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Research Progress in Aero-Engine Gas-Path Electrostatic Monitoring Technology

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Abstract

Gas-path electrostatic monitoring for aero-engines provides a new source of information for early fault detection and health management by sensing charged particles generated during fault evolution. This paper reviews the development of gas-path electrostatic monitoring technology, including particle charging and electrostatic induction mechanisms, sensor design, weak-signal denoising, feature extraction, health baseline modeling, and sensor-array-based inversion. Its applications to rub-impact, ablation, carbon deposition, oil leakage, and foreign object monitoring are also discussed. Key challenges are further summarized, including quantitative characterization of fault severity, particle-cloud inversion, dynamic baseline construction, scarcity of real fault samples, standardization, and airworthiness validation. Finally, future research directions are outlined, with emphasis on multiphysics modeling, intelligent sensing, multisource information fusion, and remaining useful life prediction.

Keywords

Electrostatic Monitoring Technology; Aero-engine; Electrostatic Sensor; Electrostatic Signal.

1. Introduction

The gas-path system of an aero-engine consists of core components including the inlet, compressor, combustor, turbine, and exhaust system, and operates for long periods under high-temperature, high-pressure, high-speed, and severe-vibration conditions. Compressor and turbine blade rubbing, foreign object ingestion, blade ablation and material loss, combustor carbon deposition and ablation, oil leakage, and progressive performance degradation can all lead to abnormal gas-path conditions. In modern aero-engine Prognostics and Health Management (PHM) systems, condition monitoring lies at the very front of the information chain, and its sensing capability largely determines the upper limit of subsequent fault diagnosis, health assessment, and remaining useful life prediction [1-4].

Traditional aero-engine gas-path condition monitoring relies mainly on parameters such as pressure, temperature, rotational speed, fuel flow, and vibration. These parameters provide good monitoring capability for evident overall performance degradation, but most of them represent the "secondary effects" of faults: significant changes in conventional parameters usually occur only after local damage has developed sufficiently to affect the overall thermodynamic performance or rotor dynamic characteristics. All three review studies attribute the principal advantage of gas-path electrostatic monitoring to its ability to detect charged particles generated directly during fault processes and thereby obtain earlier fault information. Wen et al. particularly emphasized that an important distinction between electrostatic monitoring and methods based on temperature or vibration is that the former detects direct products of a fault rather than secondary responses caused by the fault.

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The basic concept of gas-path electrostatic monitoring is as follows. Under a given operating condition, ions and soot particles produced by combustion, together with environmental particles, form a relatively stable electrostatic background in a healthy engine gas path. When rubbing, ablation, material shedding, or abnormal combustion occurs, additional abnormal particles with different quantities, sizes, materials, and charge levels are generated, thereby changing the overall electrostatic level in the inlet or exhaust. Through electrostatic induction, an electrostatic sensor converts electric-field variations caused by moving charged particles into charge or voltage signals. Features such as activity level, event rate, root mean square (RMS), kurtosis, spectrum, energy, and entropy are then used to identify abnormal particles and engine states.

Therefore, the real significance of gas-path electrostatic monitoring is not simply to add another engine sensing parameter, but to establish a new information source that is directly associated with material-damage products. It can complement conventional gas-path parameters in monitoring local mechanical damage and early hot-section faults, and may enable a transition from "abnormality identification after a fault occurs" to "early-sign detection-fault progression tracking-health assessment-degradation prediction." Hu Yu et al. summarized the field into three key technologies: electrostatic sensors, signal acquisition/processing and feature extraction, and electrostatic monitoring experiments, and pointed out that the ultimate objectives should be online condition assessment, fault early warning, and life prediction.

2. Principles of Gas-Path Electrostatic Monitoring Technology

2.1 Sources of Charged Particles in the Gas Path

Charged matter in an aero-engine gas path can be divided mainly into three categories. The first consists of ions and electrons generated by chemical ionization during combustion. Under high-temperature combustion conditions, reactive species such as CH, CHO, H_3O^+, and NO^+, together with free electrons, form the basic charged environment [23-27]. The second category comprises soot particles generated by incomplete fuel combustion. Soot is formed through complex processes including nucleation, surface growth, coagulation, and oxidation, and its particle size, concentration, and charge polarity are affected by fuel properties, air-fuel ratio, temperature, and combustion efficiency [28-30]. The third category consists of abnormal debris generated by rubbing, ablation, corrosion, or material shedding of gas-path components. Such debris is generally much larger than primary soot particles produced during normal combustion and can generate pronounced transient electrostatic pulses.

