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RESEARCH ARTICLE

Review on Compressor Surge Monitoring, Modeling, and Anti-Surge Control Approaches

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Abstract: Compressor surge is a major aerodynamic instability that constrains the performance and reliability of industrial gas turbines. To address this challenge, this paper provides a comprehensive review of recent progress in surge monitoring, modeling, and control strategies. Key difficulties in early surge detection are identified, including ambiguous precursor signals, strongly coupled system dynamics, and sensor-actuator time delays. The review categorizes existing modeling approaches into high-fidelity computational fluid dynamics (CFD), reduced-order physical models, and data-driven techniques, evaluating each in terms of accuracy, adaptability, and real-time feasibility. In terms of control strategies, both passive and active methods are analyzed, with a particular focus on closed-loop feedback, model predictive control, robust control, and intelligent data-driven approaches. The review concludes by outlining future directions that prioritize model integration, control reliability, and system-level coordination for enhanced compressor stability.

Keywords: compressor surge; intelligent control strategies; surge control; surge modeling

I. INTRODUCTION

Gas turbines are widely used as power generation equipment in the construction of fundamental energy infrastructure due to their high power-to-weight ratio, operational flexibility, and efficiency. Gas turbines are combined with five main components, including the inlet, compressor, combustion chamber, gas generator, and power turbine. The compressor can be further divided into axial and centrifugal types, depending on their internal structure. When a gas turbine enters a surge state under specific conditions, the mass flow and pressure at the compressor outlet exhibit significant low-frequency fluctuations, which in turn lead to a marked reduction in rotational speed and overall compression capability [1]. Surge not only signifies the loss of aerodynamic stability but also serves as a classic example of nonlinear dynamic in stability within the internal flow system of the engine.

This phenomenon is characterized by large-scale flow reversal, intense backflow through the compressor stages, and strong periodic oscillations in both pressure and velocity fields [2–4]. These behaviors not only disrupt the stable operation of the compressor and combustor but also impose cyclical mechanical and thermal loads on critical engine components. Consequently, the occurrence of a surge can accelerate material fatigue and wear, increase the risk of mechanical failure, and reduce the overall engine life and reliability. In severe cases, unmitigated surge events can propagate throughout the engine system, leading to flameout, thrust loss, and even structural damage. Therefore, understanding, modeling, and controlling compressor surge are crucial to developing high-performance, reliable gas turbine systems.

Compressor surge is a typical aerodynamic instability phenomenon, the essence of which is the instability of airflow. At the same time, the flow state of airflow also depends on the blade structure of the compressor. The compressor is composed of alternating rotors and stators. The rotor is mounted on a rotating shaft and accelerates the airflow through rotation to increase the kinetic energy of the air. The stator is fixed and its function is to guide the direction of the airflow and convert the kinetic energy into pressure, thereby achieving step-by-step compression of the air [5]. This structure enables the compressor to efficiently increase the air pressure in a limited space.

The schematic diagram of compressor airflow process is shown in Fig. 1.

To gain a deeper understanding of how energy is transferred within the compressor, it is necessary to analyze the velocity triangle at the blade element level [6]. Analyzing the velocity triangle also helps clarify the relationship between blade geometry, flow direction, and relative velocity, which are the key factors in understanding aerodynamic behavior and surge formation. The velocity triangle at the blade element level is illustrated in Fig. 2.

It is evident from that in the triangle, C represents the absolute velocity of the airflow, W is the velocity relative to the rotating blade, and U denotes the peripheral blade speed. The flow angles α and β indicate the directions of C and W, respectively. The change in the tangential component of absolute velocity, C_u is directly related to the work done by the rotor on the air.

