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Fiber optic sensing technology for space propulsion system applications

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Abstract: A comprehensive review of the application status, key technical challenges, and future trends of fiber optic sensing technology applied in space propulsion systems is presented, exploring the feasibility and advantages of replacing traditional electronic sensors with fiber optic sensors in extreme space environments. The fundamental principles of fiber optic sensing technology are analyzed, especially focusing on the mathematical models and operational mechanisms of fiber Bragg grating (FBG) and Fabry-Pérot (F-P) cavity sensors. Furthermore, the latest experimental research and technical solutions are summarized in three typical application scenarios: dynamic strain measurement in cryogenic pipelines, design of intelligent propellant tanks, and temperature distribution monitoring of thermal protection materials in electric propulsion systems. Results demonstrate that packaged FBG sensors can effectively suppress spectral distortion at liquid nitrogen temperatures, enabling accurate strain measurement in small-diameter pipelines; fiber optic sensors embedded in carbon fiber composites can provide real-time structural health and leakage monitoring; and distributed optical frequency domain reflectometry (OFDR) systems can achieve millimeter-level spatial resolution for temperature field monitoring. The discussion identifies remaining technical bottlenecks such as environmental adaptability, packaging techniques, cross-sensitivity, and long-term stability. Future development should focus on integration with smart materials, quantum sensing, on-orbit maintenance, and data-driven decision-making to evolve fiber optic sensing from merely replacing traditional sensors towards enabling intelligent structural systems.

Key words: fiber optic sensing technology; space propulsion systems; structural health monitoring; embedded fiber optic sensors; space applications; propellant tanks

0 Introduction

In the development of spacecraft, propulsion systems have provided the necessary force for orbit change, attitude control, etc. Spacecraft propulsion systems primarily are based on reaction principle, expelling high-speed working fluids to generate thrust in the opposite direction, thereby achieving acceleration. This enables functions such as attitude control, spin control, momentum management, gyro unloading, and stage separation, which are essential for various missions in space[1]. In the design of propulsion systems, numerous sensors have been typically utilized to collect key data such as temperature and pressure in real time for data acquisition, fault warning, and orbit control. However, spacecraft often operates under extreme conditions characterized by high pressure, high temperature, vacuum, and strong radiation. Under these conditions, the performance of traditional sensors may degrade or even fail, affecting the accuracy and stability of measured data and, consequently, the overall operation of the propulsion system. Moreover, as space technology advances, there is an increasing demand for smarter and more autonomous sensors. Traditional sensors often lack sufficient intelligence and autonomy, making them unsuitable for future space propulsion tasks.

Since the late 1970s, when Hill et al. fabricated the first fiber Bragg grating (FBG) using standing wave method, fiber optic sensing technology has garnered significant interest owing to its small size, light weight, strong resistance to electromagnetic interference, reliable corrosion resistance, high sensitivity, wide dynamic range, and ease of networking[2]. Different types of fiber optic sensors can measure different parameters such as temperature, strain, pressure, and liquid level. Compared to traditional sensors, they offer significant advantages in space propulsion systems. However, limited by technical issues, fiber optic sensors have not yet been widely used in space propulsion systems. This study aims to systematically analyze the applications of fiber optic sensors in spacecraft propulsion systems, summarize their roles in pipeline, storage tank, and temperature measurements, and propose challenges and prospects for future applications, providing references for researchers in related fields.

1 Overview of space propulsion systems

1.1 Current status of space propulsion systems

Technologically, space propulsion systems can broadly be categorized into four types: chemical propulsion system, electric propulsion system, nuclear propulsion system, and new concept propulsion system, as shown in Fig. 1. Among them, the first two are relatively mature, while the latter two remain in the research phase and are far from practical engineering applications[3].

