C with a telemetry distance of 1 m [32-33].

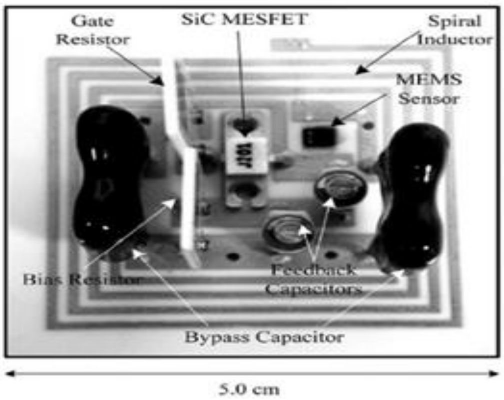


Fig 5. Colpitts oscillator circuit using a SiC MESFET. [32]

A silicon carbide reinforced with a carbon fiber (C/C-SiC) sensor is used in a spaceship because this sensor can operate at a wide range of temperatures up to 2000 ^{0} C [33].

VI. OPTICAL FIBER SENSORS

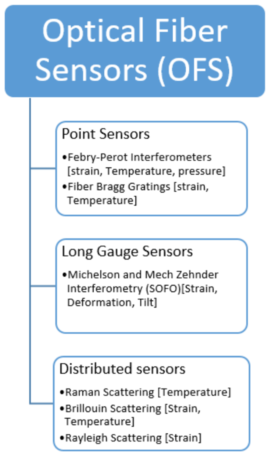


Fig 6. Classification of optical fiber sensor.

The advantage of the optical fiber sensor (OFS) is that it does not interact with electromagnetic (EM) fields, radio frequency (RF), and microwaves (MW). This unique feature of OFS made it a suitable sensor for electrical machineries, such as electric locomotives, power lines, or transformers; also, OFS can be used in a harsh

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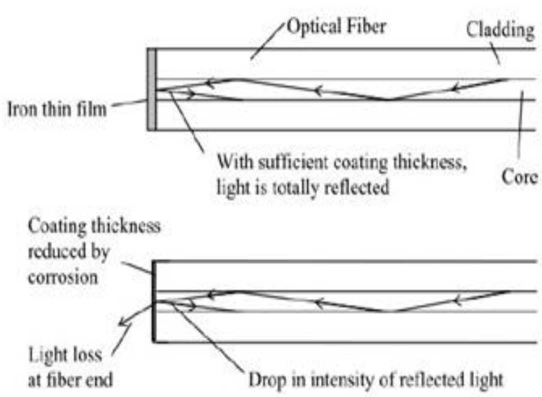
environment like gas pipelines, chemical, and nuclear power plants.
Another advantage of the OFS is that; it can measure more than twenty- kilometer distance without any active electrical component, which makes it an ideal candidate in the telecommunication industry, large pipeline, and long bridge. Both active and passive method of Structural health monitoring (SHM) is used to measure the strain and stress condition of a structure to quantify and detect the position of damage. However, traditional damage assessment techniques are less reliable and unsafe than various civil structures allowed by SHM.

The advent of high-temperature-resistant fiber Bragg gratings (FBGs) able to operate in extreme environments for sensing purposes has revitalized research on FBG transducers. Temperature resistant Fiber Bragg gratings (FBGs) can be used in a harsh environment like nuclear power plant [34-37]. Femtosecond FBGs using an infrared laser (IR-fs-FBGs) and Regenerated FBGs (R- FBGs) are using for sensing applications in a nuclear industry where temperature (around 580 ^{0} C) is very high, and the sensor needs to operate on that temperature for several years [38-40].

