



Review Structural Health Monitoring of Solid Rocket Motors: From Destructive Testing to Perspectives of Photonic-Based Sensing

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Abstract: In the realm of space exploration, solid rocket motors (SRMs) play a pivotal role due to their reliability and high thrust-to-weight ratio. Serving as boosters in space launch vehicles and employed in military systems, and other critical & emerging applications, SRMs' structural integrity monitoring, is of paramount importance. Traditional maintenance approaches often prove inefficient, leading to either unnecessary interventions or unexpected failures. Condition-based maintenance (CBM) emerges as a transformative strategy, incorporating advanced sensing technologies and predictive analytics. By continuously monitoring crucial parameters such as temperature, pressure, and strain, CBM enables real-time analysis, ensuring timely intervention upon detecting anomalies, thereby optimizing SRM lifecycle management. This paper critically evaluates conventional SRM health diagnosis methods and explores emerging sensing technologies. Photonic sensors and fiber-optic sensors, in particular, demonstrate exceptional promise. Their enhanced sensitivity and broad measurement range allow precise monitoring of temperature, strain, pressure, and vibration, capturing subtle changes indicative of degradation or potential failures. These sensors enable comprehensive, nonintrusive monitoring of multiple SRM locations simultaneously. Integrated with data analytics, these sensors empower predictive analysis, facilitating SRM behavior prediction and optimal maintenance planning. Ultimately, CBM, bolstered by advanced photonic sensors, promises enhanced operational availability, reduced costs, improved safety, and efficient resource allocation in SRM applications.

Keywords: solid rocket motors; condition-based maintenance; structural health monitoring; fiber-optic sensors; fiber Bragg gratings; diagnostics; machine learning

1. Introduction

Solid rocket motors (SRMs) are known for their simplicity, reliability, and high thrustto-weight ratio [1]. Therefore, they are ideal for applications such as space exploration. Particularly, they are extensively employed as boosters in space launch vehicles to provide initial thrust during liftoff. They help to achieve the required velocity and altitude for placing satellites, spacecraft, and payloads into orbit or on interplanetary trajectories. Notable examples include the solid rocket boosters (SRBs) used by NASA's Space Shuttle program and the strap-on boosters in the Ariane 5 [2] and Vega launchers. Additionally, SRMs are widely utilized in military applications, including ballistic missiles, tactical and strategic missiles, anti-ship missiles, and air-to-air missiles. Their high thrust-to-weight ratio, quick response time, and simplicity make them suitable for rapid deployment and use in various operational scenarios. Other SRM applications include research and development activities for studying combustion processes, material behavior under extreme conditions, and characterizing the performance of propellant formulations. SRMs are also employed



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Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). As depicted by the fields of application, the reliability of the SRMs is of utmost importance. Traditional maintenance practices based on fixed schedules or usage-based approaches may lead to either unnecessary maintenance actions or unexpected failures. Condition-based maintenance (CBM) has emerged as a promising strategy for improving the efficiency, reliability, and cost-effectiveness of maintenance practices across various industries [3]. By leveraging advanced sensing, data analytics, and predictive modeling techniques, CBM can be incorporated into an integrated health and usage monitoring system (HUMS) to enable the monitoring of critical parameters and the timely detection of defects, allowing for targeted maintenance interventions and optimizing the lifecycle management of SRMs [4].

CBM and HUMS facilitate structural health monitoring (SHM) of SRMs by analyzing sensor data in real time. Continuous monitoring and operational data recording (ODR) of parameters such as temperature, pressure, vibration, and strain can indicate variations or trends that may signify abnormal operation or potential failure modes. Advanced analytics can automatically detect these anomalies, perform diagnostic actions and generate alerts or trigger maintenance actions accordingly. Thus, several important advantages are related to the HUMS/CBM strategies for SRMs, including increased operational availability, reduced maintenance costs, enhanced safety, and optimized resource allocation. By monitoring the health of SRMs in real time and applying maintenance interventions based on actual condition data, unnecessary maintenance actions can be avoided, leading to cost savings, improved efficiency, and enhanced operational reliability.

However, the implementation of CBM strategies for SRMs comes with challenges, such as selecting appropriate sensor systems, ensuring data accuracy and reliability, developing robust predictive models, and integrating CBM into existing maintenance frameworks. This paper provides a critical review of the traditional methodologies employed for diagnosing the health state of an SRM and compares them with the emerging sensing technologies that appear promising in overcoming the challenges of this field. Among them, photonic sensors and fiber-optic sensors profit from increased sensitivity and a wide measurement range, allowing for accurate and precise measurements of critical parameters such as temperature, strain, pressure, and vibration. This enables the detection of subtle changes or anomalies that may indicate the onset of degradation or potential failure modes in SRMs. They additionally provide multiplexing capability, enabling simultaneous monitoring of multiple locations within the SRM and providing a more comprehensive understanding of its overall health and behavior. They are often nonintrusive, meaning they can be applied to the surface or embedded within the SRM without significantly affecting its structural integrity or performance, while they are inherently immune to electromagnetic interference (EMI). Photonic sensors can withstand harsh environments, including high temperatures, extreme pressures, and vibration. Their durability ensures long-term reliability and minimizes the need for frequent sensor replacements or recalibration. Finally, they can be integrated with data analytics techniques to extract valuable information from the collected data. Advanced data analysis algorithms such as machine learning can identify patterns, trends, and anomalies, enabling the prediction of SRM behavior, estimation of remaining useful life, and optimization of maintenance actions [5].