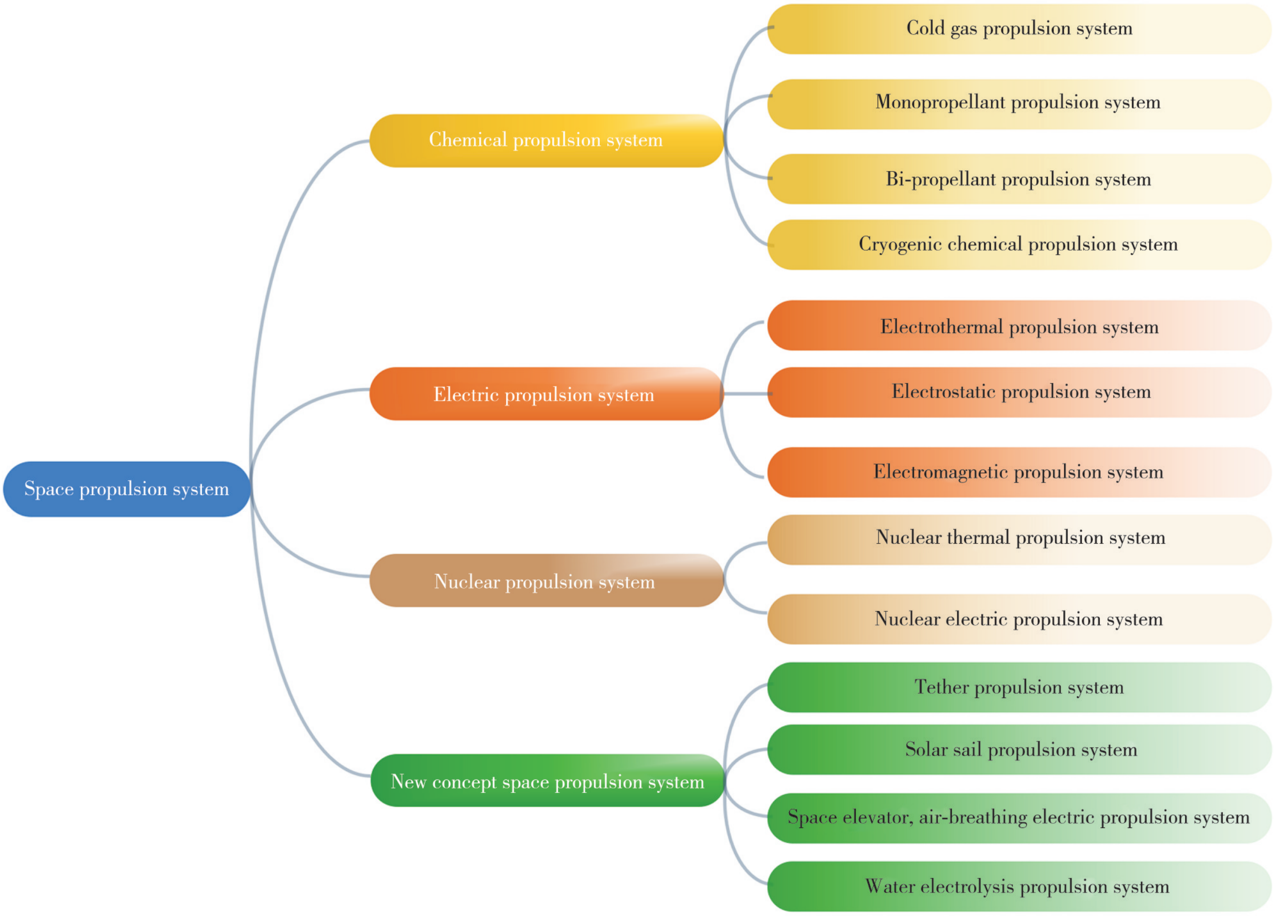

Fig. 1 Classification of space propulsion system

1.1.1 Chemical propulsion system

Chemical propulsion system uses the energy generated by chemical reaction to propel spacecrafts, which is one of the most widely used space propulsion systems today.

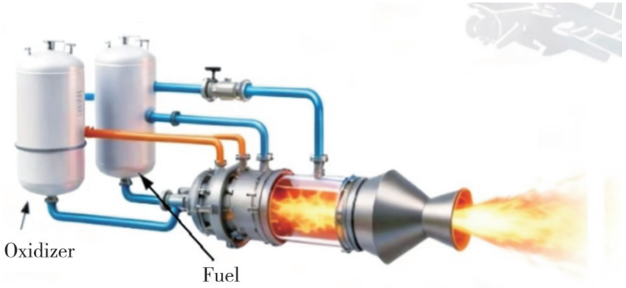

Fig. 2 Working principle of chemical propulsion system

As shown in Fig. 2, the principle involves burning propellants (fuel and oxidizer) to produce high-temperature, high-pressure gases, which are then expelled through a nozzle to generate thrust according to the Newton's third law.

This system can be further divided into conventional chemical propulsion system and cryogenic chemical propulsion system. The former includes cold gas propulsion system and mono/bi-propellant propulsion systems, with specific impulses ranging from 60 s to 335 s[4], which can offer high operational reliability and is commonly used for microsatellites, launch vehicles, and other spacecraft, whereas the latter is usually employed for rocket engines.