Early studies once attributed enhanced electrical activity in engine exhaust plumes to Trichel pulses or high-potential charge clouds [5-10]. As engine experiments by Dunn, Mitchell, Couch, Powrie, and others accumulated, researchers gradually recognized that large amounts of charged debris produced by component rubbing and ablation constitute an important physical source of increased electrical activity during abnormal engine operation [8-18]. The development histories summarized in the three reviews are broadly consistent: in the 1970s, the Air Force Institute of Technology (AFIT) first observed abnormal electrical activity in engine exhaust before failure; this work subsequently led to the Engine Distress Monitoring System (EDMS) and the Ingested Debris Monitoring System (IDMS), which were eventually incorporated into engine PHM systems.

2.2 Particle Charging Mechanisms

It should be emphasized that the "presence of abnormal particles" is not equivalent to saying that the "charge measured by a sensor directly represents fault severity." During particle generation, transport, and interaction with wall surfaces, particles undergo complex processes including contact electrification, triboelectric charging, electron transfer, ion transfer, material transfer, and discharge. Wen et al. pointed out that, after large particles re-impact internal engine surfaces, they may become further charged, discharge, or even undergo charge-polarity reversal.

Recent fundamental studies of triboelectric charging have further demonstrated that this problem is much more complex than can be explained by the conventional "triboelectric series." Lacks and Shinbrot noted that several long-standing fundamental issues in contact electrification remain unresolved [31]. Baytekin et al. found that surface material transfer can cause polarity reversal in contact charging [32]. Pandey et al. further established a correlation between the amount of material transfer and charge transfer [33], while Vasandani et al. demonstrated that contact load also affects the transferred charge [34]. These findings have direct implications for aero-engine gas-path electrostatic monitoring: before particles generated at a fault source reach an exhaust-nozzle sensor, their charge may already have been reshaped by repeated impacts along the flow path and by the high-temperature environment. Future research therefore needs to establish a full-process mechanism linking "fault damage-particle generation-charge evolution along the flow path-sensor response," rather than directly inferring fault severity solely from the charge amplitude measured at the exhaust nozzle.

2.3 Electrostatic Induction and Signal Acquisition/Processing

An electrostatic sensor is essentially a passive induction sensor. When a charged particle enters the sensing region, its external electric field causes free charges in the conductive sensing electrode to redistribute, producing an induced charge that varies with particle motion. After the particle leaves the sensing region, the electrode gradually returns to electrical equilibrium, and a corresponding voltage pulse can be obtained through a front-end charge amplifier. A complete system generally includes an induction electrode, a low-noise preamplifier, a filter, an A/D conversion module, a data acquisition and storage unit, and subsequent diagnostic algorithms.

The sensor output is not a simple linear representation of particle charge. The particle charge level, radial position, axial distance, velocity, sensor dimensions, dielectric-layer thickness and permittivity, duct structure, and frequency characteristics of the preamplifier can all alter the induced waveform. Finite-element studies summarized by Wen et al. show that induction sensitivity decreases as the particle moves farther from the sensing electrode; increasing electrode size and dielectric permittivity helps enlarge the sensing range, whereas increasing insulation-layer thickness generally reduces sensitivity. The sensor itself is therefore an indispensable part of the quantitative modeling of gas-path electrostatic monitoring.

3. Development of Research in China and Abroad

3.1 International Research: From Anomaly Discovery to PHM Integration

International research can be roughly divided into three stages. The first stage, in the 1970s, focused on phenomenon discovery and feasibility studies. Couch, Rossbach, and others first used electrostatic probes to investigate engine performance and incipient failure [5-6]. Mitchell, Dunn, and Gifford further revealed the connection between abnormal charged particles and engine faults through simulated micro-damage, rubbing, and ablation experiments [7-9]. In his classic 1978 study, Couch used exhaust electrostatic pulses to detect abnormal turbine-engine deterioration [10]. All three reviews regard this work as an important milestone in the transition of gas-path electrostatic monitoring from phenomenological research to fault detection.