2. SRM Architecture, Potential Failures, and Degradation

A solid rocket motor (SRM) is a propulsion device used to generate thrust by burning a solid mixture of fuel and oxidizer known as propellant. Unlike liquid rocket engines that rely on pumps to deliver propellants, SRMs have their propellant premixed and packed into a solid form, typically a cylindrical shape. The motor consists of a combustion chamber, nozzle, and igniter (Figure 1A) [6]. The chamber is a robust metal casing enclosing a specialized solid propellant mixture that comprises a precise blend of fuel and oxidizer. When it undergoes controlled combustion, it generates the thrust necessary for propulsion. When ignited, the propellant burns in a controlled and self-sustaining manner, producing high-pressure gases that are expelled through the nozzle, creating thrust. Once ignited, the burning of the propellant in an SRM cannot be easily controlled or stopped, making it a non-throttleable propulsion system.



Figure 1. (**A**) Basic architecture of an SRM. (**B**) Various shapes of solid propellants with the corresponding thrust patterns.

The grain cross-section, a critical aspect of SRM design, is often tailored to enhance the motor's performance. Common configurations include circular, star, and finocyl shapes, each influencing the burning rate and thrust profile differently, as shown in Figure 1B [7]. Despite their sturdy design, SRMs are susceptible to an array of defects, such as cracks, erosion, burning irregularities, delamination, and corrosion. These issues arise from various sources, including storage conditions, transportation stress, and manufacturing imperfections. More precisely, fluctuating temperatures or exposure to corrosive substances can lead to chemical degradation of the propellant material over time [8]. These changes can alter the propellant's composition, diminishing its effectiveness and potentially compromising the motor's performance and structural integrity during operation. During transportation, SRMs are subjected to mechanical stresses due to large temperature variations higher than 60 °C, excessive accelerations even beyond 100 g, and vibrations. These movements can exacerbate existing defects or create new ones such as bore cracks or delamination within the motor [9]. Additionally, imperfections that occur during the manufacturing process, such as inconsistencies in propellant mixing or bonding irregularities, can become latent issues within SRMs. These imperfections, if undetected, can transform into critical points of failure under operational stresses and compromise structural integrity and overall performance.

Moreover, the propellant itself is not immune to aging [10,11]. Over time, chemical changes, moisture absorption, temperature sensitivity, binder cracking, and oxidation can

affect the propellant's composition [12]. To mitigate these challenges, thorough inspection methods and advanced techniques such as nondestructive testing and structural health monitoring are employed. These measures are crucial for detecting defects and monitoring propellant degradation, enabling timely interventions to maintain the reliability and safety of solid rocket motors in diverse aerospace applications.

3. Traditional Maintenance Practices: Destructive Testing

Currently, the condition of SRMs is investigated by periodical destructive testing [13] performed on a limited number of SRMs, which is considered representative of a certain typical population. Particularly, the motors are separated from the missile and dissected, the charge specimens are extracted by milling and cutting (Figure 2) [14], and chemical and mechanical analysis of the specimens is performed to determine the aging state of the material and compare it with limiting values derived from qualification and structural analysis. Destructive testing includes visual inspection of the components of the SRM [13], which is the most basic form of inspection and involves looking for signs of defects on the surface of the SRM, such as cracks, bulges, or discoloration. Visual inspection is often assisted by several imaging techniques and appropriate instrumentation. The destructive testing also includes a series of experimental processes, among which the most frequent is thermal cycling. Thermal cycling tests expose the SRM to rapid and repetitive temperature variations, simulating the thermal stresses experienced during launch and atmospheric reentry [15]. By subjecting the motor to extreme temperature differentials, engineers can assess its ability to withstand thermal gradients, evaluate material fatigue, and detect potential weaknesses in the insulation and structural components. Additional processes may involve overpressurization tests, subjecting the SRM to pressures exceeding its nominal operating range [16], and static test firing, which refers to the ignition of the SRM in a controlled environment to simulate operational conditions. Pressure tests help in the identification of the SRM's structural limits and the observation of failure mechanisms such as rupture, debonding, delamination, or buckling [17]. Static test firing allows for the measurement of thrust, chamber pressure, and burn rate, providing information on the motor's performance and enabling the validation of design predictions [18].



Figure 2. Characteristic images from the process of destructive testing of SRMs based on MBDA Group/Bayern Chemie GmbH experimental procedures [19]. (**A**) Milling and cutting of an SRM case. (**B**) Separation of the SRM from the missile. (**C**) Charge specimens extracted from the SRM. (**D**) Dog-bone-shaped specimens for experimental analysis of the mechanical properties.

In general, destructive testing processes are assisted by strain gauges, which are used to measure structural deformation and stress distribution during destructive testing, and high-speed imaging digital cameras or video recorders, which capture the dynamic behavior of the SRM during testing.

Despite the fact that destructive testing is an essential process for understanding an SRM's performance limitations, failure modes, and structural integrity, it is an expensive, tedious, and time-consuming process, providing results with a considerable delay [19], when additional aging may have taken place. Moreover, destructive testing cannot guarantee the detection of every potential problem or failure scenario, as it is performed on a limited number of samples considered representative of a specific SRM population [20].

Additional measures, such as statistical analysis, modeling, and simulation, are at least indispensable to expand the test results to the broader population. Still, variations in manufacturing processes, material properties, or environmental conditions can result in unique challenges in life-expectancy predictions (Figure 3) or failure mechanisms that may not be fully captured, leading to unreliable predictions—depending on specific samples—in the condition and life expectancy of a high number of SRMs, resulting in increased loss and limited reliability.



