

## Smart Materials for Aerospace Sensing: Development & Prospects

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**Abstract.** The aviation industry stands as a testament to human ingenuity, continually pushing the boundaries of innovation to achieve greater efficiency, safety, and performance. When it comes to improving aircraft design, functionality, and operational capabilities, the incorporation of smart materials becomes increasingly important as technological breakthroughs transform aviation. Smart materials (e.g., piezoelectric materials, shape-memory materials, and giant magnetostrictive materials) have unique physical properties and excellent integration properties, and they perform well as sensors or actuators in the aviation industry, providing a solid material foundation for various intelligent applications in the aviation industry. This abstract offers an overview of the state of smart materials in aerospace sensing through a thorough analysis of current developments and case examples. It highlights the significance of these discoveries for aircraft performance, structural health monitoring, and environmental sensing. It looks at significant advancements in manufacturing materials, sensing techniques, and integration tactics. Since piezoelectric materials can transform mechanical energy into electrical impulses and vice versa, they are essential to aeronautical sensing. These materials find utility in sensing systems for energy harvesting, vibration, impact, and structural health monitoring in aerospace applications. They have emerged as the most researched materials for practical applications among the numerous smart materials. Structural health monitoring (SHM) is a critical use case for piezoelectric materials in aerospace sensing. Guided-wave Structural Health Monitoring systems with piezoelectric sensors are investigated for localisation of barely visible impact damage in CFRP plates under vibration and different thermal conditions. The incorporation of piezoelectric materials in aerospace sensing systems revolutionizes monitoring, detects anomalies early, and bolsters structural integrity. This advancement promises safer, more reliable, and more efficient aircraft and spacecraft operations. As research progresses, the potential for piezoelectric sensing technology to further elevate aerospace engineering is undeniable.

**Keywords:** Piezoelectric Materials, Aeronautical Sensing, Structural health monitoring

## 1. Introduction

The dynamic field of aviation has recently seen a revolution in aircraft design and manufacture due to the introduction of composite materials, especially carbon fiber-reinforced polymers (CFRPs). They have challenged the dominance of conventional metallic alloys in current aerospace engineering due to their lightweight design and exceptional strength-to-weight ratio. The introduction of smart materials signifies a significant change in the methods used in the building of aeroplanes. Smart materials are a family of materials that are listed in advanced materials. These groups of materials have self-accommodation with the environment and they are classified according to their responses, such as physical (pressure, temperature, humidity, light, electric field, magnetic field), chemical (pH, CO<sub>2</sub>, etc.), or biological stimuli [1]. Of them, CFRPs have received a lot of praise for their remarkable qualities. Their lightweight design improves operational performance and fuel efficiency while simultaneously decreasing structural bulk. CFRPs provide an extended service life and operational reliability through their fundamental resistance to corrosion, fatigue, and environmental degradation, which sets them apart from metallic alloys. Because of these qualities, they are now widely used in the design of modern aircraft, completely changing the way the industry approaches structural integrity and performance efficiency. Critical component performance and composition have been transformed by the integration of CFRPs into many aspects of aircraft construction. Interestingly, CFRPs are widely used in wing structures, where their application allows for the achievement of ideal aerodynamic profiles at the lowest possible total weight. In addition, CFRPs are essential for improving the structural integrity of fuselages, providing increased safety in crashes, and reducing the possibility of catastrophic collapse. CFRPs have high specific strength up to 4500 Mpa stiffness with damping feature, notionally zero thermal expansion coefficient [2]. The use of composite materials in empennage parts improves control and stability, improving the aircraft's handling characteristics in a variety of flight conditions. They improve fuel economy, increase passenger comfort, and lower the total weight of aircraft interiors. Monitoring the health and performance of CFRPs is a significant problem, despite the many benefits they offer. In contrast to metallic materials, which frequently show obvious indications of deterioration, CFRPs are prone to interior loss that is hard to identify without specific tools and methods. This creates a significant challenge to maintaining the flying ability of composite structures since safety and operational integrity may be risked by undetected defects or degradation. Furthermore, the absence of all-encompassing monitoring capabilities restricts lifecycle management and predictive maintenance, which may result in higher maintenance expenses and downtime for aircraft fleets with a significant amount of composite materials. With their exceptional efficiency, performance, and sustainability, CFRPs will result in a paradigm shift in aerospace engineering with the rise of modern aircraft construction. However, the inherent disadvantages of composite materials highlight the necessity of ongoing study and advancement in this area, particularly health monitoring and maintenance. Unlocking material's full potential and securing their broad use in the aerospace sector will depend on addressing these issues. We can only fully realise the revolutionary potential of composite materials by overcoming these obstacles, opening the door to a future in which aircraft will be stronger, lighter, smarter, and more robust.