The second stage, from the 1990s to the early 21st century, was characterized by systematic development. Cartwright and Fisher applied gas-path electrostatic techniques to marine gas turbines and promoted the formation of the IDMS/EDMS concepts [11]. Powrie and McNicholas validated EDMS through accelerated-mission testing and developed features such as activity level, event rate, and shaft order [12]. Powrie, Fisher, and others further incorporated electrostatic monitoring into Total Prognostics and PHM frameworks [13-17]. Lapini et al. and Wilcox et al. extended the application to large industrial gas turbines, confirming that exhaust electrostatic-charge monitoring is applicable not only to aero-engines but also to early anomaly detection in gas turbines [18-20,22].

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The third stage involves system integration and application to operational equipment. Around 2006, Novis and Powrie publicly discussed the engineering implementation of electrostatic PHM sensors and reported the integration of Gas Path Debris Monitoring into the F-35 propulsion system [4,21]. The review by Wen et al. considers this stage to mark the transition of electrostatic monitoring from laboratory/test-rig research to deployment in real PHM systems. This remains an important engineering objective that domestic research is continuing to pursue.

3.2 Early Research in China: Principles, Sensors, and Simulation Experiments

Continuous research on aero-engine gas-path electrostatic monitoring in China began to emerge around the late 2000s. Wen Zhenhua, Zuo Hongfu, and colleagues conducted systematic work on the principles of gas-path particle electrostatic monitoring, finite-element sensor models, signal processing, and simulation experiments [35-37], and published a study on electrostatic monitoring of aero-engine gas-path debris in IEEE Transactions on Reliability in 2011 [41]. The central questions addressed at this stage were "whether the particles can be detected" and "what types of signals can reflect abnormal particles."

Li Yaohua and colleagues subsequently conducted studies using simulated particles and real engines, demonstrating that different materials, particle sizes, concentrations, and combustion backgrounds produce different electrostatic responses. They also performed rubbing-fault simulations and long-duration tests on turboshaft engines [38-40]. These efforts enabled domestic research to progress from laboratory pipelines to actual engine test rigs. Sun Jianzhong et al. further used data from real turboshaft engines to investigate the effects of operating condition and health state on the Exhaust Gas Electrostatic Monitoring Signal (EGEMS). They found that fuel flow and engine operating condition are important influencing factors over short time scales, whereas electrostatic parameters over longer time scales can reflect gradual performance degradation [42]. A health baseline for exhaust electrostatic signals was subsequently established, using electrostatic parameters under normal operating conditions as references for anomaly detection [44]. The research focus thus began to shift from "fault-signal identification" toward "normal-background modeling and anomaly-deviation detection."

3.3 Fault Validation and Health Assessment

Liu Pengpeng and colleagues investigated faults in turbojet engines including oil leakage, abnormal exhaust conditions, rubbing, and combustor carbon deposition [43,45-49]. In particular, combustor carbon-deposition experiments showed that features such as RMS and kurtosis can respond to combustion abnormalities [49]. Related studies further developed the concept of multi-condition adaptive electrostatic health baselines: a single fixed threshold should not be applied to all operating states; instead, the reference should be dynamically adjusted according to operating condition, individual engine, and historical state. On this basis, Yin Yibing, Fu Yu, and others expanded the analysis from individual statistical parameters to permutation entropy, energy-domain features, sparse decomposition, machine learning, and multi-source information fusion [52,58,61-66]. Of particular note, the fusion of electrostatic signals with conventional gas-path performance parameters for health assessment enabled electrostatic information to enter integrated engine-performance assessment models in a more systematic manner, rather than serving merely as an alarm variable. In its 2017 review, Wen et al. made an important judgment: for gas-path electrostatic monitoring to truly enter PHM, it is necessary not only to improve sensors but also to address dynamic baselines, information fusion with FADEC and other sensors, electrostatic-information-based life prediction, and system cost-effectiveness evaluation. This judgment remains essentially valid today.

3.4 Sensor Arrays and Quantitative Inversion of Particle Information

The greatest theoretical limitation of a single sensor is the "position-charge coupling" effect. The same charged particle produces a relatively large amplitude when passing close to the sensing electrode but a weaker signal when traveling near the duct center or farther away from the electrode. Therefore, observing a low-amplitude pulse does not allow one to determine directly whether it results

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from a "particle carrying a small charge" or a "particle carrying a large charge but passing at a greater distance." This is one of the main reasons why conventional electrostatic monitoring is difficult to quantify and is prone to threshold uncertainty.