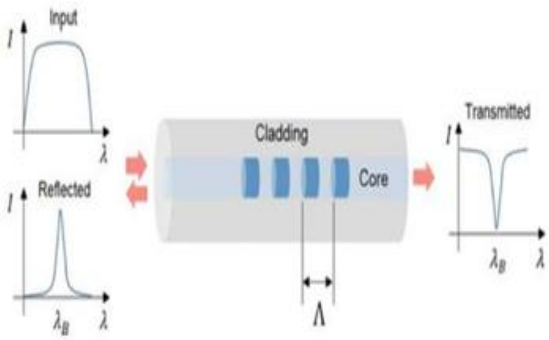
1. Optical sensor for structural health monitoring of oil and natural gas infrastructure

In figure 6(a), ferrous or ferrous carbon alloy film is attached at one end of the optical fiber. When corrosion occurs at the Fe or Fe-C film, the transmission of the light will increase.

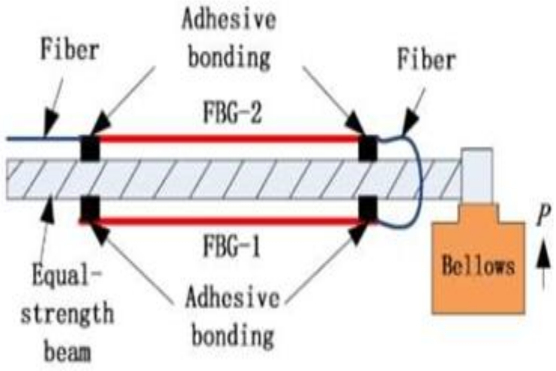
Figure 6(b) describes the fundamental principle of fiber Bragg grating (FBG). Only Bragg wavelength light will be reflected and transmitted the rest of the wavelength of the incident light. FBG can be used as a pressure sensor and can be used to identify the crack in the pipeline based on the negative pressure wave (NPW) method. To monitor the hoop strain or circumferential strain of the pipeline, the FBG strain sensor is used. It can measure the pipeline's inner pressure and identify the corrosion or crack of pipe (Fig 6c and d) [41-44].



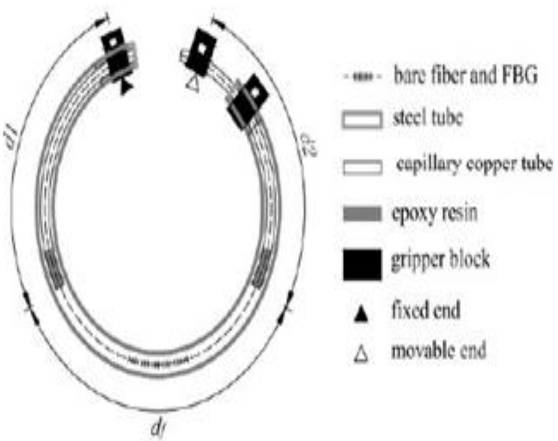
(a) Point OFS for sensing corrosion based onreflected light from the Fe thin film coating. [45]



(b) Schematic of FBG [46]



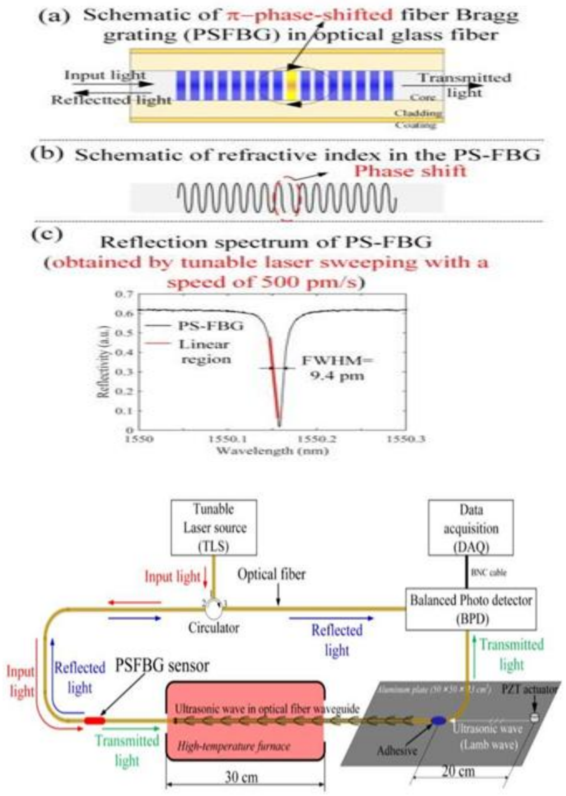
(c) Schematic of FBG-based pressure sensor. [47]