The development of smart composites in the field of aerospace engineering marks an evolutionary change in which traditional composite materials combine with cutting-edge sensor technology to completely change aircraft design and operation. By integrating sensors into composite constructions to enable real-time health monitoring and performance optimisation, smart composites are an innovative marriage of technology and design. This innovative idea has the potential to completely change the way that aeroplanes are built, maintained, and operated by providing previously unavailable information about environmental factors, load distribution, and structural integrity.

Smart composites enable operators and maintenance staff to identify and resolve possible problems early on, improving efficiency, safety, and durability. These characteristics include strain, temperature, pressure, and vibration. In addition, by improving maintenance schedules and increasing the service life of aircraft structures, smart composites real-time data support forecasting methods. Smart composites, which provide information on aerodynamic loads, ice accumulation, and interior conditions, have the potential to enhance operational performance and safety in flight in addition to structural monitoring. But to fully utilise smart composites, several obstacles must be overcome. These include creating reliable sensor technologies, handling cybersecurity and data processing issues, and handling certification and regulatory issues. Despite these difficulties, smart composites have definitely the potential to transform aircraft design and operation, changing aviation's future by making planes safer, smarter, and more effective than in the past. The objective of this research paper is to explore the development and potential applications of multifunctional composite materials incorporating piezoelectric elements in aerospace engineering. Specifically, the paper aims to investigate the synergistic benefits of integrating structural reinforcement and sensing capabilities within composite materials for enhanced aircraft performance, safety, and efficiency.

## **2. Piezoelectric Materials: Powering Smart Composites**

Piezoelectric materials are a unique class of materials with many uses in aviation and other industries due to their outstanding characteristics. Their capacity to transfer mechanical stress into electrical signals and vice versa—a phenomenon known as the piezoelectric effect—lies at the core of their uniqueness. These days piezoelectric materials are being utilized for a variety of analytical applications, i.e., sorption detectors, detectors for gas and liquid chromatography, detectors for water, analysis of trace metals, detection of viruses, COVID-19 detection, detectors for air pollutants, electrogravimetry, different compound detection, and solution measurements [3]. Because of its outstanding properties, piezoelectric materials are the best options for sensor applications in smart composites, providing unmatched capabilities for performance optimisation, safety improvement, and structural health monitoring. In this talk, we examine the basic concepts of piezoelectricity, the various uses of piezoelectric materials in aerospace, and how important they are in enhancing the efficiency of smart composites. In some materials, a phenomenon known as the piezoelectric effect occurs whereby mechanical stress causes an electrical charge or voltage to be generated, and vice versa, the application of an electrical field causes a material to deform or strain. The uneven arrangement of atoms or molecules in the lattice structure of crystals of piezoelectric materials is the cause of this phenomenon. Positive and negative charges separate along particular structural axes as a result of the material's lattice structure breaking under mechanical stress. This produces an electric field, which in turn causes a measured voltage to be created across the material. On the other hand, mechanical deformation or strain results from a change in the lattice structure caused by the application of an electric field to the material.

Lead zirconate titanate (PZT), a ceramic substance known for its high piezoelectric coefficient and durability, is one of the most often used piezoelectric materials. PZTs are most widely used as sensors and actuators for active vibration control of aero structures, structural health monitoring (SHM), precision opening and closing of valves, sonar transducer etc. In recent years, the direct piezoelectric effect has been used for vibration energy harvesting [4]. Because of its strong piezoelectric features, PZT can be used in a variety of sensing applications. Other widely used piezoelectric materials are polyvinylidene fluoride (PVDF), quartz, and lithium niobate. Each of these materials has special qualities and benefits that are appropriate for a particular application.