To address this issue, research has gradually evolved from single-electrode sensing to annular, hemispherical, planar-array, and multi-electrode sensing configurations [50-57,64,67-70]. Tang et al. used hemispherical electrostatic sensor arrays together with compressive sensing to reconstruct the number, charge, and spatial position of abnormal particles [57,64]. Guo et al. further employed Tikhonov regularization, compressive sensing, and cross-correlation algorithms to simultaneously estimate particle position, charge, and velocity. In the central region of an experimental duct, errors in position and charge estimation were both controlled at approximately 5%, whereas errors increased markedly near the duct wall. This result is important because it indicates that aero-engine electrostatic monitoring is evolving from "signal-feature monitoring" toward "inversion of the physical parameters of fault particles." In 2022, Guo et al. further developed an annular electrostatic-sensor model for foreign-object monitoring in engine inlets, using pulse amplitude and width to estimate the radial position, charge, velocity, and material category of foreign objects, with experimental errors controlled within approximately 10%. Such work allows IDMS to move beyond merely answering "whether a foreign object is present" and toward determining "where it is, how fast it enters, and how much charge it carries," which is of greater engineering value.

4. Research Progress in Online Gas-Path Electrostatic Monitoring Technology

4.1 Research on Electrostatic Sensor Design

Current gas-path electrostatic sensors mainly include annular, rod/probe-type, flat-plate, button-type, hemispherical, and array configurations. Annular sensors provide good coverage of the entire cross-section and cause relatively little disturbance to the flow field, making them suitable for engine inlets. Rod-type sensors are structurally simple, compact, and easy to install or retrofit, making them more suitable for exhaust nozzles; however, their sensitivity field is nonuniform and the electrode protrudes directly into the flow. Hemispherical and array designs attempt to strike a compromise between ease of installation and uniformity of the sensitivity field [50-57].

Hu Yu et al. pointed out that unified evaluation standards for sensitivity, bandwidth, spatial coverage, interference resistance, temperature tolerance, and installation compatibility are still lacking across different sensor types, while the intake and exhaust systems of different engine types differ significantly in cross-sectional dimensions, temperature, velocity, and flow pattern. Future sensor design therefore needs to move beyond simply pursuing "maximum sensitivity" toward multi-objective optimization of sensitivity uniformity, detection range, response bandwidth, high-temperature tolerance, flow disturbance, structural strength, and reliability.

Two notable new directions have emerged in recent years. The first is the use of arrays for spatial charge imaging and high-resolution local monitoring. For example, an electrostatic array developed by Tian et al. in 2024 can generate surface-charge distribution maps and correlate local charge with oxidized-wear regions, offering a new approach to high-spatial-resolution electrostatic sensing. The second is a transition from purely electric-field models toward multiphysics models of real engines. In 2024, Ali et al. established a multiphysics-coupled model accounting for random particle release, temperature-dependent charging, nonuniform particle trajectories, high-speed exhaust flow, and complex gas-path geometry, closely approaching the "gas-solid-electric" multiphysics coupling research need proposed by Hu Yu et al.

4.2 Denoising of Weak Electrostatic Signals

Gas-path electrostatic monitoring is a typical weak, nonstationary signal-detection problem. During engine testing, power-frequency interference, electromagnetic coupling, random white noise, vibration disturbance, and impulsive noise may all be present simultaneously. More importantly, transient pulses that would often be regarded as "abnormal spikes" in conventional signal processing

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may in electrostatic monitoring be precisely the critical valid signals generated by large fault debris. Therefore, denoising algorithms must satisfy the dual requirement of "reducing background noise" while "preserving transients from abnormal particles." Early studies used median filtering, wavelet thresholding, independent component analysis (ICA), empirical mode decomposition (EMD), and other methods [54-56,63]. Wen et al. argued that, because electrostatic signals are nonstationary, have continuous spectra, and depend on operating condition, methods based solely on fixed cutoff frequencies are unsuitable, whereas time-frequency and time-scale analyses have greater potential.