1) Cold gas propulsion system

This type of system uses compressed gases, such as ammonia, as propellants, generating thrust by releasing the gas. Although it has low specific impulse, the system is simple and reliable. Therefore, cold gas propulsion system is rarely used as the main propulsion system in long-life satellites but is commonly applied for high-precision control in microsatellites, for example, micro-Newtonian variable thrust cold gas propulsion system used on "Tianqin-1" satellite[5].

2) Monopropellant propulsion system

This type of system primarily uses single propellant, such as hydrazine compound. The propellant decomposes under the action of a catalyst to produce high-temperature gases, with a specific impulse of about 220 s. It offers a wide range of thrust and is commonly used for attitude control in launch vehicle upper stages, satellites, probes, and spacecraft.

3) Bi-propellant propulsion system

This type of system consists of fuel and oxidizer, which mix and combust to produce high-temperature, high-pressure gases. It offers a specific impulse approximately 1.5 times higher than that of monopropellant system and is widely used for major propulsion tasks such as interstellar flight, satellite orbit insertion, and orbital maintenance. For example, 750 N bi-propellant thrusters was utilized in the descent, hover, and soft landing phases of the Chang'e-3, Chang'e-4, and Chang'e-5 missions[6].

4) Cryogenic chemical propulsion system

This type of system utilizes cryogenic propellants like liquid hydrogen/liquid oxygen or liquid oxygen/methane. It offers high specific impulse and is non-toxic and environmentally friendly, significantly improving space propulsion system performance and reducing spacecraft size while enhancing maneuverability[7]. However, cryogenic propellants have low boiling points and are prone to evaporation. In space environments, spacecraft are affected by solar radiation, Earth albedo, infrared radiation, and internal heat sources, making cryogenic propellant storage challenging. Thus, this type of system is mainly used in launch vehicle's main engines and upper stages but less so in space vehicles.

1.1.2 Electric propulsion system

Electric propulsion system uses electrical energy to heat, ionize, or dissociate the propellant (working fluid) and accelerate it for thrust generation. It includes electrothermal, electrostatic, and electromagnetic propulsion systems, is characterized by long life and high thrust precision, and is suitable for tasks such as satellite orbit transfer, position keeping, drag compensation, attitude/orbit control, deorbiting, and deep space exploration[8].

1) Electrothermal propulsion system

This type of system uses electrical energy to heat the propellant, which is then accelerated through a Laval nozzle to generate thrust.

2) Electrostatic propulsion system

This type of system is divided into grid ion thruster and Hall effect thruster. The former accelerates ions using an electric field, offering high specific impulse and efficiency, which is suitable for deep space exploration. The latter uses a combination of magnetic and electric fields to accelerate ions, featuring high specific impulse and efficiency, which is widely applied in high-orbit communication satellites and deep space probes.

3) Electromagnetic propulsion system

This type of system, like magnetoplasmadynamic thruster (MPDT) and pulsed plasma thruster (PPT), uses electromagnetic force to accelerate working fluid.

1.1.3 Nuclear propulsion system

Nuclear propulsion system utilizes nuclear energy in space to generate thrust. The energy released per unit mass of fuel is much greater than that of chemical fuel, offering high thrust, high specific impulse, and multiple restart capabilities. This technology finds its primary applications in large spacecraft, long-distance deep space exploration, and Earth-Moon transport missions[9]. It can be classified into nuclear thermal propulsion and nuclear electric propulsion, with ongoing research into dual-mode nuclear electric propulsion. However, it faces significant technical challenges and stringent pollution prevention requirements, and has not yet achieved in-orbit applications.

1.1.4 New concept space propulsion system

New concept space propulsion system utilizes innovative propulsion methods still in the experimental stage with significant potential applications. Notable examples include electrodynamics tether propulsion system[10], solar sail propulsion system[11], space elevator[12], air-breathing electric propulsion system[13], and water electrolysis propulsion system[14].

1.2 Traditional detection techniques and limitations in space propulsion systems

Since chemical and electric propulsion systems are the most commonly used ones, we focus on them to introduce key inspection parameters and commonly used sensors.

In the chemical propulsion system, the core components are the propellant storage tank, fluid control system, and thruster system. Various traditional sensors, such as pressure sensors, temperature sensors, and flow sensors, are widely used to monitor critical parameters like propellant pressure, temperature, and flow rate, ensuring normal operation. However, traditional sensors face numerous challenges in harsh space environments. For instance, they may suffer from electromagnetic interference, leading to reduced measurement accuracy.