Because piezoelectric materials can transform mechanical energy into electrical signals, they are very useful for sensing and actuation in the aerospace sector. This property has led to several uses for piezoelectric materials. Piezoelectric sensors integrated into composite materials used in aircraft constructions are capable of detecting temperature, vibration, and strain variations. This allows for real-time input on the structural integrity and health of key components. Piezoelectric sensors, for example, that are included in wing surfaces can track aerodynamic highlights and identify the beginning of flutter or structural fatigue, allowing for a prompt intervention to prevent catastrophic failure. Similar to this, piezoelectric sensors installed in fuselages can identify impact damage or delamination, which makes it easier to identify and fix structural problems early on. Moreover, adaptive morphing is made possible by the active manipulation of the stiffness or form of an aircraft wing using piezoelectric actuators.

Piezoelectric materials are crucial for real-time structural health monitoring and performance improvement in the context of smart composites. Engineers can continually monitor characteristics like strain, vibration, and temperature through the use of piezoelectric sensors within composite constructions. This allows for important insights into the operational performance and structural integrity of aircraft components. For example, piezoelectric sensors included in composite wing structures can identify variations in aerodynamic loads while in flight, allowing flight parameters to be changed to maximise fuel efficiency and minimise pressure on the structure. Similarly, during ground operations, piezoelectric sensors placed in fuselage panels may detect impacts or tensions, enabling timely inspections and maintenance to avoid structural failure or damage. Piezoelectric sensor's durability in high-temperature, high-vibration, and mechanically challenging aerospace conditions is one of their main advantages in smart composites. Piezoelectric-type sensors for harsh conditions offer many advantages compared with other types of sensors with different mechanisms [5]. Because of their inherent strength and capacity to withstand harsh environments, piezoelectric materials are ideally suited for aerospace applications where dependability and durability are crucial. Furthermore, the great sensitivity and quick reaction times of piezoelectric sensors enable real-time monitoring and abnormality or structural change detection. Piezoelectric materials can be utilised in smart composites for energy harvesting as well as structural health monitoring. Piezoelectric sensors absorb mechanical vibrations or deformations during flight and transform them into electrical energy that can be stored or used to power aboard devices. The idea of energy harvesting has the potential to decrease dependency on traditional power sources, increase overall energy efficiency, and improve the sustainability and efficiency of aircraft operations. Piezoelectric energy harvesters (PEHs) are piezoelectric architectures that are smartly designed to maximum capture ambient vibration/motion energy into piezoelectric material and convert the mechanical energy into electrical energy [6]. Piezoelectric materials have many benefits, but they also have several drawbacks and restrictions. For instance, factors like mechanical fatigue, humidity, and temperature swings may have an impact on the functionality of piezoelectric sensors. In addition, to guarantee the best possible performance and dependability, piezoelectric sensor incorporation into composite constructions calls for strict design considerations. Additionally, to glean useful information from the massive amount of data produced by piezoelectric sensors, advanced signal processing algorithms and data analysis methods must be developed. In order to sum up, piezoelectric materials are an essential component in modern aerospace technology because of their exceptional sensing, actuation, and energy-harvesting capabilities. They are the perfect choice for sensor applications in smart composites because of their exceptional capacity to transform mechanical stress into electrical signals and vice versa. This allows for real-time monitoring of structural health, performance optimisation, and safety enhancement. Piezoelectric materials are expected to become more important in determining the future of aircraft design and operation as the aerospace industry pushes the boundaries of innovation, opening the door to safer, more effective, and more environmentally friendly aerospace systems.