Figure 3. The variability in life expectancy outcomes inevitably arises due to varying conditions among the sampled sub-lots [19].

4. Non Destructive Testing: Imaging Approaches

The limitations of destructive testing have led to the development of various nondestructive testing approaches that can provide valuable information for defect detection, characterization, and assessment, facilitating proactive maintenance and preventing catastrophic failures. The most frequently employed methods, presented in brief in Table 1, include ultrasonic testing (UT) [21], X-ray inspection [22] and CT imaging [23], magnetic particle inspection [24], acoustic emission testing [25], thermography [26], and digital image correlation (DIC) [27].

Technique	Description of the Method	Advantages	Limitations
Ultrasonic testing	High-frequency sound waves are transmitted into the material and the reflections are analyzed to identify any abnormalities such as voids or cracks.	Detection of both surface and internal defects with high accuracy and resolution. Assessment of the size and shape of the defect. No material damage is caused.	Direct contact with the material required. UT difficult to use in some areas. UT may be affected by the shape and orientation of the defect. Nondetectable defects that are too small or located in certain areas of the material.
X-ray inspection and CT imaging	X-rays pass through the material, with a detector located on the other side of it. Areas of the material that are denser or thicker, such as those containing defects or anomalies, will absorb more X-rays and appear darker in the resulting image. CT imaging involves taking multiple X-ray images of the material from different angles and using computer software to reconstruct a 3D image of the internal structure.	3D visualization of the defect. Detection of both surface and internal defects with high accuracy and resolution. Assessment of the size and shape of the defect. No material damage is caused.	Specialized equipment and expertise are required. Time-consuming and expensive method. Heightened safety concerns and stringent precautions associated with high-energy radiation. Nondetectable defects that are too small or located in certain areas of the material. Delaminations can be detected only if not perpendicular to the beam.

 Table 1. Nondestructive imaging techniques employed for structural integrity testing of SRMs.

			
Technique	Description of the Method	Advantages	Limitations
Magnetic particle inspection	MPI involves magnetizing the SRM and then applying iron oxide magnetic particles to the surface. Any defects in the material will cause the magnetic particles to gather in that area, making it easier to identify the defect.	Detection of both surface and near-surface defects, including cracks, voids, and other discontinuities. Relatively simple and cost-effective testing method. It is performed quickly and easily in the field.	Internal defects or defects located deeper in the material are not detectable. The method can only detect defects that are located near the surface of the material. The particles used in MPI may not adhere well to certain types of materials or may obscure the defect in some cases. Cleanup procedures, complying with relevant decontamination, and safety protocols are necessary to mitigate potential health and environmental risks.
Acoustic emission testing	AET involves the use of sensors that are attached to the surface of the material being tested. As the material undergoes stress or deformation, it will emit acoustic waves that are detected by the sensors. These waves can be analyzed to determine the location, size, and nature of any defects in the material.	Real-time monitoring is feasible.	Sensitive to ambient noise. Limited to surface monitoring. Skilled interpretation is necessary to differentiate between harmless noise and critical signals indicating potential damage.
Acoustic thermography	This technique involves using a combination of acoustic and thermal imaging to detect defects in the SRM. The method uses high-frequency acoustic waves that induce thermal gradients within the material. Thermal changes are detected with an infrared camera and can be used to detect subsurface defects or anomalies.		Sensitive and expensive instrumentation. Highly skilled inspectors are required. Lack of clarity of too-deep defects.
Digital image correlation	DIC involves the use of high-resolution cameras to capture images of the surface of the material being tested. These images are then analyzed using software to track the movement of individual pixels on the surface of the material, providing information on the deformation and strain of the material.	Relatively simple and cost-effective method. It can be performed in real time during operation. It can provide high-resolution measurements of deformation and strain, and can detect defects that may not be visible to the naked eve.	

Table 1. Cont.

In general, all of these approaches benefit from specific advantages, but they also have limitations in terms of inspection depth, sensitivity to certain defect types, or limited access to certain areas of SRMs. As nondestructive imaging techniques evolved, each method introduced unique capabilities and limitations. Ultrasonic testing (UT) provided valuable insights into internal structures but had challenges in detecting surface defects. X-ray inspection and computed tomography (CT) imaging offered comprehensive internal views but were limited in surface defect detection [28]. Magnetic particle inspection excelled in surface flaw identification but struggled with subsurface defects. Acoustic emission testing provided real-time monitoring but had challenges pinpointing specific defect locations.

Thermography proved effective for surface defects but lacked precision and in-depth assessment, and digital image correlation (DIC) offered full-field deformation data but

was not designed for subsurface defect detection. Each method's limitations were often complemented by the strengths of others. For a comprehensive evaluation, integrating multiple techniques became essential, ensuring a thorough assessment of solid rocket motor components by overcoming individual limitations.

5. Sensing Approaches for the SHM of SRMs

Structural health monitoring (SHM) plays a critical role in ensuring the reliability and safety of solid rocket motors. While imaging techniques have been valuable in assessing certain aspects of their structural integrity, there is a growing need to go beyond these methods and embrace sensor networks. Imaging techniques, such as visual inspection and nondestructive testing, may provide valuable surface-level information, but they often fail to capture the underlying complexities and potential hidden defects within a motor's structure. More precisely, nondestructive testing, associated with manual inspection and point measurements, focuses on material scale assessment rather than on structural scale assessment, and it can be performed only at certain times. Sensor networks, on the other hand, offer a comprehensive and real-time monitoring approach that can continuously gather data on various parameters such as strain, temperature, pressure, and vibration. By deploying sensor networks, engineers can gain deeper insights into structural behavior, identify early signs of degradation, and predict potential failure points more accurately. This proactive approach enables timely maintenance and intervention, ultimately leading to improved safety, enhanced performance, and increased lifespan of solid rocket motors. A number of well-known technologies have been employed for the development of customized sensors for SRMs, such as: (a) semiconductor-based strain gauges, particularly dual bond stress temperature (DBST) sensors; (b) piezoelectric sensors; and (c) electric sensors. These three main categories are analyzed in the following sections in terms of application benefits and limitations or restrictions related to their use.