From the perspective of the velocity triangle, the airflow entering the rotor must have an appropriate incidence angle relative to the blade leading edge to maintain efficient and stable operation. As the mass flow decreases, the axial velocity component of the incoming flow drops. However, the rotational velocity remains nearly constant. This change alters the relative flow angle, increasing the incidence angle at the rotor inlet. When the incidence angle exceeds a critical value, the airflow no longer follows the blade contour smoothly, which leads to boundary layer separation [7] and local flow reversal [8], and furthermore deteriorates the pressure rise capability of the compressor stage. If this condition persists or even intensifies across

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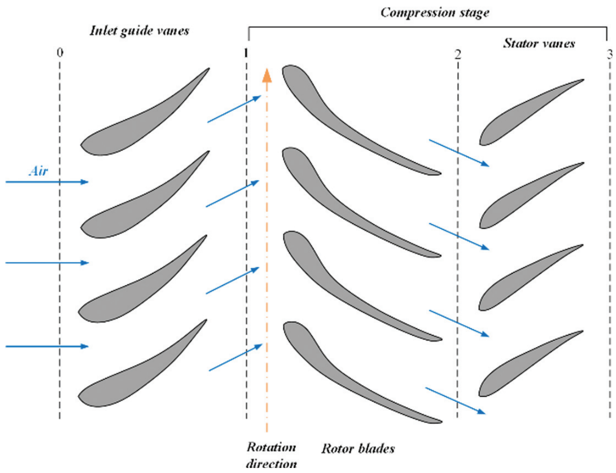

Fig. 1. Compressor airflow process.

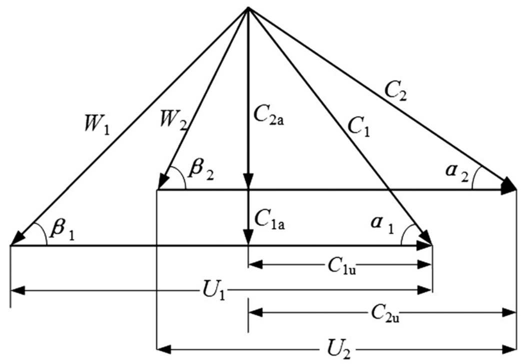

Fig. 2. Blade element level velocity triangle.

multiple stages, the compressor fails to push flow downstream, resulting in airflow to reverse, which then develops into surge.

II. RESEARCH STATUS OF SURGE MONITORING

Currently, compressor surge monitoring methods are, to some extent, focused on detecting precursor signals such as stall. Based on the type of signal, these methods can be broadly categorized into pressure-based, flow-based, vibration-based, and acoustic signal monitoring approaches. Importantly, the true purpose of surge monitoring lies not in detecting the surge event itself, but in identifying its precursors early enough to allow timely intervention, thus preventing the onset of surge and ensuring operational safety.

A. FLOW-BASED MONITORING

Flow-based surge monitoring techniques detect aerodynamic instability by directly measuring airflow or mass flow rate within the compressor. The most intuitive indicator of surge is a sudden reversal or sharp fluctuation of flow, which these methods attempt to capture by tracking instantaneous flow rates at key compressor locations such as the inlet, mid-stage, or outlet. Commonly used sensors include mass flow meters [9] and ultrasonic flow probes [10]. In laboratory settings, advanced visualization techniques like particle image velocimetry (PIV) have also been applied [11], though their practical use in aero-engine and industrial gas turbines remains limited. A major advantage of flow-based monitoring is its direct physical relevance to surge phenomena, which inherently involve breakdowns of stable flow. However, this approach faces significant challenges:

1) Sensor limitations: Accurate and high-speed flow measurement in the harsh compressor environment is technically demanding, especially under high-pressure and high-temperature conditions.
2) Installation constraints: Flow sensors often require intrusive installation or complex structural modifications, which hinder their deployment in real engines.

In order to address these limitations, researchers have explored indirect flow sensing techniques such as virtual sensing [12], where flow rates are inferred from other measurable parameters using computational models. As described in [13], surge and rotating stall behaviors were experimentally investigated in a single-stage axial compressor equipped with a downstream capacity tank and a tip-region jet injection system. By monitoring unsteady wall pressure and internal velocity fluctuations, the study identified various surge cycles influenced by system capacitance, throttling, and flow injection.