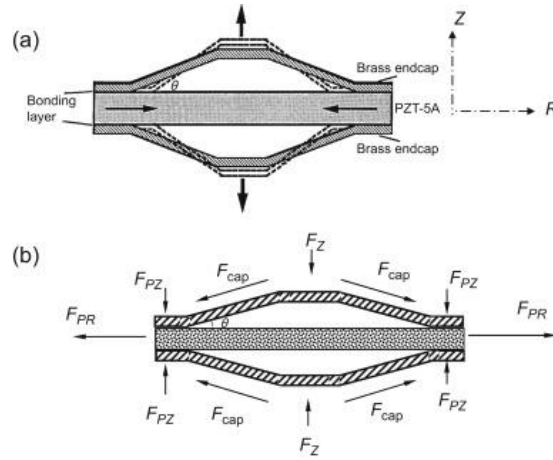


Fig. 1. Energy harvesting using piezoelectric materials in aerospace structures

### 3. Benefits of Aerospace Sensing

Aerospace applications require a range of chemical sensing technologies to monitor conditions in both space vehicle environments and in aircraft or spacecraft operations [7]. Aerospace sensing can benefit significantly from piezoelectric materials, which are essential for several applications such as collecting energy, vibration and impact detection, and structural health monitoring (SHM). These materials are excellent choices for sensing applications in flight conditions because of their special abilities to transform mechanical energy into electrical signals and vice versa. Structural Health Monitoring (SHM) is indeed just the combination of traditional experimental/theoretical structural mechanics, electronics, material science, and information and communications technologies [8]. One of the most promising uses of piezoelectric materials in aircraft is energy harvesting. Vibrations and vibrations are common in the dynamic environment of an aeroplane, arising from several sources including engine activity, instability, and airframe bending. By carefully incorporating piezoelectric materials into the aircraft construction, these vibrations and distortions can be captured and used to produce electrical energy via the piezoelectric effect. The vibrations that the aircraft's structure experiences when it travels through the air force the piezoelectric materials to distort, producing an electric charge. To power onboard sensors or low-power systems, this charge can subsequently be collected and stored using energy storage devices like batteries or capacitors. The capacity to harvest energy can help aircraft makers reduce their need for conventional power sources. Piezoelectric materials are excellent at vibration and impact detection in addition to energy harvesting, which offers important information on the strength and health of aircraft components. Several things might cause vibrations and impacts on the structure of an aeroplane, including actions, turbulence, or ground handling operations. These impacts and vibrations can be identified and measured by piezoelectric sensors incorporated into the composite structure, which can provide real-time information on the dynamic behaviour of important parts. Piezoelectric sensors enable the early identification of possible damage or anomalies, enabling swift repair and maintenance, by monitoring alterations in vibration patterns or identifying sudden impacts. This capacity is especially important when evaluating the structural integrity of composite materials because they can be prone to wear or impact damage. In addition, piezoelectric materials are vital for structural health monitoring (SHM) systems because they provide unmatched capacity for identifying and tracking damage to the aircraft structure.

Composite materials are frequently used in the construction of modern aeroplanes, although they are capable of supporting a variety of damages, such as delamination, cracking, and degradation of the material. When piezoelectric sensors are incorporated into composite constructions, they can identify alterations in the mechanical characteristics or sound emissions linked to the beginning and spread of damage. Through consistent monitoring of these characteristics, SHM systems can detect possible anomalies or weaknesses early on, allowing for proactive maintenance and repair procedures. In addition to improving reliability and security, this proactive approach to maintenance lowers downtime and maintenance expenses related to unexpected repairs or inspections. A key component of aircraft sensing technology, piezoelectric materials provide several advantages in energy harvesting, vibration and impact detection, and structural health monitoring. They are crucial for sensing applications in flight conditions because of their special capacity to transform mechanical energy into electrical signals. This helps aircraft manufacturers save money on maintenance, increase system autonomy, and improve safety and reliability. Piezoelectric materials have the potential to significantly impact aircraft design and operation in the future, opening the door to safer, more effective, and environmentally friendly aerospace technologies as the aerospace industry grows.

## **Case Study**

A famous case study showing the success of piezoelectric sensors in structural health monitoring (SHM) systems utilises guided-wave technology to detect barely obvious impact damage in a carbon fibre-reinforced polymer (CFRP) plate. In this work, guided waves travelling through the CFRP plate were generated and detected by researchers using piezoelectric sensors. Impact damage that is barely evident, such as delamination of the matrix cracking, within the composite structure has been identified and localised by researchers through the analysis of changes in wave propagation characteristics, such as retardation and dispersion. This case study demonstrates how piezoelectric sensors may identify tiny structural changes that may be signs of corrosion. This allows for early maintenance and action to stop further corrosion and guarantee that aircraft components remain safe to fly [9].

## **4. Advancements in Smart Composite Technology**

### **4.1 Manufacturing Techniques**

Innovation in aerospace engineering is being driven by continuous improvements in smart composite production techniques, which allow for the seamless incorporation of piezoelectric sensors into composite structures while maintaining structural integrity. The needs of modern aircraft design, which calls for lightweight, multipurpose materials with real-time monitoring and adaptive reactions, can only be met by these advancements. By integrating piezoelectric sensors into composite structures, structural changes and damage may be detected, which improves performance, safety, and dependability in aircraft applications. In-situ sensor embedding techniques are an important advance in smart composite production processes that enable the direct incorporation of piezoelectric sensors into the composite matrix during creation. Conventional methods frequently include post-processing operations that can endanger the mechanical qualities and dependability of composite structures, such as securing or embedding sensors onto their surface. On the other hand, the in-situ embedding methods allow the smooth integration of piezoelectric materials into the composite matrix, ensuring close contact and peak performance while lowering the possibility of damage or delamination. A vital part of this process is the exact control that additive manufacturing (AM) technologies, such as 3D printing, provide over the orientation and placement of sensors inside the composite structure.