Additionally, they are bulky and heavy, adding to the spacecraft's burden. In the electric propulsion system, sensors are equally indispensable. It converts electrical energy into thrust, providing power for spacecraft. During this process, it is essential to monitor the stability of the power system, the electrode wear inside the thruster, and the accuracy of the control system. Therefore, various sensors, such as current and voltage sensors, are installed in the electric propulsion system. However, these sensors may encounter sealing issues in a vacuum environment, affecting their long-term reliability.

With the development of fiber optic sensing technology, its unique advantages have gradually found applications in space propulsion systems. Compared to traditional sensors, fiber optic sensors exhibit superior characteristics such as electromagnetic immunity, small size, lightweight, and low power consumption, making them particularly suitable for replacing traditional sensors in harsh space environments. Indeed, fiber optic sensors have already seen extensive research in space propulsion systems.

2 Fundamentals of fiber optic sensing technology

2.1 Basic principles of fiber optic sensors

Fiber optic sensing technology utilizes optical fibers as the media to transmit light signals from a light source to a modulator. Inside the modulator, light signals interact with external substances, causing changes in optical properties such as intensity, wavelength, frequency, phase, and polarization state. These modulated light signals are then transmitted back to a photodetector via optical fibers, converted into electrical signals, and demodulated to extract information about the measured parameters.

Throughout this process, optical fibers and their sensor components play crucial roles in signal transmission and external physical quantity perception, forming the key parts of fiber optic sensing. Unlike communication optical fibers used for long-distance transmission, to sensitively perceive external information, optical fibers' waveguide structures are often specially designed and processed into various high-precision fiber optic sensors [15].

2.2 Types of fiber optic sensor detection

Currently, primary detection parameters of fiber optic sensors in space propulsion systems include pressure, strain, temperature, real-time structural health, etc.

In the chemical propulsion system, pressure is a vital reference for determining whether the propulsion system can function normally. Additionally, health monitoring of propellants and storage tanks is critical. Fiber optic sensors such as FBG sensors and distributed fiber optic sensors can provide high-precision temperature measurement and real-time structural health monitoring[16-17]. These sensors detect potential leaks in storage tanks and enhance propellant measurement accuracy through temperature mapping. In the electric propulsion system, strain measurement of pipelines and temperature measurement of propellants and key components are crucial considerations for designers. Therefore, the application of fiber optic sensors is expanding. For instance, fiber optic sensors based on optical frequency domain reflectometry (OFDR) can monitor the temperature distribution of thermal protection materials in the electric propulsion system[18]. Such sensors offer millimeter-level spatial resolution, enabling precise monitoring of critical components in the electric propulsion system.

2.3 Mathematical models of fiber optic sensors

Fiber optic sensors rely on the interaction between light and external physical quantities, which can be realized through various optical structures. Below are two typical fiber optic sensor principles and mathematical models.

1) FBG

FBG achieves wavelength-selective reflection by periodically modulating the refractive index of the fiber core. When broadband light is incident, wavelengths satisfying the Bragg condition are reflected, while others are transmitted. Fig.3 shows the schematic diagram of an FBG.

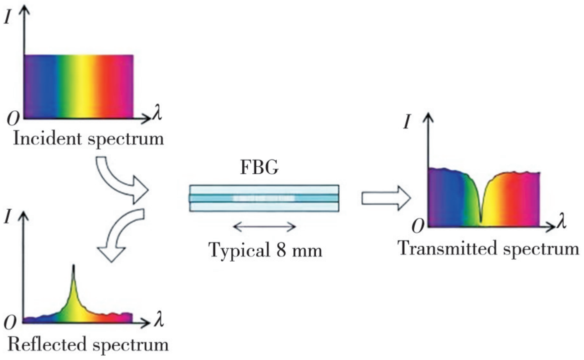

Fig. 3 Schematic diagram of an FBG

The Bragg wavelength is determined by

$$\lambda_B = 2n_{\mathrm{eff}}\Lambda, \tag{1}$$

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the fiber, and Λ is the grating period. External strain or temperature changes cause variations in n_{eff} and Λ, leading to a shift in λ_B. Therefore, by detecting the wavelength shift, the measured physical quantity can be inferred as

$$\frac{\Delta\lambda_B}{\lambda_B}=(1-p_e)\varepsilon+(\alpha+\zeta)\Delta T, \tag{2}$$

where p_e is photoelastic coefficients, ε is the strain coefficient, α is the thermal expansion coefficient, ΔT is the temperature, and ζ is the thermal optical coefficient. This equation explains how the Bragg wavelength varies with strain and temperature.