Furthermore, reference [14] analyzed spike-type stall inception in axial compressors, attributing its onset to tip-clearance backflow and tip-leakage spillage. Their work emphasized the need for stall control strategies that mitigate these tip-region flow interactions. In addition, reference [15] utilized full-annulus unsteady RANS simulations to investigate the surge process in an eight-stage high-speed axial compressor. The study showed that mid-stage stall initiates a surge, and identified several key unsteady features such as acoustic reflections during flow reversal, hot air re-inhalation, and multi-row rotating stall during recovery. It also demonstrated that single-passage models can provide useful approximations of the transient blade during surge cycles.

B. PRESSURE-BASED MONITORING

Pressure changes typically precede flow variations during compressor surge. To some extent, the change in total pressure of each section caused by a surge further leads to the change in flow; so, the change in pressure can reflect the state of surge. Pressure-based monitoring operates by capturing the fluctuations in total pressure at critical locations [16], such as the compressor inlet, outlet, or intermediate stages.

In practice, pressure sensors are installed to enable continuous monitoring [17] of the dynamic behavior of the compressor. Many researchers also investigate the mechanisms of stall and surge from the perspective of pressure variation, aiming to understand the underlying instability dynamics. One of the earlier studies was conducted by [18], who provided stall inception mechanisms in a low-speed axial compressor, focusing on two distinct disturbance types: short length scale “spike” and long length scale “modal oscillation.” Through detailed pressure measurements, they demonstrated that modal oscillations are associated with system-wide instabilities, while spikes result from localized three-dimensional flow breakdown at high rotor incidence. A predictive model was also proposed to explain the observed stall patterns under varying operating conditions. [19] conducted a combined numerical and experimental study to investigate the physical mechanism behind spike-type stall inception in axial compressors. The results revealed that spike formation originates from leading-edge flow separation due to high incidence, leading to vortex shedding and propagation across adjacent blade passages. Experimental studies [20] have been conducted to investigate the relationship between inlet distortion and surge margin in engines. The plug-plate distortion generator was used to induce controlled distortions on a test bench, and static pressure variations at various compressor stages were monitored. Results showed that the increased distortion index caused by higher plate height led to a reduced surge margin, especially at higher rotational speeds. These simulations and pressure measurements confirmed that these vortices are distinct from tip clearance vortices and are driven primarily by local flow conditions such as corner separation or adjacent blade tip leakage.

In a more recent study, Liu [21] investigated the reliability of four pressure-based stall warning methods: auto-correlation, cross-correlation, root mean square, and fast wavelet analysis on a low-speed axial flow compressor. Their findings revealed that practical factors such as rotational speed fluctuations, sensor placement, and inlet distortion significantly impact method performance. Among the evaluated techniques, the cross-correlation method exhibited the greatest robustness under non-uniform conditions, indicating strong potential for stall and surge warning applications. Zhang [22] has proposed an incipient instability warning method based on adaptive wavelet synchrosqueezed transform to address the limitations of traditional stall/surge detection approaches in terms of computational complexity and threshold. By extracting instantaneous frequency features from low-pass filtered outlet pressure signals using dynamic time-frequency analysis, this method enables early and accurate detection of instability. The main advantage of pressure-based monitoring is its direct correlation with surge phenomena. The pressure variations are often the most immediate and reliable indicators of flow instability, allowing for accurate detection once a surge has occurred. Moreover, pressure sensors are relatively mature, low-cost, and straightforward to deploy in both laboratory and industrial environments.

C. VIBRATION-BASED MONITORING

Vibration-based monitoring utilizes structural vibration measurements—particularly those originating from the compressor casing or rotor shaft—to detect surge events. During a surge, abrupt flow reversal and pressure oscillations induce mechanical vibrations in engine structures, which can be captured by accelerometers, proximity probes, or strain gauges mounted at strategic locations on the casing or rotating components [23]. These methods provide sensitive, indirect indicators of abnormal aerodynamic behavior without requiring direct airflow or pressure measurements. Moreover, vibration sensors are generally robust and already integrated into many industrial systems for general condition monitoring.