5.1. Strain Gauges and DBST Sensors

Strain gauges are sensors that can be attached to an SRM to measure deformation of the material to which they are attached and translate it to the corresponding changes in strain or stress [29]. These measurements can be used to identify areas of the SRM that are under excessive stress, which may indicate the presence of defects. Dual bond stress and temperature (DBST) sensors are specifically designed for health monitoring of SRMs [30]. They measure both radial stress (bond stress) and temperature at their active surface near the case wall simultaneously during manufacturing and thermal cycling. DBSTs are embedded in the motor against the inner case wall during the manufacturing process and can use wired or wireless technologies to obtain data [31]. DBSTs use two thin metal foils bonded to the surface of the solid rocket motor, one of which is coated with a temperature-sensitive material. As the SRM experiences changes in temperature and stress, the metal foils undergo changes in their electrical properties, which can be measured using a Wheatstone bridge circuit, as seen in Figure 4A together also with typical implementations of DBST sensors in Figure 4B–D [32]. This configuration provides real-time data on the health condition of the SRM as seen in real characterization cases in Figure 4E. Such typical sensors developed by industrial manufacturer (Micron Instruments Inc., Simi Valley, CA, USA) consist of a stainless-steel diaphragm, typically 7.62 mm in diameter and 2 mm thick, fitted with four precision semiconductor strain gauges and a temperature sensor. This temperature sensor is a silicon element the same size as the strain gauges, which has negligible strain sensitivity and is not affected by pressure or case-induced strains.

The use of multiple sensors—at least three—placed in the circumferential direction of the SRM cross-section, at the midplane of the motor, can assure the detection and localization of bore cracks and debonding in the vicinity of that cross-section (Figure 5) [30,33]. DBST sensors have also been used to determine the effects of aging on the propellant modulus and stress-free temperature by slowly heating and cooling the motor while measuring stress at various temperature plateaus [34].



Figure 4. A typical DBST sensor developed particularly for strain and temperature measurements in SRMs [32]. (**A**) electrical and mechanical schematic of the dual DBST sensor. (**B**,**C**) The two sides of the sensor with an indication of its size. (**D**) DBST sensor bonded to shim. (**E**) SRMs with embedded DBST sensors.



Figure 5. (**A**) Schematic of an SRM containing a debond along with the location of the four DBST sensors at the cross-section for the detection of the corresponding flaws [30] From [30]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc. (**B**) Similarly, schematic of an SRM containing a bore crack along with the location of the four DBST sensors [31] From [31]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc. (**C**,**D**) Subscale motor along with the embedded DBST sensor within the casing and insulation layers [34] From [34]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

5.2. Piezoelectric Sensors

Piezoelectric sensors play a pivotal role in the field of structural health monitoring (SHM), not only in the context of solid rocket motors but also in various other sensing applications [35]. These sensors are based on the piezoelectric effect, which allows certain materials, such as piezoelectric crystals or polymers, to generate electric charges when subjected to mechanical stress or deformation. In SHM, piezoelectric sensors are strategically placed within structures, such as solid rocket motors, to monitor their mechanical integrity over time. When structural defects or changes occur, they induce mechanical stress or vibrations, which are promptly detected by the embedded sensors. The resulting electric charges are then converted into measurable signals, enabling real-time monitoring of the structure's health. This technology is invaluable for the early detection of defects, cracks, or anomalies, allowing for preventive maintenance or timely intervention to avert catastrophic failures. Piezoelectric sensors offer a noninvasive, highly sensitive, and efficient means of monitoring structural health in a wide range of applications, ensuring the safety and reliability of critical systems.

More precisely, a piezo film (ceramic or polymer) has been developed and positioned between conductive plates in the form of a "sandwich" that is protected by polyester laminates [36] (as can be seen indicatively in Figure 6). Experiments conducted at room temperature on propellant during the curing phase using an embedded piezoelectric PVDFbased sensor showed a reduction in capacitance of 35 pF during the initial 6 days of curing [36]. This reduction in capacitance serves as an indicator of changes in the propellant's modulus and provides valuable information for monitoring the curing process and the structural health of the propellant. However, the long-term monitoring of propellant health is not addressed. Additionally, the corresponding study do not delve into the practical challenges and complexities associated with implementing a remote data acquisition system for multiple sensors in a full-scale motor, which is crucial for real-world applications. The efficiency of this type of sensor also depends on the sensors' position, which is tightly related to the purpose of their use. To determine the modulus, the sensors are placed in a low-stress area (e.g., far from the bulb tip stress reliefs), while damage detection implies the positioning of sensors in areas where flaws are expected to appear (i.e., the propellant liner interface). An alternative architecture of piezoelectric capacitance device was proposed and demonstrated [37] where one or multiple sensors could be embedded in the SRM's energetic propellant material.



Figure 6. (**A**) Internal structure of a PVDF-based sensor. (**B**) Typical form of a PVDF-based sensor. (**C**) Process of embedding the PVDF-based sensor into the propellant.