Additionally, new piezoelectric nanocomposites with enhanced properties have been created as a result of developments in the synthesis and processing of nanomaterials. Researchers can add piezoelectric functionality to the composite material itself during production by propagating piezoelectric nanoparticles or microfibers throughout the polymer matrix, therefore avoiding the necessity for separate sensor integration methods. By guaranteeing a uniform distribution of piezoelectric elements throughout the structure, this method not only simplifies the production process but also improves the overall performance and reliability of smart composites. These functionalized nanocomposites present previously unknown chances to improve sensing performance and allow multifunctionality in aeronautical applications. Additionally, the exact integration of piezoelectric sensors onto composite surfaces is made possible by innovative deposition and patterning processes including inkjet and aerosol jet printing. With the use of these additive manufacturing techniques, conformal sensor arrays with great spatial resolution may be constructed, enabling dispersed sensing and real-time structural health monitoring over wide regions. Furthermore, advanced surface modification methods such as functionalization by chemicals and plasma treatment improve piezoelectric sensors' compatibility and adhering to composite substrates, guaranteeing strong and long-lasting sensor integration. All things considered, the ongoing advancement of smart composite manufacturing processes has great potential to transform aerospace applications. Piezoelectric sensors can be effortlessly integrated into composite structures without compromising their strength. This allows engineers to create materials that are lightweight, versatile, and capable of self-monitoring, adaptive responses, and improved performance. Because they make it possible to construct safer, more effective aircraft that satisfy the changing needs of modern aviation, these developments could have an important effect on the aerospace sector.

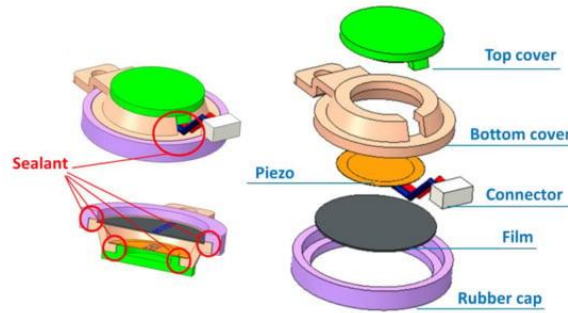


Fig.2. The cavity structure of the pulse wave sensor [10].

### 4.3 Sensing Techniques

The creation of smart composite applications has reached new heights thanks to recent advances in sensor technology, which provide solutions that make use of smaller sensors, greater sensitivity, and better data transfer capabilities. One major area of study has been the miniaturisation of sensors, which allows them to be seamlessly integrated into composite constructions without losing structural integrity. In this context, the development of micro-electro-mechanical systems (MEMS) technology has been instrumental in enabling the production of sensors with micron- or nanometer-scale dimensions. During the production process, these small sensors can be integrated into composite materials to offer dispersed sensing capabilities over vast structural regions. Additionally, improvements in sensitivity have been made possible by advances in sensor design, making it possible to detect minute variations in environmental factors and structure function. To enable quick action and maintenance, enhanced sensitivity is especially crucial for identifying early indicators of decline or degradation in composite structures.



Also, real-time monitoring and remote diagnostics of smart composite systems are now possible thanks to developments in data transmission technologies like wireless communication and Internet of Things (IoT) connectivity. These features improve overall safety and dependability in aircraft applications, support proactive maintenance initiatives, and maximise operating performance. Smart composites have the potential to completely transform aircraft design and operation as sensor technology advances, opening the door to safer, more effective, and environmentally friendly aerospace systems.