To enhance reliability in complex environments, recent research has focused on combining vibration signals with other sensing modalities, such as pressure, flow, or acoustic data. The interpretation of vibration signals often requires advanced signal processing methods, including frequency domain analysis, time-frequency transforms, or machine learning algorithms. Reference [24] proposed a rotor-stator coupling method based on frequency domain analysis, termed the time and space mode decomposition and matching method, for studying unsteady flow in multi-blade turbo-machinery. The method extracts and matches time and space modes across interfaces using a nonreflective boundary treatment. Validation on a transonic compressor showed good agreement between frequency domain results and time-domain simulations in capturing unsteady pressure harmonics. In [25], an online condition monitoring system was proposed to detect faults in unbalanced induction motors by analyzing both motor current and rotor vibration signals using Hilbert and wavelet transforms. The method successfully identified fault severity and location under various load conditions.

Furthermore, reference [26] investigated blade vibration induced by surge in a high-performance single-stage centrifugal compressor with varying impeller and diffuser geometries. Using blade-mounted strain gauges and dynamic pressure transducers, the study revealed that both rotating stall and nonperiodic pressure fluctuations during surge can excite dangerous blade vibrations. Notably, the strongest excitations occurred at the onset and end of surge cycles. Reference [27] explored incipient surge detection in a micro turbine system using acoustic and vibration-based diagnostics under varying connected volume conditions. The emergence of the surge was marked by specific vibrational signatures, uncovered through multi-domain analysis of acoustic and vibration signals. These methods could extract meaningful features that distinguish surge-induced vibrations from other phenomena. Vibration-based monitoring provides indirect sensitive indications of abnormal aerodynamic behavior without the need for direct airflow or pressure measurement. In addition, vibration sensors are often robust and already present in many industrial engines for other diagnostic purposes.

D. ACOUSTIC-BASED MONITORING

Acoustic-based monitoring detects the surge by analyzing sound waves generated by unsteady flow and pressure fluctuations within the compressor. Surge events typically produce characteristic acoustic signatures such as low-frequency oscillations, broadband noise, or periodic pressure waves that propagate through the intake, compressor casing, or exhaust ducts. Acoustic sensors, including microphones and pressure transducers, can capture these signals non-intrusively, making this approach particularly attractive for retrofit applications or systems where direct flow or pressure measurements are difficult to implement. Furthermore, acoustic methods have the potential to identify early-stage flow instabilities that precede full surge, offering a valuable time window for prediction and prevention.

Several recent studies demonstrated the diagnostic potential of acoustic monitoring. For example, reference [26] conducted experimental investigations on a centrifugal compressor and revealed a previously overlooked acoustic signature in the 30-85Hz range that emerged before surge onset. While traditional dynamic pressure sensors failed to detect this signal due to its low amplitude, it was clearly captured by microphones, highlighting the sensitivity of acoustic measurements to early disturbances. In [28], acoustic and pressure signals from centrifugal and axial compressors were analyzed using approximate entropy (ApEn) to reveal early indicators of surge. The analysis showed that as the system approached surge, ApEn values increased, reflecting rising flow irregularity. Interestingly, both compressor types exhibited similar trends, suggesting that acoustic signal complexity may serve as a reliable precursor for surge onset.

To detect early signs of surge in a gas turbine system with reduced surge margin due to large compressor volume, reference [29] utilized acoustic sensors and performed Fast Fourier Transform (FFT) analysis on the recorded sound signals system natural frequencies and rotor harmonics. These findings suggest that such frequency components serve as acoustic indicators of surge onset. Overall, the study supports the use of acoustic monitoring as an effective real-time strategy for ensuring compressor stability.