2) Fabry-Pérot (F-P) cavity sensor

An F-P cavity consists of two parallel high-reflective surfaces, where light undergoes multiple reflections within the cavity, forming interference. The resonant wavelength (or interference peak) in the output spectrum satisfies

$$m\lambda = 2nL\cos\theta, \tag{3}$$

where m is the interference order, n is the refractive index of the medium in the cavity, L is the cavity length, and θ is the incidence angle. Changes in external pressure or temperature alter the cavity length or refractive index, causing the interference peaks to shift. The sensitivity of F-P cavities can be enhanced by optimizing the cavity length and reflective surface materials, making them suitable for high-precision pressure and acoustic wave testing[19].

2.4 Performance characteristics of fiber optic sensors

Due to the high frequency and short wavelength of light, fiber optic sensors can achieve higher measurement accuracy and faster response to capture subtle environmental changes compared to traditional sensors, demonstrating higher sensitivity.

Additionally, because light propagation is unaffected by electromagnetic waves, fiber optic sensors remain stable and accurate in high-electromagnetic-interference environments, offering better adaptability than traditional sensors.

Moreover, fiber optic sensors possess strong multiplexing capabilities. allowing multiple sensors to be integrated on a single optical fiber for multi-point distributed measurements. This capability enables simultaneous monitoring of changes in different locations and parameters, providing better measurement efficiency and accuracy compared to traditional sensors.

Thanks to the high precision and sensitivity of fiber optic sensors, they hold broad application prospects in space, addressing many issues that traditional sensors cannot handle.

3 Application cases of fiber optic sensors in space propulsion systems

Optic fiber sensing technology has demonstrated application potential in multiple critical components of space propulsion systems owing to its unique advantages. To clearly outline the current status of its applications, Table 1 summarizes key information from several typical scenarios. Subsequent sections will provide detailed discussions on these applications.

Table 1 Typical application cases of fiber optic sensing in space propulsion system

Application scenarios	Core sensing technology	Key measured parameters
Dynamic strain measurement of cryogenic pipelines	FBG	Dynamic strain and vibration
Intelligent propellant tank	Embedded fiber optic sensor	Fluid leakage and structural health
Thermal protection monitoring in electric propulsion system	OFDR	Temperature field distribution and thermal gradient

3.1 Dynamic strain measurement of cryogenic pipelines

Dynamic strain measurement of cryogenic pipelines is crucial for ensuring the safe operation of space propulsion systems. Pipeline vibration-induced defects pose a significant threat to rocket engine safety, making dynamic strain measurement essential for analyzing and mitigating engine pipeline vibration problems[20]. Fiber optic sensors, especially FBG sensors, excel in this area owing to their wide operating temperature range, high stability, small size, light weight, ease of multi-point quasi-distributed measurement, inherent safety, and electromagnetic interference resistance.

Currently, encapsulating FBGs into metal-based substrates is a common method to suppress spectral distortion in FBGs[21], but this approach requires the measured structure to be locally planar, limiting its applicability to small-diameter, complex-shaped engine pipelines. For cryogenic environments, researchers have tested methods such as straight specimen stretching of FBGs with overall adhesive bonding, stretching and bonding only the sides of the FBG, and stretching the FBG inside a capillary tube followed by overall adhesive bonding[22] to inhibit spectral distortion at liquid nitrogen temperatures. However, these methods' effectiveness in suppressing spectral distortion and achieving accurate strain measurement in cryogenic, small-diameter pipelines remains to be verified. To address dynamic strain measurement in cryogenic small-diameter pipelines of engines, researchers conducted liquid nitrogen tests on stainless steel mock-up tubes using overall adhesive bonding of stretched FBGs, adhesive bonding only on the sides of stretched FBGs, and overall adhesive bonding of capillary-encapsulated stretched FBGs. They identified methods that effectively suppress spectral distortion and enable accurate strain measurement. Their results indicated that capillary-encapsulated stretched FBGs can effectively suppressed spectral distortion and achieve accurate strain measurement in cryogenic small-diameter (⩽30 mm) pipelines[23].

3.2 Design of intelligent propellant tank

Propellant tanks are critical components of propulsion systems, responsible for storing and supplying propellants for spacecraft liquid propulsion systems. These propellants are essential for spacecraft operations in space, speed control, attitude control, and orbit adjustment. Therefore, the design and manufacturing of spacecraft propellant tanks attract widespread attention in rocket propulsion and space structural engineering. The performance, reliability, and stability of propellant tanks significantly impact the efficiency and success of spacecraft missions.