Despite their benefits, piezoelectric sensors also come with certain limitations and drawbacks. The surface charge produced by an applied force in a piezoelectric sensor can be affected by various factors, including charges from the environment (airborne charges), current leakage due to the nonzero conductivity of the dielectric material, or the input resistance of the connected electronics. These factors can collectively act as a high-pass filter for input signals, which can make it challenging to use piezoelectric sensors for pure static measurements [38]. Additionally, their sensitivity to environmental factors such as temperature can be a drawback. This is due to the fact that changes in

temperature can affect the piezoelectric material's properties, potentially leading to false readings or requiring complex compensation techniques. The temperature fluctuations can induce crystal deformation within the sensor, leading to an electrical output. If different components of the sensor, such as clamping parts and electrodes, have different thermal expansion coefficients, it can result in the crystal experiencing unintended mechanical forces, further affecting the sensor's performance [38]. While the piezoceramic films are very effective and thermally stable, they often have a poor mechanical impedance match with certain materials, such as propellants, and they tend to be brittle, which can be a limitation in applications where flexibility or durability is required. On the other hand, piezoelectric polymer films (e.g., PVDF, polyvinylidene fluoride) offer better impedance matching with materials such as propellants, and they are flexible, allowing for versatile use, but they have poor thermal stability, rendering them suitable for high-temperature environments. Finally, piezoelectric sensors are susceptible to electromagnetic interference, which can introduce noise into the collected data [39]. Their installation can be challenging in some structures, especially those with irregular shapes or limited access points. Maintaining a reliable electrical connection over extended periods can also be a concern.

6. Photonic Sensing Approaches: Towards CBM of SRMs

The evolution of SHM techniques for SRMs has paved the way for more advanced and accurate monitoring systems. While strain gauges, DBST sensors, and piezoelectric sensors have served as valuable tools in the past, the need to overcome their limitations and achieve CBM has driven the exploration of photonic sensors. In particular, traditional strain gauges and temperature sensors often present challenges in terms of installation complexity and potential interference with the motor's structural integrity. Additionally, their limited spatial coverage may not provide a comprehensive understanding of the entire motor's behavior, leading to potential blind spots in detecting critical defects. Furthermore, piezoelectric sensors, while effective in capturing vibration data, can be sensitive to environmental factors and may require additional calibration efforts.

In contrast, photonic sensors offer a promising solution to address these drawbacks. Based on light propagation principles, photonic sensors and—especially—fiber-optic sensors can be embedded directly into the material, minimizing structural disturbance and interference. Their distributed sensing nature allows for continuous and real-time monitoring along the entire length of the solid rocket motor, capturing intricate strain and temperature profiles. Moreover, photonic sensors are less susceptible to environmental influences, ensuring more accurate and reliable data collection. By adopting photonic sensor networks for SHM, engineers can gain a comprehensive understanding of the solid rocket motor's condition, enabling proactive maintenance and timely intervention. This shift towards CBM improves safety, enhances performance, and extends the operational life of solid rocket motors, all while mitigating potential risks and ensuring optimal reliability for critical aerospace applications. A number of photonic sensing implementations are available and have been employed to date, with different capabilities and complexity depending on the specific application cases in SRM monitoring.

6.1. Interferometric Sensors

Interferometric sensors have emerged as a groundbreaking technology in the field of SHMs for aerospace composites, enabling precise and comprehensive assessment of their integrity [40]. Operating on the principle of interference, these sensors utilize advanced optical techniques, such as fiber-optic interferometry, to measure infinitesimal changes in the environment they are embedded within [41]. A distinct case of interferometric-based sensors could be laser Doppler vibrometers (LDVs) [42] for remote monitoring of vibrations. Although their operation is entirely different from that of waveguide-based interferometers and other fiber-optic sensors considered here, they offer the advantages of easier or seamless integration and real-time monitoring [43]. By employing interferometric sensors, engineers can monitor distributed strain, temperature variations, and other critical parameters along

the entire length of the solid rocket motor. The most common type of interferometric sensors used in SHM are fiber-optic interferometers (FOI), which can be also classified as intrinsic or extrinsic depending on the design of the cavity and the corresponding sensors' footprint. Such interferometric sensors have been based in various architectures utilizing also Bragg gratings [43], long-period gratings (LPGs) [44], and photonic crystal fibers (PCFs) [45]. The key advantage of interferometric sensors lies in their remarkable resolution, which can exceed 1 $\mu\epsilon$ for strain measurement. Worth noting that early applications of fiber-optic sensors in SHM, pioneered by McDonnell Douglas in the 1980s, employed the Sagnac interferometer as a strain sensor [46].

Among the most common types of FOI are Fabry-Perot interferometers (FPIs), which consist of two reflective surfaces separated by a small gap. Changes in the gap distance due to structural deformations or temperature fluctuations lead to alterations in interference patterns [47]. FPI sensors boast resolutions as high as 0.15 $\mu\epsilon$ and a broad measurement range from $-5000 \ \mu\epsilon$ to $+5000 \ \mu\epsilon$. These sensors are compact, ranging from 1 to 20 mm in length, allowing seamless integration into structures without significantly impacting their mechanical properties. They can withstand temperatures of up to 250 °C; however, their limited multiplexing capability restricts their application to a relatively small number of measurement points [48]. FPI sensors offer high accuracy, versatility, and the ability to measure both static and dynamic strains, making them suitable for real-time monitoring of SRM components during ignition and flight.