In recent years, this direction has clearly shifted toward adaptive methods. Zhong et al. used a nonlinear total-variation model in 2022 to process low-SNR electrostatic signals and demonstrated advantages in preserving pulse edges [73]. In 2024, Liu Yan et al. combined CEEMD, adaptive IMF selection, and wavelet-threshold denoising, focusing on improving the preservation of weak fault information under strong background noise [80]. Liu et al. further adopted CEEMDAN and adaptive low-pass screening to improve algorithm automation [78,79]. In 2026, Yan et al. combined ICEEMDAN, IMF correlation-based selection, and wavelet soft thresholding, and validated the approach using data from a real miniature turbojet engine. Their method suppressed random noise and power-frequency interference while enhancing the preservation of abnormal-particle pulses [82].

This evolution indicates that the objective of electrostatic-signal denoising has shifted from simply "making the curve smoother" to high-fidelity reconstruction oriented toward the preservation of physical fault information.

4.3 Development of Electrostatic Signal Characteristic Parameters

Activity Level (AL) and Event Rate (ER) are the two most classical features in electrostatic monitoring. AL represents the overall level of electrostatic activity within a given time window and more strongly reflects the baseline formed by normal soot and large quantities of fine particles. ER describes the proportion of high-charge events exceeding a specified threshold and is more responsive to large abnormal particles. By dividing the event rate into Positive Event Rate (PER) and Negative Event Rate (NER), information on particle-charge polarity can also be obtained.

As research has progressed, RMS, peak value, peak-to-peak value, kurtosis, skewness, waveform indices, permutation entropy, spectral entropy, frequency centroid, band energy, symbolic-dynamics features, and other parameters have been introduced [42-66]. Frequency-domain information is particularly noteworthy because electrostatic-pulse width and frequency structure are affected by particle velocity, while particles generated by rotor-stator rubbing may also carry information related to rotational speed and its harmonics. Wen et al. proposed the use of Shaft Order Analysis to determine whether particle generation is associated with the rotational speed of a particular rotor.

A 2025 study further identified a power-turbine rotational frequency of 170-180 Hz and its harmonics from electrostatic signals measured on a real turboshaft engine under multiple power conditions, indicating that electrostatic signals can not only reflect "particles" but can also provide rotational-speed sensing capability [81]. This creates new possibilities for integrating electrostatic sensors with conventional speed measurement, overspeed protection, and rotating-component fault-diagnosis functions.

The normal exhaust electrostatic level of an engine is not constant; it varies with fuel flow, rotational speed, thrust, environment, and engine health state. Consequently, a rule such as "trigger an alarm when a fixed voltage is exceeded" is difficult to apply under complex engine operating conditions. Sun Jianzhong et al. established baseline models for electrostatic signals [42,44], and Liu Pengpeng et al. further developed multi-condition and adaptive health baselines [43-49], gradually forming the concept of "first predicting the electrostatic level that should be observed in a healthy state, and then monitoring the deviation of the measured value from the health baseline."

This concept is more consistent with the PHM framework because it can distinguish normal operating-condition variations from genuine abnormalities. In 2024, Yin et al. proposed new features such as LECR and NECR based on exhaust electrostatic signals and combined electrostatic features

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with engine performance parameters as inputs to a Logistic Regression model to construct a Gas-Path Health Index. The results showed that adding electrostatic information enabled earlier indication of gas-path faults or performance degradation than using conventional performance parameters alone [76]. Electrostatic monitoring is therefore evolving from an "alarm sensor" toward a "health-state variable."

4.4 Expansion of Electrostatic Monitoring Targets

Early electrostatic experiments mainly focused on iron powder, graphite, soot, and metallic rubbing debris. However, as ceramic-matrix composites are increasingly used in the hot-section components of next-generation aero-engines, a feature database containing only metallic and carbonaceous particles is no longer sufficient. In 2024, Liu et al. conducted simulated experiments on SiC/SiC particles using a J20 miniature turbojet-engine platform and found that the particles maintained relatively stable positive polarity under different test conditions, while particle concentration, particle size, and exhaust velocity all affected the induction characteristics [77].

These studies indicate that future "fault-particle databases" must evolve in parallel with engine material systems. A lack of understanding of the charging behavior of new materials such as coatings, ceramic-matrix composites, sealing materials, and wear-resistant layers will directly limit the ability of electrostatic methods to identify faults in advanced aero-engines.