As space technology advances, propellant tanks are continuously improved and innovated. For instance, using new lightweight materials and fiber optic sensing technology can reduce tank weight and improve structural efficiency. Carbon composite materials are emerging as the next-generation material for manufacturing spacecraft propellant tanks, offering low cost and light weight. Currently, the European Space Agency has signed contracts with several European entities to develop the “Black Stage” launch phase for the Ariane 6 launch vehicle[24-25].

Additionally, as space missions evolve, intelligence has become a focus in spacecraft design. Propellant tanks, especially those with operational control, condition monitoring, and health detection features, are evolving into important and complex subsystems within propulsion systems and spacecraft structural systems[26].

Based on the idea of optimizing propellant tanks, Nosseir et al. developed an intelligent spacecraft propellant tank with embedded fiber optic sensors. This design discussed embedded optical fiber sensors in carbon fiber composite materials, proposing optimal fiber optic sensors embedding methods for composite pressure vessels and discussing relevant placement and positioning methods for the sensors. The cross-section view is shown in Fig.4.

Experimental comparisons showed that, compared to traditional electronic sensors, embedded fiber optic sensors in carbon fiber structures provided accurate real-time measurement data and monitored structural integrity under harsh conditions. Furthermore, Nosseir suggested that this fiber optic sensing application could extend to detecting fluid leaks and temperature mapping, providing precise measurements for ground qualification, pre-flight testing, and in-orbit operation condition and structural health monitoring[17].

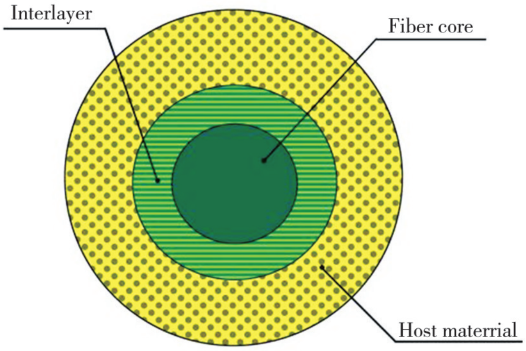

Fig. 4 Cross-section view of embedded fiber optic sensors model

3.3 Temperature distribution monitoring of thermal protection materials in electric propulsion system

Thermal protection systems are among the most critical technologies for ensuring the safe service of space vehicles in extreme high-temperature environments[27]. Spacecraft operating in space are exposed to thermal effects from solar radiation and heat from their own engines. Therefore, effective thermal protection must be implemented in the design of spacecraft propulsion systems to prevent heat conduction. Traditional sensors are highly restricted in monitoring systems due to the harsh space environment, including vacuum, high radiation, and temperature differences. Researchers have developed a high-spatial-resolution distributed OFDR demodulation system to analyze high-density weak reflection FBG sensors and reference light interference signals in thermal protection materials, obtaining position and spectral information of fiber optic sensors for high-spatial-resolution distributed temperature measurements[18].

Researchers conducted heating experiments on integrated high-density weak reflection fiber sensors in thermal protection samples to obtain temperature distributions in the gradient direction under single-sided heating.

Their experiments demonstrated that the OFDR fiber sensing demodulation system and the integrated high-density weak reflection FBG sensors could achieve distributed temperature measurements at the bottom, middle, and top layers of thermal protection samples. Compared to traditional point sensors, this system provides richer temperature information inside the sample, offering an effective means for monitoring thermal protection structure responses, reconstructing temperature fields, and evaluating performance.

4 Challenges and prospects

4.1 Technical challenges

Despite the potential of fiber optic sensing technology in space propulsion systems, several technical challenges remain:

1) Environmental adaptability

Spacecraft experience complex space environments during launch, orbit change, docking, and in-orbit operation, including space radiation, micrometeoroid and space debris impacts, aerodynamic heating, and thermal cycling. These factors can cause structural deformation, fatigue, and damage. Fiber optic sensors need to reliably operate in these extreme environments over long periods.

2) Sensor deployment methods

Key challenges in structural health monitoring applications include reliable sensor deployment, impact on structural performance, and measurement accuracy and durability after deployment. Current deployment methods include adhesion, welding, and embedding, each with drawbacks. Adhesive deployment can easily break or peel off in harsh environments, welding increases onboard system weight and creates stress concentrations and high residual stresses, while embedding affects the mechanical properties and fatigue life of composite materials.

3) Fiber coatings and adhesives

Existing fiber coatings primarily use plastic materials like acrylate or polyimide, which do not adequately protect fibers in complex environments, with temperature resistance generally below 400 ℃. The performance of chemical adhesives is crucial for the performance of adhesively deployed fibers. Existing epoxy adhesives perform poorly in complex environments, especially at high temperatures.