(d) Schematic of FBG-based hoop strain sensor. [48]
Fig 7. Optical sensor for structural health monitoring.

VII. ULTRASONIC WAVEGUIDE IN HIGH-TEMPERATURE ENVIRONMENT

A phase shifted FBG (PSFBG) is developed for highly sensitive Acoustic emission (AE) sensing. In figure 8a-c), πphase-shifted fiber Bragg grating (PSFBG) causes the change in the reflective index and produces a sharp notch in the reflection spectrum [49]. The adhesive method for remote measurement (ADRM) configuration is used for high-temperature AE detection, where the waveguide is stable even at 1000 ^{0} C.



(d) Ultrasonic detection in high temperature.
Fig 8. PS-FBG waveguide in high temperature. [50]

VIII. PIEZOELECTRIC SHM APPLICATIONS FOR HARSH ENVIRONMENT

1. High-Temperature Nuclear Application

As an alternative energy source, nuclear energy is getting more widely, but most nuclear power plants (NPP) are over structural aging [51]. Under the concern of the public, the damage detection of

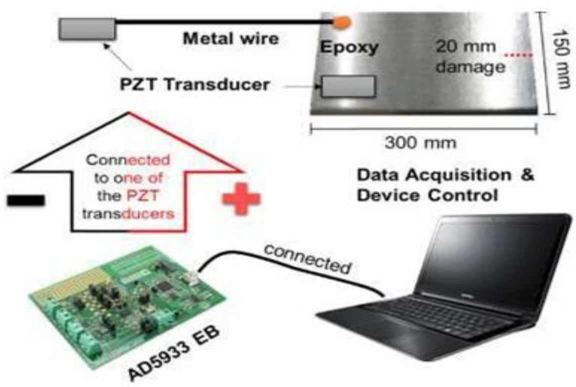


Fig 9. Metal wire EMI technique set-up. [52].

NPPs structures draw more attention to the government and researchers. Numerous non- destructive testing (NDT) methods have been well developed for the high-temperature environment of NPPs. However, the sensing capability is strongly affected at high temperatures through depoling [52].

To perform the high-temperature SHM using conventional piezoelectric materials, one possible solution would be decreasing the temperature effect on the piezoelectric materials themselves. Na and Lee proposed an SHM technique based on electromechanical impedance (EMI) for NPP high-temperature pipelines using metal wire connections [53]. Based on the electromechanical coupling effect, the change in mechanical impedance of piezoelectric materials can reflect the defects of the structure.

A metal wire connecting the room temperature surrounded PZT Piezoelectric wafer active sensor (PWAS), a high dielectric and piezoelectric properties material, to the high-temperature NPP pipeline (about 200 °C to 300 °C), is used to transmit ultrasonic signals as shown in the figure below. As expected, their experiment shows a slight temperature increase of PZT (less than 20 °C) as the pipeline temperature increase to 300°C, which means the high-temperature environment can be converted to normal piezoelectric NDT. A disadvantage of the metal wire EMI method is that it requires a metal wire as a connection. Since most structures in NPPs are enclosed and drill a hole to place the metal wire is not applicable for these NPP structures.