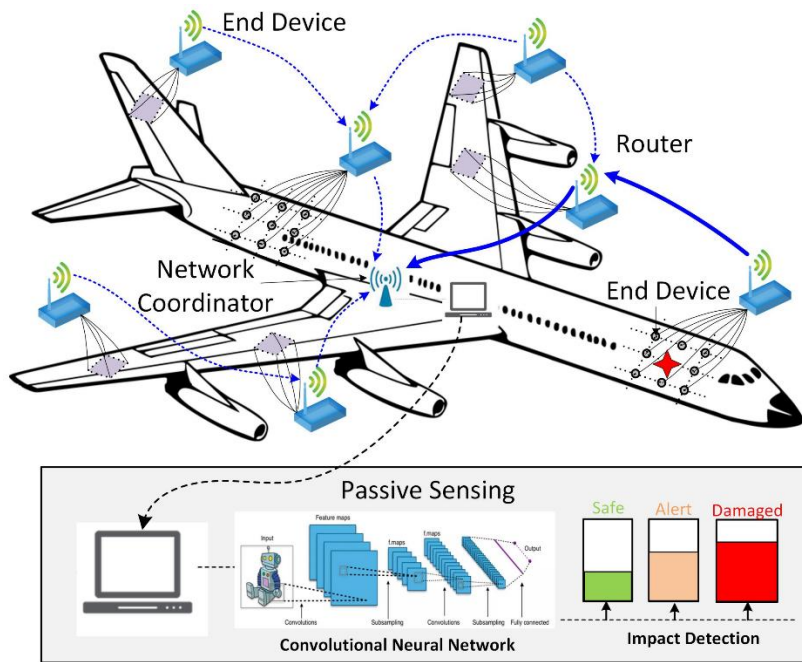


Fig. 1. Passive sensing with embedded wireless sensor networks and CNN [10].

#### 4.4 Integration Strategies

One of the most important aspects of modern engineering is the integration of sensors into composite structures, which enable real-time structural performance and health monitoring across a range of sectors. Co-curing and embedding are two popular methods for inserting sensors into composite structures during production. These techniques have unique benefits and considerations that influence how well they work in various contexts. Before the curing process, co-curing entails adding sensors to the composite material's surface or within its structure. By using this technique, a strong mechanical bond is formed between the sensors and the structure as the resin hardens. The preparation of the composite layup, which involves layering reinforcing fibres—like carbon or glass—into the appropriate structure, is usually the first step in the process. Sensors are arranged either within or on top of the composite layers, and they might be anything from gauges of strain to fibre optic sensors. After layup, the entire assembly goes through to a curing process that forms polymers in the resin matrix and basically merges the sensors into the structure. Co-curing has several important advantages. Firstly, doing away with the requirement for further processing to integrate sensors, improves the production process. This is a cost-effective, time-saving, and efficient method of production that makes it suitable for large-scale manufacturing. Additionally, because the sensors and the composite framework are cured together as a single unit, co-curing ensures a strong mechanical link between



them. This bond lowers the possibility of delamination or separation during operation while increasing the sensors' reliability and life expectancy. Moreover, co-curing enables compatibility with intricate geometries and designs using many materials since it enables the exact placement of sensors within the composite. Sensors are inserted into the composite substance either before to or during the laminating process in order to be embedded during the production process. By using this technique, it is made sure that the sensors are completely covered by the resin matrix, protecting them from the elements and mechanical harm. Usually, the procedure begins with the creation of the composite matrix, in which the resin is combined with other additives or strengthening fibres. The sensors are then carefully placed—either by hand or with the aid of automated insertion techniques—within the composite material. After the sensors are installed, the composite layup is put together, and the structure is then allowed to cure in order to set up the resin matrix. There are many strong advantages of incorporating sensors during the production process. First of all, it ensures a seamless integration of sensors into the composite structure, improving the durability and reliability of those sensors. Since the sensors are protected from wear and outside impacts, they are less likely to suffer damage or degrade over time when inserted in the composite material. In addition, distributed sensing capabilities made possible by this technique enable real-time structural performance and health monitoring over wide areas. In addition, because sensors can be precisely positioned within the composite matrix, inserting them during manufacturing facilitates the creation of complex geometries and multi-material designs. Sensitivity integration can be done by co-curing or embedding sensors during manufacture; the decision is based on various aspects including manufacturing limitations, sensor capabilities, and application requirements. Applications such as high-volume production environments or those with strict performance requirements, where strong mechanical connecting and streamlined manufacturing processes are critical, are ideal for co-curing. However, in applications like aerospace structures, automobile parts, or civil infrastructure where seamless integration, increased durability, and distributed sensing capabilities are critical, embedding sensors during manufacture is appropriate. In order to fully employ smart composite materials in a variety of industries, it is important that you understand the numerous approaches for incorporating sensors into composite constructions. Embedding and co-curing are two popular techniques with different benefits and things to consider. In today's quickly changing technology scene, engineers can create novel solutions for adaptive control, real-time monitoring, and improved performance by utilising these strategies efficiently.