Fiber-optic Mach-Zehnder-based interferometers (MZIs) have also been implemented and employed for the study of intrachamber processes in SRMs [49]. In this experimental study of a model solid propellant rocket motor, noninvasive control with MZI fiber-optic sensors enabled monitoring of the burning rate of solid propellant (Figure 7). The results revealed the feasibility of noninvasive control by recording combustion front arrival time and analyzing spectrogram peaks, providing insights into the combustion chamber's longitudinal modes and confirming a nearly constant combustion rate [49].



Figure 7. Observation of a model SRM featuring the installed MZI based sensor (**A**), a schematic with dimensions illustrating the main SRM components and the MZI (**B**), and the post-operation section of the SRM (**C**) [49]. Reproduced with permission from [49].

Michelson interferometers split incoming light into multiple paths, allowing for the detection of phase shifts caused by mechanical vibrations, temperature changes, or structural deformations. While they provide high sensitivity and precision, Michelson interferometers may require complex optical setups and alignment procedures and are more complex compared to MZI architectures [50]. Despite the inherent high sensitivity of FOIs, their main limitation is the lack of scalability in a single fiber. As a result, it is not easy to integrate multiple sensors in a fiber, limiting the capabilities for multipoint or distributed sensing. The interrogation unit of such FOIs is also quite complex, with high costs and multiple interrogators needed for multiple FOIs, increasing overall installation costs.

6.2. Intensity-Based Fiber-Optic Sensors

A much simpler fiber-optic configuration applied in SRM's propellant monitoring is pristine optical fibers employing a simple amplitude interrogation unit. Different types of polymer optical fibers (POFs), including both jacketed and unjacketed types, were embedded in propellant specimens using specialized primer and glue that assured an excellent bonding between fiber and propellant. The high elasticity (low Young's modulus) of such polymer optical fibers [51] allowed for the consistent transfer of propellant stress or strain behavior into the embedded fiber, which responded accordingly. These fibers were fabricated with a core made of PMMA and a cladding of fluorinated polymer. In their bare form, such typical multimode POFs with a core diameter of 980 µm and with a 10 µmthick cladding layer that increased the total diameter to 1 mm were employed. while also jacketed types of fiber-optic cables, with a polyethylene or polyamide jacket, have also been employed. Two distinct fiber arrangements were utilized in previous studies: one involved a longitudinal orientation of the fiber within the propellant, parallel to the stretching direction, while the other incorporated a closed fiber loop. In the first arrangement, both unjacketed PMMA POF and polyamide jacketed POF responded consistently, closely mirroring the behavior of the sample even under excessive strains of up to 8% (Figure 8) and 30%, respectively. This response was due to a decrease in transmitted light caused by higher optical propagation losses attributed to axial elongation. For the fiber loop arrangement, the unjacketed PMMA POF, through macro-bending induced optical losses, closely followed the applied force and elongation up to a strain value of 10% [52,53].



Figure 8. The behavior of an unjacketed PMMA-POF in destructive tensile testing of propellant [53]. Reproduced with permission from [53].

Intensity-based POF sensors [51] offer several advantages in the context of SHM for SRMs. They are relatively easy to embed within propellant specimens due to their small size and flexibility. Their construction from PMMA and fluorinated polymer grants them resistance to environmental factors typically present in rocket motor environments. Additionally, their ability to respond consistently to strain allows for accurate monitoring of structural changes [54] in the propellant material. POF sensors exhibit notable characteristics, including good stability, cost-effectiveness, and a substantial strain range of 60% [55]. In relevant studies, the findings emphasize the versatility of POFs in not only tracking the

strain state of viscoelastic solids but also in identifying initial cracks and monitoring their propagation until reaching ultimate failure [55,56].

However, these sensors also have serious limitations. Successful embedding might require specialized primers and careful implementation, especially during the propellant casting process. Moreover, optical propagation losses due to axial elongation or macrobending cannot be isolated by other environmental factors such as temperature, and the temperature compensation process would be very difficult. The amplitude-based interrogation provides a response signal by the net effect of strain in the fiber without providing means of distributed information, as in FBGs, which are described in the following section. These limitations emphasize the importance of precise installation and understanding the specific strain conditions under which these sensors can effectively operate in SRM applications.

6.3. Fiber Bragg Gratings (FBGs)

In the realm of SHM and CBM for SRMs, FBG-based sensors have emerged as invaluable tools that could offer precise insights into the structural integrity and performance of these critical aerospace components. FBGs are fabricated by laser-inducing permanent periodic variations in the refractive index along an optical fiber, creating a wavelengthspecific reflection. When subjected to strain, the spacing between these periodic variations changes and causes a shift in the reflected wavelength, which can be measured to accurately determine the strain experienced by the structure of the SRM, enabling precise strain or temperature monitoring. The way of enhancing SRM monitoring begins with single-mode silica optical fiber FBGs [57,58]. FBGs can be inscribed inside the core of the fiber in a continuous, seamless, nonintrusive way (by a laser-based writing process), providing the capability of fully customizing their optical properties and accommodating in a single fiber—theoretically—an infinite number of FBGs separated optically and spatially in a way to offer multipoint or distributed sensing over the entire fiber's length. These sensors, embedded strategically within SRMs, provide high-resolution measurements of various parameters, such as strain and temperature. In one approach, FBG sensors made from ordinary quartz single-mode fibers, embedded in raw composite material, were employed to monitor the entire curing process, ranging from heating and insulation/curing to cooling, occurring between 20 °C and 140 °C [59]. The subtle shifts in wavelengths they record over time can provide not just insights but a roadmap into the curing degree of the propellant grain. This level of granularity is crucial for CBM, allowing engineers to gauge the exact state of the SRM at any given moment. These FBG sensors have exhibited remarkable sensitivity to both tensile and compressive stresses, making them effective tools for monitoring debonding tests where artificial defects were created, enabling the precise determination of debonding locations.