Lin and his colleagues directly bond PZT-PWAS to the high-temperature metal wall of the NPPs, and they found that the PZT material is not applicable for high-temperature environments because the temperature environment will result in the potential bonding failure, which will finally reduce the overall performance of PZT-PWAS [54]. The high-temperature piezoelectric material BiScO3- xPbTiO3, a solid perovskite solution with similar piezoelectric properties as PZT, is proved to have about 100 °C higher transition temperature than common PZT [55-56], which can be used in NPP SHM.

Besides, if the BiScO3-xPbTiO3 is modified by Pb(Mn1/3 Nb2/3)O3, the mechanical quality factor can reach 1000 °C with a similar material cost [55].

With the limitation of mechanical twinning, quartz-based high-temperature piezoelectric transducers experience phase transition at around 573 °C [57], but it is good enough for some NPP applications not exceeding 300 °C [58]. For other suitable piezoelectric materials of EMI methods, the ferroelectric material like Bismuth-titanate compositions has majority Curie temperatures higher than 500 °C. In contrast, the low piezoelectricity below 500 °C makes it not suitable material for NPP SHM.

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Furthermore, Lithium tetraborate (Li2B407), a 4mm group crystal, was proved to have zero effect of resonant frequency at elevated temperature [59-60], and the piezoelectric properties are stable up to about 500 °C [57]. Moreover, the modified piezoelectric materials, such as manganese modified Pb (Sc1/2 Nb1/2) O3–PbTiO3 [59], show excellent performance on high-temperature SHM relatively stable piezoelectric properties at elevated temperature.

In the NPPs, other than high environmental temperature, the degradation of the polarizability of the piezoelectric transducers under radiation is also significant [58-59]. Haider and other researchers investigated the performance of PZT and GaPO4 PWASs after Gamma irradiation, of which the curie temperatures are 350 °C and 950 °C [60-61]. They found that the charges generated by nuclear radiation will be accumulated near the electrode, thereby decreasing the piezoelectric materials' polarizability.

After irradiation, the EMI of PZT-PWAS changed slightly, whereas the EMI of GaPO4-PWAS stays the same, which means GaPO4-PWAS has a higher temperature and radiation stability piezoelectricity properties [60-62]. However, the wiring and bonding adhesives for GaPO4-PWAS should be carefully selected since the high temperature will significantly affect the bonding connections [62].

IX. AEROSPACE APPLICATIONS

1. PWAS-based Methods:
The harsh environment for piezoelectric SHM in aerospace is extreme temperature and space radiation [63-64]. Therefore, the behavior of piezoelectric in this harsh aerospace environment is crucial to consider for the actual application, and experiments were conducted to evaluate the performance of EMI transducers [54, 58, and 65].

For piezoelectric material by EMI method in high-temperature aerospace applications, the piezoelectric single crystal YCa4O(BO3)3 was reported to survive up to 1500 °C without any phase change [66], which can be used in ultra-high temperature aerospace SHM. Furthermore, another high-temperature piezoelectric crystal family, Langasite (LGS), can be used in remote-controlled SAW devices with the temperature up to 1000 °C [57, 67-70].

For extreme cold (cryogenic) temperature SHM, several experiments using liquid N2 were performed to verify the feasibility of the PWAS-based EMI method [59, 58, and 65]. In [59], the result shows that APC-850 PWAS can be operated under cryogenic conditions and space radiation. Like high-temperature PWAS, an essential thing for PWAS-based material at cryogenic temperature is selecting the bonding material between the structural surface and PWAS itself, which will significantly affect signal transmission quality.