Nevertheless, acoustic monitoring presents several challenges. The acoustic environment in gas turbines is extremely noisy due to combustion, rotating machinery, and environmental interference. This makes it difficult to isolate surge-specific sound patterns without sophisticated filtering and signal analysis techniques. In addition, the propagation characteristics of sound waves can be affected by duct geometry, temperature gradients, and boundary conditions, which may distort the acoustic signals. To overcome these limitations, recent studies have explored the use of advanced algorithms such as neural networks and multi-sensor fusion to enhance the performance of surge detection using acoustic data. One such study is [30], which proposed a multi-sensor fault diagnosis framework for rotating machinery that integrates thermal imaging and vibration data using deep learning and data fusion techniques. Compared to single-sensor approaches, the method improves robustness against noise and enhances diagnostic accuracy when handling corrupted or anomalous sensor readings. Through three case studies, the system demonstrated reliable performance across varying noise conditions and sensor faults. These results highlight the effectiveness of multi-sensor fusion in maintaining diagnostic reliability in complex industrial environments. Another relevant work is presented in [31], where a real-time fault classification model for air compressors was developed based on empirical acoustic time-series data sampled at 50 kHz. FFT and a masking operation are applied to extract key spectral features, which are then fed into a lightweight multilayer perceptron (MLP) neural network for efficient and accurate classification. The proposed system achieves an accuracy of 91.32%, outperforming an long short-term memory (LSTM)-based model in both training time and memory consumption. These findings demonstrate the promise of integrating acoustic signal analysis with machine learning techniques for real-time monitoring and diagnosis of surge-related faults.

Although various monitoring methods have been developed and deployed for stall and surge detection, which include flow and pressure sensing, vibration monitoring, and acoustic signal analysis, each method has its own strengths, limitations, and application scenarios. For instance, flow-based methods offer direct aerodynamic insight but are often intrusive, while acoustic-based approaches enable remote detection yet are sensitive to environmental noise. To facilitate a clearer comparison and support method selection in practical applications, a summary of the key advantages and limitations of each technique is provided in Table I.

III. RESEARCH PROGRESS AND PROSPECTS IN SURGE MODELING

In existing research, researchers usually rely on fluid dynamics experiments for analysis and validation of surge phenomena. However, these methods are limited by high costs and safety concerns, making large-scale or extreme-condition testing difficult [32,33]. This highlights the importance of developing models that can represent the dynamic behavior of surge, particularly those capable of identifying early signs of its onset.

Surge modeling approaches can mainly be categorized into three types: high-fidelity computational fluid dynamics (CFD) models, mathematical simulation models, and data-driven models. CFD models offer detailed spatial and temporal resolution of flow fields [34], making them suitable for analyzing complex surge mechanisms and validating physical insights. CFD models' high computational cost limits their applicability in real-time control or system-level simulations. Mathematical simulation models, including lumped-parameter and control-oriented formulations, provide reduced accuracy but offer significant benefits in terms of computational efficiency and model transparency, which makes them well-suited for control design. In recent years, data-driven modeling has gained increasing attention as a complementary approach. By learning dynamic patterns

Table I. Comparison of Surge Monitoring Techniques.

Monitoring Type	Advantages	Limitations	Representative works
Flow-based	Directly reflects; aerodynamic stability; enables early detection.	Intrusive sensor installation; impacts flow path; measuring in harsh environments.	[9–11,13,15]
Pressure-based	Mature technology; easy to implement; good correlation with surge onset.	Sensor placement affects accuracy; may suffer from noise; limited spatial resolution.	[16–20]
Vibration-based	Non-intrusive; sensitive to the response of the relevant structure.	Requires high sampling rate; complex signal processing; susceptible to interference from irrelevant vibrations.	[21–25]
Acoustic-based	Remote and non-intrusive; sensitive to weak surge precursors; suitable for retrofitting.	Susceptible to ambient noise; affected by pipe geometry; requires filtering.	[24,26–29]

directly from sensor data or simulation outputs, these models can improve adaptability to complex and time-varying conditions.

In the following parts, all three modeling approaches are discussed in detail, highlighting their advantages, limitations, and roles in surge modeling development.

A. COMPUTATIONAL FLUID DYNAMICS MODELS

CFD models provide a high-fidelity numerical approach for simulating the detailed unsteady flow fields associated with compressor surge. By solving the Navier–Stokes equations with appropriate turbulence models and boundary conditions, these methods can capture the intricate flow structures, pressure waves, and separation phenomena involved in surge onset and development. The governing equations for fluid motion are given by the Navier–Stokes equations:

$$\begin{aligned} &\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f} \\ &\nabla \cdot \mathbf{u} = 0 \end{aligned} \tag{1}$$

where $\mathbf{u}$ is the velocity vector, p is the pressure, ρ is the density, ν is the kinematic viscosity, and $\mathbf{f}$ represents body forces. Owing to their high spatial and temporal resolution, CFD simulations are particularly valuable for analyzing localized flow mechanisms and validating theoretical insights derived from experiments.