5. Challenges Facing Online Gas-Path Electrostatic Monitoring

First, a stable causal mapping has not yet been established between fault severity and the ultimately measured charge. Existing models generally calculate sensor responses starting from known charged particles, whereas the inverse problem that PHM truly needs to solve is to infer, from the signal measured at the exhaust nozzle, which stage and which component has suffered what type of damage and to what severity. This chain includes at least fault dynamics, material removal, particle-size distribution, initial charging, repeated particle-wall collisions, charge decay/enhancement, and sensor response. Research on these links is currently fragmented, and a complete physical chain has not yet been established. Second, particles in a real engine form a multiscale particle population, whereas most current quantitative models remain based on individual particles. Array technology has demonstrated that the charge, position, and velocity of a single particle can be inverted, but real exhaust simultaneously contains large quantities of nanoscale soot, environmental particles, and a small number of micron-scale fault debris. Recovering sparse fault-particle information from a strong background particle population is a key difficulty in moving from laboratory studies to real engines. Third, the nonuniform sensitivity field of sensors still introduces observational uncertainty. Array studies in 2021 showed that estimation errors are relatively low for particles in the central region of a cross-section but increase as particles approach the duct wall. This indicates that simply increasing the number of sensors cannot automatically solve all problems; array geometry, multi-section deployment, and the observability of inversion algorithms must also be studied jointly. Fourth, health baselines show clear dependence on engine type, individual engine, operating condition, and life-cycle stage. As early as 2017, Wen et al. explicitly identified baseline/threshold determination under different engines, operating environments, fuels, and maintenance states as a key issue and suggested that dynamic thresholds are more suitable for long-term use. Although adaptive baseline studies are now available, data support across engine types and at fleet scale remains insufficient. Fifth, the shortage of real fault samples remains a fundamental limitation of data-driven algorithms. Fault injection into engines is costly and risky, while naturally occurring faults are sporadic; therefore, many algorithms are still based mainly on simulated particles or laboratory test-rig data. Hu Yu et al. explicitly noted that domestic research remains weak in the accumulation of raw gas-path condition data from real engines, in understanding electrostatic variation patterns under different states, and in establishing baseline standards. Even with deep learning, the absence of engineering-representative real fault samples can lead to high laboratory accuracy but poor generalization to actual engines. Sixth, there is an inherent conflict between strong noise and transient fault pulses. Increasingly sophisticated denoising algorithms can significantly improve SNR, but if the optimization objective is limited to mean-square error or smoothness, fault-pulse amplitude, polarity, or pulse width may still be altered. Future algorithm evaluation should therefore include physical-feature preservation rate, event-detection rate, and consistency of diagnostic results, rather than relying only on conventional signal-quality metrics. Seventh, electrostatic monitoring still lacks unified standards and an airworthiness-validation framework. Different research teams use different sensor dimensions, preamplifier gains, sampling frequencies, installation locations, baseline definitions, and feature formulas, making data difficult to compare directly across engines and experiments. Liu Ruochen et al. have identified standardization as an important constraint on technological development. For aero-engines, this issue will ultimately extend to sensor fail-safety, electromagnetic compatibility, high-temperature service life, software trustworthiness, and airworthiness compliance.

Future development of aero-engine gas-path electrostatic monitoring should move beyond the currently fragmented areas of "sensor research, signal processing, and fault classification" toward a systematic health-management technology based on the physical processes of faults.