In another instance, FBG sensors, using polymer packaging, have been strategically placed to measure bond stress between the propellant and insulation during the curing, demolding, and debonding processes. These sensors, distributed along the circumference of the motor at the propellant/insulation interface, detected shifts in the FBG center wavelength, indicating variations in bond stress. The sensors were also subjected to axial and uniaxial tensile stresses, revealing significant stress gradients in the circumferential direction [60], which can be vital markers for CBM algorithms. They hint at areas of potential weakness, allowing for proactive maintenance measures before structural integrity is compromised. Additionally, simplified fiber filament wound scale SRM models have been created, incorporating FBG sensors in key locations within model shells (Figure 9). These sensors monitored the internal hydraulic pressure applied to simulate SRM shell casing working conditions, providing crucial data on circumferential and axial strains [61].

Moreover, an active sensing method utilizing FBG strain sensors has been discussed for monitoring solid propellant integrity. This method involves applying dynamic loads to a structure and observing resulting deformations. The active sensor, comprising a flexible ring with a Terfenol bar and Bragg grating sensor (Figure 10), provided valuable insights into the mechanical properties of SRM propellant grains [62]. The system's ability to characterize these properties by measuring the amount of deflection due to applied loads demonstrated its potential for robust SHM in SRMs, in addition to further enabling the predictive analyses that form the cornerstone of CBM.



Figure 9. (**A**) FBG sensor locations on scale SRM models [61] (**B**) The scale SRM models along with the embedded FBG sensor network [61]. Reprinted with permission from [61].



Figure 10. The active sensing method for the structural integrity monitoring of the propellant as demonstrated in [62]. The figure shows the three basic configurations which specifically are: (**A**) An FBG sensor bonded to a bar of Terfenol to monitor the charging properties of the adhesive bonding. (**B**) An FBG incorporated in an aluminum ring section to monitor vibrations under magnetic field influence. (**C**) Cantilever arrangement to measure deflection of solid propellant sample. Reproduced with permission from [62].

The use of silica optical fibers encounters certain limitations, notably related to their susceptibility to mechanical damage and challenging installation procedures [63]. It is important to note that the current limited practice in the integration of FBGs into the SRM structure lacks standardization, with high-temperature-resistant adhesives/primers or epoxy glues being necessary to assure precise strain or temperature measurement within SRMs. A notable advancement in FBG technology comes in the form of polymer optical fiber FBGs (POFBGs) [64]. These sensors, composed of polymer materials, offer enhanced flexibility and easier installation, addressing the fragility issues encountered with silicabased FBGs. Polymer FBGs exhibit improved mechanical robustness, making them suitable for the harsh conditions within SRMs [65]. With the provided strain sensitivity being much better than that of glass/silica optical FBGs (GOFBGs) [66], the strains that can be measured exceed 6% [67] or even 10%.

The main drawback of typical POF FBG sensors is the interrogation process. Indeed, POFs usually operate in a multimode regime, meaning they support multiple propagation modes for light within the fiber core. Interrogating FBGs in multimode fibers, including POFs, is more complex compared with single-mode fibers (SMFs) due to the overlapping spectra from different modes [68]. Among the most common techniques used to overcome this limitation involves mode demultiplexing or the use of mode-division multiplexers (MDMs) [69]. Mode-demultiplexing involves employing specialized devices or algorithms to distinguish the responses from different modes. For instance, modal filtering can be employed to selectively couple light into specific modes of the multimode fiber, making it possible to isolate the reflection from the desired mode. MDMs can selectively couple light into specific modes and decouple it after the transmission through the fiber. By employing MDMs, it is possible to separate the modes, allowing for individual interrogation of the FBGs inscribed in different modes. Additionally, advanced interrogation systems using algorithms and signal-processing techniques have been developed to analyze the complex responses of multimode FBGs. These systems utilize mathematical methods to distinguish the different modes' signals and interpret the data accurately. However, these approaches are very complex with very high interrogation costs, and not suitable for demanding applications such as SRM or aerospace applications where proven and robust solutions are needed.

Recently, novel approaches have emerged for developing single-mode FBGs in fewmode polymer optical fibers (FM-POF) FBGs [70–73] by using special laser-based inscription techniques. Implementing a single FBG in multi-/few-mode polymer optical fibers [74] enables the integration of the favorable characteristics of POFs (higher elasticity) with the capability for interrogation by standard FBG interrogation units typically used for glass-based FBGs.

FBGs in single-mode fibers (SMFs) have been implemented also in microstructured polymer optical fibers (photonic crystal fibers, or PCFs); however, this is a more complex process both for the Bragg Grating inscription process and for the termination and interconnection of these PCFs to standard silica-based telecom SMFs, resulting in serious handling difficulty. The primary technical limitation that hindered the use of FBGs in single-mode POFs is the difficulty of consistently and reliably producing truly single-mode fibers with a solid core and minimal dimensions, as the fiber drawing process, in this case, is exceptionally demanding and poses significant challenges. Therefore, there are no widely commercially available single-mode, single-core POFs yet. However, there is increasing research activity on and limited production of experimental single-mode POFs [64] featuring directly defined FBGs. Robust and customizable solutions of POF FBGs are anticipated to emerge in the near future.