4) Cross-sensitivity issues

Fiber optic sensors often face cross-sensitivity issues between strain and temperature. For example, the wavelength shift of FBGs is influenced by both strain and temperature, requiring decoupling techniques such as using a reference grating (isolated from strain) for temperature compensation or employing auxiliary temperature sensors. Additionally, multi-physics coupling effects in complex loading environments (e.g. vibration and thermal cycling) may lead to signal distortion, necessitating adaptive demodulation algorithms.

5) Long-term stability and lifetime assessment

Space propulsion systems can have mission cycles lasting decades, and the degradation mechanisms of fiber optic sensors under prolonged irradiation and thermal cycling are unclear. Studies show that polyimide coatings become brittle after exceeding a certain cumulative radiation dose, increasing the risk of fiber breaks. Accelerated aging models need to be established to quantify sensor lifespan and reliability.

6) High-density integration and signal crosstalk

The spatial resolution of distributed fiber optic sensing systems (e.g., OFDR) is limited by pulse width and detection bandwidth. When sensor density exceeds 10^4 per kilometer, adjacent sensor reflection signals may overlap, leading to positioning errors. Machine learning algorithms can optimize signal separation, or new coding grating technologies can be developed.

7) In-depth analysis of domestic-foreign technology gap

The core disparities lie in engineering ecosystem, systemic integration, and application philosophy. Domestic technologies are trapped in a vicious cycle: lack of in-orbit validation hinders adoption, and lack of adoption prevents maturity advancement. Research remains fragmented without end-to-end standards or core component sovereignty. Applications are still limited to replacing traditional sensors, failing to evolve into critical functional elements for smart structures, risking missed opportunities in the next-generation technological paradigm.

Additionally, comparing the status of fiber optic sensing research domestically and internationally, it is evident that foreign countries have applied fiber optic sensing technology to various spacecraft structures, including manned cabins, thermal protection systems, and launch vehicles. Domestic research mainly focuses on basic theory and is primarily applied in civil sectors such as construction, power, oil, and steel. space applications are just beginning, with the first in-orbit application occurring in 2016[29]. From an application depth perspective, foreign countries have used fiber optic sensing technology for critical tests on some spacecraft, forming specialized service capabilities. China needs further exploration in this area. In terms of measurement accuracy, range, and density, existing domestic fiber optic sensing systems lag behind those of National Aeronautics and Space Administration (NASA) and other international counterparts[30].

4.2 Application prospects

Fiber optic sensing technology, as a novel sensor technology not yet widely applied in spacecraft propulsion systems, holds significant potential values primarily in the following areas:

1) Real-time monitoring and early diagnosis

Fiber optic sensors can achieve real-time monitoring of critical parameters in spacecraft propulsion systems, such as temperature, pressure, and strain, enabling early detection of structural damage and leakage issues[31]. This real-time monitoring capability helps enhance the performance and reliability of spacecraft propulsion systems.

2) Improved response speed and reliability

Fiber optic sensors offer high precision, rapid response, and electromagnetic interference resistance, making them widely used in spacecraft health monitoring[32]. These characteristics are crucial for improving the performance of spacecraft propulsion systems.

3) Reduced testing time and costs

Using fiber optic sensing data to monitor structural health reduces testing time and costs, lowering maintenance expenses for spacecraft structures. This enhances efficiency and reduces overall operational costs.

4) Micro-thrust and high-power Hall thruster lifespan detection

Large Hall thrusters used in electric propulsion systems face high costs and long testing cycles due to their size and high gas propellant flow rates. Fiber optic sensing technology can potentially address these issues.

5) Smart materials and self-healing technology

Combining fiber optic sensors with shape memory alloys and self-healing polymers can create propulsion systems with environmental adaptability. For instance, when micro-cracks are detected in tanks, self-healing materials can fill the damaged areas, with fiber optics monitoring the repair process in real-time, forming a closed-loop health management system.

6) Quantum fiber optic sensing technology

Quantum entangled and squeezed-state fiber sensors can surpass classical sensing sensitivity limits. For example, quantum-enhanced FBGs offer extremely high strain detection sensitivity, suitable for high-precision vibration monitoring of micro-thrusters.

7) On-orbit maintenance and data-driven decision-making

Combined with on-board edge computing, fiber optic sensing data can be analyzed in real-time to trigger autonomous control strategies. For example, when abnormal temperatures occur in electric propulsion systems, automatic adjustments can be made to power output or backup modules can be switched, reducing delays in ground intervention.