2.Laser Ultrasonic Methods:
Comparing to other noncontact SHM methods, the traditional piezoelectric SHM has the disadvantage of low spatial resolution, complicate transducer installation, high maintenance cost, and limited environmental temperature capabilities [71]. A combination method using laser Doppler vibrometer (LDV) and PZT mentioned by Sohn can be used to detect the damage of the composite plate of the aircraft surface, as shown in the figure below [71]. The composite place is excited by eight concyclicPZT

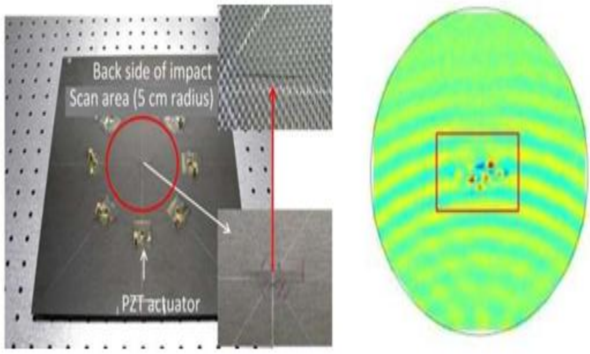


Fig 10. PZT excited LDV scanning system (left) and scanned image (right). [71]

actuatorsand the LDV receive the generated Lamb wave by scanning the 5 cm radius area from the center. The scanned image can easily show the location and the size of the defect remotely. Similarly, the wireless guide wave EMI system excites the structure by PZT excitation node transmitting via laser. It uses the PZT sensing node to receive the signal wirelessly, as shown in the figure below [72]. Compared to the setup in [71], the guided wave setup is much more straightforward and more comfortable implementing in real aerospace SHM because it requires less PZT and sensing area.

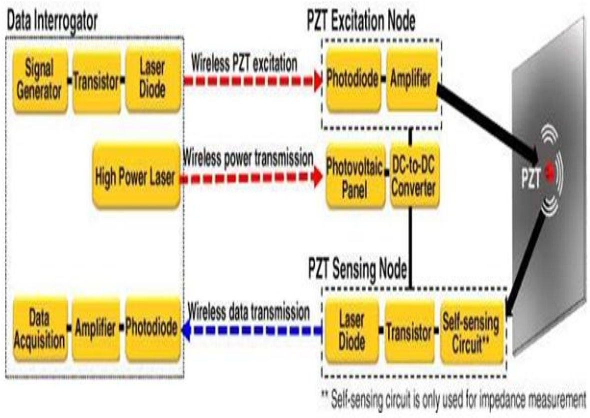


Fig 11. Optics-based wireless guided wave EMI system. [72]

3. Other Methods:

For methods other than the piezoelectric method used to monitor aircraft surface defects, Roach described a real-time SHM system based on Comparative Vacuum Monitoring (CVM) Sensors of the hazardous environmental condition like the surface SHM aircraft [73]. Combining in-situ CVM sensors and remote controller enables the remote real-time SHM of the defect location and depth from the surface. As expected, the experimental results show that the CVM method can detect a 1mm length flaw under a 95% confidence interval effectively.

X. ALGORITHMS

1. Genetic Algorithm:

The Genetic Algorithm (GA) is used to find out an optimized total number of sensors and their suitable positions on the structure in a harsh environment. Generally, either local information theory-based or information-based sensor placements optimization is applied to control and detect the damage of the structure [74-84]. The researcher used several modified GA for sensor optimization [85-90].

In a harsh environment, sometimes need to use multiple sensor types like temperature sensor, vibration sensor, and strain sensor. GA is used to determine the optimized number of each kind of sensor.