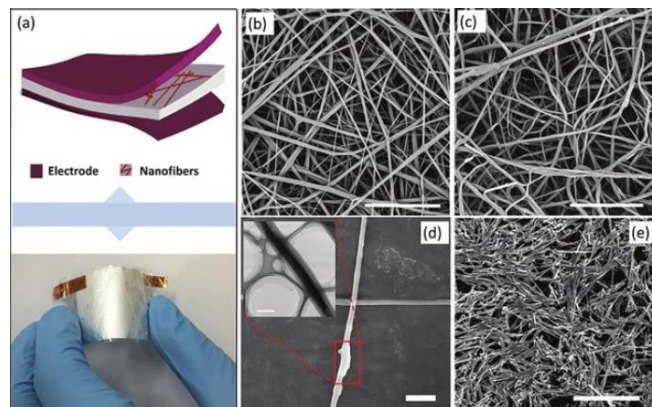


Fig2 a) Schematic and photograph of the piezoelectric pressure sensor. (b) SEM images of the electrospun pure PVDF fibrous membrane and (c) PVDF/BaTiO<sub>3</sub> NW nanocomposited fibrous membrane. (d) High-magnification SEM image of an individual fiber containing BaTiO<sub>3</sub> NWs (inset is the corresponding TEM image). (e) SEM image of the BaTiO<sub>3</sub> NWs. Scale bar is 20  $\mu\text{m}$  (b-c) and (e), 5  $\mu\text{m}$  ((d), SEM), and 500 nm (inset of (d), TEM) [11].

## **5. Impact on Aircraft Performance and Safety**

### **5.1 Performance Enhancement**

Using real-time data from embedded sensors in aircraft structures offers a crucial chance to improve performance, safety, and operational effectiveness. The creation of active control systems and improved load distribution are two important areas where such data might be used. Manufacturers and operators of aircraft can achieve maximised load distribution, which improves aerodynamic efficiency and fuel consumption, and develop complex active control systems that modify wing shapes based on sensor data for increased mobility and stability by using the insights provided by embedded sensors. The distribution of stress across the aircraft structure must be optimised to optimise aerodynamic performance and minimise fuel consumption. During this process, embedded sensors are vital because they continually collect a variety of data, including ambient factors, vibrations, and structural loads. The sensors are set up strategically in the wings, fuselage, and empennage of the aircraft to record detailed data on the stresses and pressures faced during flight. Aircraft operators can constantly change the arrangement of cargo, fuel, and passenger loads to maximise overall balance and decrease aerodynamic drag by using real-time data from embedded sensors. For example, sensors may detect uneven loading situations or cargo movement while in flight, allowing automated systems to adjust the distribution of weight to maintain the best possible aerodynamic performance. Through ongoing monitoring and modification of load distribution in reaction to developing flying conditions, aircraft can attain improved fuel efficiency and decreased operational costs. Predictive maintenance procedures are further made possible by real-time data from embedded sensors, which monitor structural health and identify any problems before they become severe failures. Operators can reduce downtime and improve the lifespan of aircraft components by actively planning maintenance and repairs in places where there is significant stress or wear. Despite reducing repair costs and operational delays, this proactive approach to maintenance improves reliability and security. Embedded sensors not only enhance load distribution but also make it simpler to create complex active control systems that improve the performance, stability, and agility of aircraft. To maximise aerodynamic performance and adapt to shifting flying conditions, these systems dynamically modify wing forms, control surfaces, and other flight control parameters utilising real-time sensor data.

Reactive wing morphing is one of the applications for active control systems, in which built-in sensors continually modify the shape and configuration of the wings during flight through tracking airflow, structural loads, and aerodynamic forces. With the dynamic morphing of the wings in reaction to sensor data, aircraft may optimise lift, drag, and stability characteristics, resulting in increased fuel efficiency, lower emissions, and higher agility in a variety of flying scenarios. Moreover, active reducing technologies that reduce vibrations caused by roughness and enhance passenger comfort are made possible by embedded sensors.