Furthermore, considering the development of fiber optic sensing technology and the tasks of space propulsion systems, the future trends of fiber optic sensing technology in space propulsion systems include large-scale, high-density, high-precision, multi-parameter systems, and the application of intelligent structures and materials, ensuring that future fiber sensors provide more detailed data to support complex analysis and decision-making.

5 Conclusions

5.1 Summary

To date, fiber optic sensor technology has played an indispensable role in various critical components of space propulsion systems, including engines, propellant tanks, and valves. Compared to traditional electronic sensors, fiber optic sensors exhibit superior performance and reliability in harsh environments, with smaller size, weight, and power consumption. However, the application of fiber optic sensing technology in space propulsion systems is not yet mature, remaining largely in conceptual and ground test stages, with only a few successful in-orbit experiments providing objective and effective experimental data, like NASA, European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA) have successfully demonstrated this technology in various flight missions, monitoring structures in crewed capsules, cryogenic tanks, and thermal protection systems. These on-orbit experiments are crucial for raising the technology readiness level, proving its reliability in the actual space environment, and paving the way for its future widespread adoption in propulsion systems.

5.2 Recommendations

For the future direction of fiber optic sensor applications in space propulsion systems, more attention should be paid to fiber optic sensing technology in flight vehicle and launch vehicle propulsion systems. By leveraging similar propulsion system fiber sensors, such as flight vehicle deformation monitoring systems, leak detection technology for pipelines, and strain detection technology for rocket engines, more targeted research can be conducted on how these technologies can be adjusted for use in space propulsion systems.

Additionally, further research should be conducted on fiber optic sensor packaging technology. Given the small and fragile nature of fiber optic sensors, especially their poor shear resistance, directly attaching them to propulsion system structures for measurement in complex and harsh environments poses reliability and safety concerns. Therefore, packaging technologies tailored to the structures of space propulsion systems should be developed.

Specifically, packaging technologies for spacecraft propulsion systems must account for their uniquely harsh environments:

1) Extreme vibration and shock loads during launch require packaging structures with higher mechanical robustness, whereas aircraft primarily face aerodynamic loads and fatigue.

2) The wide temperature fluctuations in orbit (ranging from −100 ℃ to over 100 ℃) and high vacuum conditions impose far greater demands on the packaging materials' thermal fatigue resistance and outgassing characteristics compared to aircraft cruise environments.

3) Long-term exposure to space radiation necessitates packaging materials with radiation resistance.

Consequently, directly transferring mature bonding or embedding techniques from the aviation sector often falls short. Targeted solutions must be developed, such as specialized packaging based on high-temperature metal welding or ceramic matrix composites, to ensure sensor survivability and signal stability under extreme conditions. This translational research is crucial for realizing the reliable application of fiber optic sensing in space propulsion systems.

Finally, it is important not to overlook the gaps and differences in the development of fiber optic sensing technology between domestic and international efforts. Efforts should be strengthened in fiber optic sensing technology research, standardization of fiber optic sensing technology, and active international cooperation to stay abreast of the latest developments in fiber optic sensors.

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Declaration of conflicting interests

The authors declare that they have no competing interests.

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面向空间推进系统应用的光纤传感技术

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摘　要：系统地综述了光纤传感技术在空间推进系统中的应用现状、关键技术挑战及未来发展趋势，旨在探究光纤传感器在极端航天环境中替代传统电子传感器的可行性与优势。方法上，分析了光纤传感的基本原理，重点介绍了光纤布拉格光栅（Fiber Bragg grating，FBG）和法布里-珀罗（Fabry-Pérot，F-P）腔传感器的数学模型与工作机制，并围绕低温管路动态应变测量、智能推进剂储罐设计与电推进系统热防护材料温度分布监测三个典型应用场景，综述了国内外最新实验研究与技术方案。结果表明，封装后的FBG传感器可在液氮温度下有效抑制光谱畸变，实现小口径管路的精确应变测量；嵌入碳纤维复合材料的光纤传感器可实时监测结构健康与泄漏情况；基于光学频域反射（Optical frequency domain reflectometry，OFDR）的分布式光纤传感系统可实现毫米级空间分辨率的温度场监测。讨论部分指出，光纤传感技术在空间应用中仍面临环境适应性、封装工艺、交叉敏感、长期稳定性等技术瓶颈，未来发展应聚焦于智能材料集成、量子传感、在轨维护与数据驱动决策等方向，推动光纤传感从“替代传统传感器”向“构建智能结构”转变。

关键词：光纤传感技术；空间推进系统；结构健康检测；嵌入式光纤传感器；航天应用；推进剂储罐

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