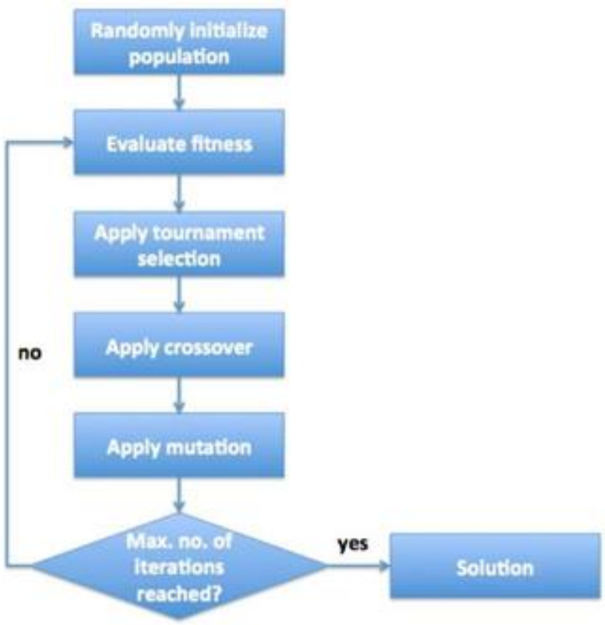
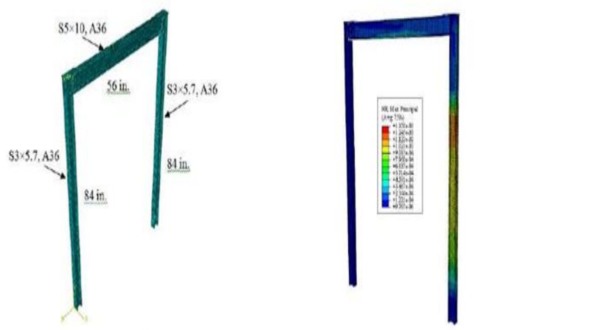


Fig 12. Flowchart of Genetic Algorithm. [91]

In the Genetic Algorithm (GA) method, the first step is to initialize the population randomly. The second step is to evaluate the fitness, then applying tournament selection. Finally, to get a better solution, the crossover and mutation operation is applied. When we get the maximum number of iterations, the algorithm becomes ended, and we will get an optimum quantity of sensors.

In Figure 13, a single bay steel frame is used in a harsh environment where high temperature and enormous strain was applied. From the middle of the left column, the temperature distribution changed from room temperature to 700 C. Middle of the top beam strain was applied.

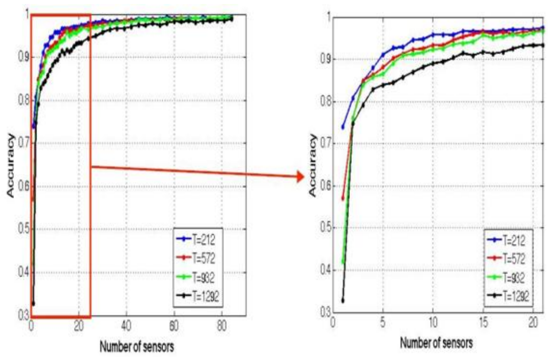


(a) The setup of FEM model (b) Strain distribution at temperature environment 212°F (100°C)

(c) Laboratory experimental setup.

Fig 13. FEM model (a) and the simulated strain(b) and Laboratory experimental setup (c) [91]distribution at fire temperature of 212 °F (100 °C)

Find the optimum number of sensors for accuracy at different temperatures is shown in figure 14.



(a) 3~84 strain sensors with an interval of 3 sensors (b) 1~21 strain sensors with an interval of one sensor

Fig 14. Measurement accuracy versus several strain sensors for various temperatures. [91]

XI. CONCLUSION

This paper outlines the various suitable sensors in a harsh environment. This monitoring system (SHM) has several types, but the priority is mainly on implementing sensor units. The reason is the ability of sensor units to identify the location and magnitude of a defect within the structure, which creates a distinction between the process and non-destructive testing. Most modern-day implementations of structural health monitoring make the use of spread-out sensor units on a structure.

In a harsh environment selecting the appropriate sensor, the selection is also crucial. SiC, doped SiC material, ceramics materials, piezoelectric crystals, langasite crystal (LGS), and OFS are excellent for sensing applications at very high temperatures. In a harsh environment, to assess the structural condition precisely, we need to employ multiple types of sensors in some cases. Using GA, we can identify the suitable number of the sensor to get an accurate result, which will save the project cost. SHM is very important for human safety, especially essential structures like nuclear power plants, aerospace, turbine exhaust systems, gas, chemical pipelines, etc.

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