6.4. Distributed Fiber Optic Sensors

Fiber-optic sensors can be classified as point or distributed. FBG-based sensors are essentially multipoint sensors with a potentially indirect distributed capability depending on the number of embedded BGs in the fiber. Distributed sensors can monitor several thousand points simultaneously, thus providing a drastically reduced cost per sensed point. However, depending on their specific technology and performance requirements, their total cost can be particularly high. The operational principles of distributed fiber-optic sensors can be based on Rayleigh, Raman, or Brillouin scattering effects. Rayleigh scattering is an elastic process, attributed to inhomogeneity in the density of the optical material. Brillouin and Raman scattering-based sensors' operation is based on propagating light interacting with the propagating acoustic phonons and molecular vibrations of the optical fiber, respectively, exhibiting a frequency shift with respect to the incoming propagating light in the fiber. The best-suited distributed technologies for real-time SHM are considered to be those based on Rayleigh and Brillouin scattering, while Raman-based sensors are commercially available for temperature monitoring. Brillouin sensors are relatively costly; however, they are accurate and offer high spatial resolution and extended sensing range. On the other hand, Rayleigh distributed sensors are relatively fast and very sensitive, while their interrogation costs depend strongly on the target resolution performance [43].

Such distributed sensors are better suited for long-scale systems; for limited-scale SRM systems, employment is considered cost inefficient due to the very high costs of interrogation units. Furthermore, FBGs provide increased flexibility, as they can be customized for measuring a number of mechanical parameters or chemical and environmental factors, and all of these different sensors can be interrogated by a single unit.

Furthermore, to enhance system robustness and reliability, a novel approach, distributed optical fiber smart sensing (DOFSS), has been developed. In this architecture, smart transducer interface modules (STIMs) are strategically placed at network nodes, enabling the simultaneous distribution of sensing, power, and communication [75]. This innovative approach addresses challenges associated with damage to fibers or optoelectronic components, ensuring the seamless operation of SHM systems. These advancements collectively represent a significant stride in the realm of fiber-optic-based SHM, enhancing our understanding of SRM behavior and contributing to the safety and reliability of aerospace systems.

7. Machine Learning as an Enabling Tool for the CBM of SRMs

The integration of cutting-edge technologies such as computational intelligence, deep learning algorithms, machine learning, and neural networks has revolutionized the way we approach defect diagnosis and predictive maintenance strategies [76–78]. One of the primary applications of machine learning in this domain involves the accurate interpretation of continuously collected data from sensors embedded within SRMs [79]; machine learning algorithms can identify patterns and anomalies associated with strain, temperature, and other critical factors. Nondestructive imaging techniques have also been used in this field of defect diagnosis [22,80,81]. These algorithms learn to recognize precursor signals that indicate potential issues, allowing engineers to proactively address problems before they escalate. Machine learning models, trained on historical data from FBGs or other sensors, can identify specific patterns associated with different types of faults or structural degradation in SRMs. Whether detecting microcracks, delamination, or other forms of damage, these algorithms can provide detailed insights, aiding engineers in understanding the nature and severity of these issues [82].

Discriminating normal operational variation from abnormal behavior is feasible through neural network and machine learning approaches. At the same time, they make it possible to detect subtle changes that could go unnoticed through traditional analysis methods. Scientific approaches published in the field of SHM depict the necessity to study uncertainties as a crucial aspect affecting the interpretation of sensor data in the route to diagnosing the structural integrity of a material; however, only a restricted number of studies explicitly refer to SRM models [83,84].

Moreover, various sophisticated algorithms can optimize the placement of state of the art sensing elements, such as DBSTs or FBGs [85], within SRMs. By analyzing computational models and historical data, these algorithms [86–89] can suggest the most strategic locations

for sensors to maximize their effectiveness. This ensures that the acquired data are not only comprehensive but also highly relevant, enhancing the overall efficiency of the SHM system [90,91].

In summary, the integration of machine learning techniques revolutionizes the landscape of SRM structural health monitoring. By providing predictive insights, enabling early fault detection, and optimizing sensor placement, machine learning plays a pivotal role in ensuring the safety, reliability, and performance of solid rocket motors in various aerospace applications.

8. Conclusions

In this comprehensive review, we have explored the spectrum of techniques essential for the maintenance and SHM of SRMs. Our analysis encompassed traditional destructive testing and visual inspections, nondestructive imaging methods tailored for SRMs, and emerging research-level approaches, with a specific emphasis on the imperative need for CBM in SRM systems. Drawing inspiration from sensor development in related fields such as aircraft and civil structures, our study elucidated the unique challenges faced in SRM SHM. A pivotal aspect of our discussion revolved around promising future prospects, highlighted by the integration of photonic sensors, especially FBGs, as a primary sensing element. These sensors offer enhanced accuracy, an extensive dynamic range, and real-time monitoring capabilities, making them pivotal in enhancing SRM monitoring precision. Although the employment of FBGs in SRMs is still very limited, it is expected to be greatly extended in future implementations, especially with the development of FBG-based sensors in polymer optical fibers. While the adoption of machine learning techniques in this arena is presently limited, our review underscores their untapped potential. Machine learning holds the key to refined data interpretation, defect diagnosis, and predictive maintenance. Moreover, these algorithms can significantly optimize monitoring systems through the implementation of advanced sensor placement algorithms, which have already been developed and proven effective.

In summary, this review not only provides a panoramic view of existing practices in SHM for SRM but also points towards future developments, where the amalgamation of cutting-edge photonic sensors and intelligent machine learning algorithms stands poised to revolutionize SRM monitoring, ensuring unprecedented accuracy, efficiency, and longevity in aerospace applications.

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