First, a multiphysics digital model should be established that links gas-path faults, particle generation, gas-solid two-phase flow, triboelectric charging, electrostatic fields, and sensor response. The gas-solid-electric multiphysics coupling concept proposed by Hu Yu et al. and the 2024 multiphysics model of Ali et al. have laid a foundation, but the next step is to genuinely incorporate blade-rubbing dynamics, material-shedding rates, and particle-generation models into coupled calculations. Second, research should move from quantitative inversion of single particles to sparse-information inversion of particle populations. Compressive sensing, regularization, and array methods have demonstrated the feasibility of recovering particle position and charge [64,69-74]. In the future, sparse Bayesian learning, spatiotemporal tracking, and multi-section arrays could be combined to improve observability under complex particle-population conditions while providing confidence intervals for parameter estimates. Third, miniaturized, high-temperature, and intelligent sensors should be developed. An ideal airborne electrostatic sensor must not only withstand high temperature, severe vibration, and contamination, but also integrate low-noise amplification, online self-test, temperature-drift compensation, health diagnostics, and automatic calibration, while addressing the limited sensing range in large-diameter exhaust nozzles. Fourth, dynamic health baselines should be established across engine types and throughout the full life cycle. The key is not simply to accumulate more data, but to explicitly incorporate thrust, rotational speed, fuel parameters, environment, individual-engine differences, maintenance events, and life-cycle stage into baseline models so that the definition of "abnormality" is physically and statistically consistent. Fifth, machine learning should be upgraded from a "fault classifier" to a diagnostic and prognostic model driven by physical information. The 2023 VMD-random-forest method [75] and the 2024 Logistic Regression health index [76] demonstrate that data-driven methods can effectively exploit electrostatic features. In the next stage, physics-constrained machine learning, transfer learning, unsupervised anomaly detection, and domain generalization deserve greater attention to mitigate the shortage of real fault samples. Sixth, the research objective should progress from "fault detection" to fault localization, severity assessment, progression trend estimation, and remaining useful life prediction. A true PHM application ultimately needs to answer when a fault will reach a maintenance threshold rather than simply providing a normal/abnormal label. Because electrostatic information is directly related to material loss, it offers a unique opportunity for constructing degradation-state indicators; however, mature models linking electrostatic parameters to remaining useful life are still lacking. Seventh, multi-source fusion among electrostatic signals, vibration, performance parameters, rotational speed, and blade-tip parameters should be strengthened. Wen et al. have long pointed out that the most appropriate role of electrostatic monitoring is not to replace conventional monitoring, but to serve as a new complementary information source integrated into FADEC/PHM systems. Future information fusion should evolve from simple feature concatenation toward hierarchical causal-fusion models based on the physical processes of different faults. Eighth, standardized testing and airworthiness evaluation systems should be established. Standards are needed for static/dynamic sensitivity calibration of sensors, standard particle sources, typical fault-simulation methods, data formats, calculation rules for features such as AL and ER, alarm-performance evaluation methods, and test-environment requirements. Further research should also assess the effects of airborne installation on engine safety and airworthiness compliance. The 2025 study of electrostatic sensors for overspeed monitoring has already begun to discuss function expansion from the perspective of airworthiness-safety requirements. This shift from "algorithmic feasibility" toward "airworthiness-requirement-driven" research deserves particular attention.

6. Conclusion

Over more than 50 years of research, aero-engine gas-path electrostatic monitoring has undergone a clear technological evolution. In the 1970s, the central question was "why engine faults are accompanied by increased electrical activity in the exhaust." From the 1990s through the 2000s, the focus shifted to "how electrostatic signals can be used for online early warning of faults." Research in China from approximately 2008 to 2018 mainly addressed "how to design sensors, process weak signals, establish health baselines, and validate the technology on real engines." Since 2018, attention has increasingly focused on "how to use sensor arrays and inverse-problem methods to quantitatively obtain particle charge, position, number, and velocity." Since 2021, research has advanced further into triboelectric-charging mechanisms, multiphysics modeling, intelligent denoising, health indices, and PHM integration. Related publications from 2024 to 2026 continue to deepen this trajectory.

Accordingly, the core issue that will truly constrain future breakthroughs in gas-path electrostatic monitoring is no longer "whether electrostatic signals can be detected," or even merely "whether a particular fault can be identified," but how to establish a complete, quantifiable, and verifiable relationship chain: gas-path component damage → abnormal particle generation → particle charging and charge transfer along the flow path → transport in high-temperature gas-solid two-phase flow → dynamic response of electrostatic sensors → inversion of particle information → fault localization and severity → health state → remaining useful life.

Within this chain, the first four links determine the physical interpretability of electrostatic signals; the sensor and inversion links determine observability and quantitative capability; and the final two links determine whether electrostatic monitoring can truly enter engine PHM and maintenance-decision systems. From the perspective of doctoral-research value, the most worthwhile future direction is not to continue adding isolated signal features, but to bridge the key gaps among "fault physics-electrostatic sensing-quantitative inversion-health management" around the complete chain described above.

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