## 6. Future Outlook and Applications

In the future, smart composites have truly amazing potential to change aircraft architecture. Imagine aircraft with aircraft frames that are lighter and more effective because of the revolutionary features of smart composites. Because of these materials, weight can be distributed evenly throughout the aircraft structure thanks to improved load distribution. This reduces fuel consumption and increases aerodynamic efficiency, making air travel more economical and less harmful to the environment. Furthermore, engineers can now closely monitor the aircraft's status in real-time thanks to smart composites' enhanced health monitoring capabilities. Early detection of wear or damage enables preventive maintenance to be taken out, protecting both passengers and crew.

However, smart composites have much more use than just aeroplanes. Self-healing composites are a different area of research since they have the ability to self-heal little damage. These materials have the ability to heal themselves from tiny cuts or cracks, much like how human bodies do. This might boost safety even further and extend the life of aircraft parts, lowering the frequency of repairs. In addition to conventional aircraft, smart composites have potential uses in many other fields. Considering unmanned aerial vehicles (UAVs). Unmanned aerial vehicles (UAVs), also known as drones, are being widely used and have gained significant attention in the last decade. [12] For autonomous travelling operations, real-time structural health data from smart composites is required. Engineers can make sure the UAV is safe to fly and airworthy even in the absence of direct human supervision by keeping a close eye on its condition. This is especially important for extending the usable range of UAVs, allowing them to undertake longer missions without frequent inspections or maintenance stops. Nowadays, more and more UAVs are recruited for civilian applications in terms of surveillance and infrastructure inspection, thanks to their mechanical simplicity [13]. As for the search for space, smart composites might potentially be very important. Consider spacecraft including structures crafted from these cutting-edge materials, paired with sensors to track their condition and identify any indications of harm while in orbit. For mission success and safety, this real-time data would be crucial since it would allow engineers to quickly resolve any problems that may occur in orbit. Smart composites can completely change spacecraft design and operation, from tracking the integrity of the spacecraft's hull to identifying possible impacts from tiny meteors. All things taken into account, smart composites have a very promising future. These innovative substances have the power to completely change the way we think about transportation, from enabling new uses in UAVs and spaceships to transforming aircraft architecture. We expect even more fascinating developments in the field of smart composites in the years to come thanks to further research and development, which will usher in a new era of safer, more effective, and more environmentally friendly transportation options.

## 7. Conclusion

To sum up, smart composites have undoubtedly the ability to change the aviation sector. They offer synergistic benefits that have the potential to change aircraft design, performance, and safety. These modern components are a huge growth, giving operators and builders of aircraft new and unheard-of opportunities to boost efficiency and reliability. Smart composites are changing aviation by allowing real-time structural health monitoring, load distribution optimisation, and maybe even self-healing capabilities through the incorporation of sensors into composite structures. It is impossible to exaggerate the synergistic benefits of smart composites. Through the combination of embedded sensors and lightweight materials, such composites present a unique opportunity to simultaneously increase aircraft efficiency, safety, and performance. Smart composites offer proactive maintenance techniques, reducing the risk of unplanned failures and extending the lifespan of aircraft components by continuous monitoring of structural health and environmental conditions. In addition, smart composites' ability to evenly distribute loads efficiently improves aerodynamic efficiency, which lowers fuel use and emissions and ultimately benefits the environment and airlines alike.

Smart composites have an enormous opportunity to completely change the aviation industry. Smart composites can be created by embedding the shape memory alloy fiber into a metal matrix [14]. With the aid of these cutting-edge materials, aircraft design might be completely changed, allowing for lighter, more efficient airframes, improved structural health monitoring, and maybe even self-healing capabilities. Manufacturers of aircraft can obtain important real-time insights into the state of their aircraft by incorporating sensors into composite structures. This enables scheduled repairs and reduces downtime. In addition, smart composites' lightweight design lowers fuel consumption and operational costs, thereby improving the sustainability and profitability of air travel. The potential uses for smart composites in aircraft appear bright. By extending the limits of what is possible with these cutting-edge materials, ongoing research and development efforts are opening the door for broader acceptance and additional developments in the industry. The performance and safety of aeroplanes could be further improved by innovations like self-healing composites and adaptive constructions, creating new opportunities for aviation in the future. Smart composites have the potential to completely transform aviation with ongoing funding and cooperation, making air transport safer, more effective, and environmentally friendly for future generations.

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