Several studies have leveraged CFD modeling to gain deeper insight into compressor surge phenomena. These efforts focus on reproducing the complex unsteady flow fields during surge, revealing its onset mechanisms, and validating physical interpretations through detailed numerical simulations. One representative study [35] proposes an extended CFD domain with an upstream intake and a downstream variable nozzle, enabling realistic boundary conditions and flexible operating point selection. This method successfully captures post-stall behavior and reproduces the characteristic hysteresis loop associated with compressor surge. Another study [36] combines extensive experiments with high-fidelity CFD simulations on a six-stage axial compressor to improve stall prediction. By comparing steady and transient simulations against experimental data, the work demonstrates accurate performance map prediction up to stall inception and offers a physical perspective into key flow features and modeling discrepancies. Reference [37] compares steady and unsteady CFD simulations of an axial compressor and highlights the accuracy of unsteady predictions in capturing stage loads and spanwise profiles. It further proposes a practical method to reduce computational cost by using single-stage steady simulations with time-averaged boundary conditions derived from unsteady multistage results. Reference [38] assesses the capability of an unsteady CFD solver to simulate rotating stall in a full-annulus axial compressor. Spectral analysis reveals the influence of rotor-stator interactions, and the findings emphasize that accurate stall prediction requires modeling the complete geometry, including inlet distortions and downstream volumes. Reference [39] employs a high-fidelity CFD approach by solving the three-dimensional, unsteady, compressible Navier–Stokes equations with a sliding mesh technique to investigate centrifugal compressor surge. Collectively, these studies highlight the crucial role of CFD modeling in investigating compressor surge and stall. By enabling detailed simulation of unsteady flow behaviors under various conditions, CFD serves as a useful tool for revealing instability mechanisms, validating experimental observations, and guiding the development of more accurate and efficient compressor designs.

B. MATHEMATICAL SIMULATION MODELS

In contrast to the computationally intensive nature of CFD approaches, mathematical simulation models aim to describe the essential dynamics of compressor surge using simplified physical assumptions. These models, often based on lumped-parameter or control-oriented formulations, are capable of capturing key system behaviors such as pressure-flow oscillations or limit cycle dynamics. Among them, the Moore-Greitzer (MG) model stands out as a foundational framework that provides a system-level explanation of surge dynamics and has been widely applied in both surge analysis and control design due to its clarity and mathematical simplicity.

From a system dynamics perspective, Greitzer [40] proposed a one-dimensional nonlinear model to describe the dynamic process of surge and rotating stall in axial compression systems, introducing the well-known B-parameter to characterize different types of stall. Then, Moore [41] developed a two-dimensional model for rotating stall, which analyzed the conditions under which flow distortions can propagate steadily through multistage compressors, despite constant upstream and downstream pressure conditions. By incorporating compressor hysteresis and lag effects from inlet and outlet ducts, the model derived an expression for stall cell propagation speed. The theoretical predictions, when compared with experimental data under various configurations (including different stage numbers and blade geometries), thereby providing a solid foundation for further modeling of large-amplitude stall phenomena. Building on their individual contributions, Moore and Greitzer [42] jointly developed an unsteady and nonlinear model capable of capturing the essential dynamic characteristics of compression systems. Their work introduced a low-order framework that couples surge and rotating stall-like motions through a set of simplified governing equations derived from an approximate theory of post-stall transients. By applying a Galerkin method to reduce a system of third-order Partial Differential Equation (PDEs) to a set of first-order Ordinary Differential Equation (ODEs) in time, the model successfully describes the growth, propagation, and potential decay of rotating stall cells under transient flow conditions, while also accounting for variations in the compressor's instantaneous pressure–flow characteristics.

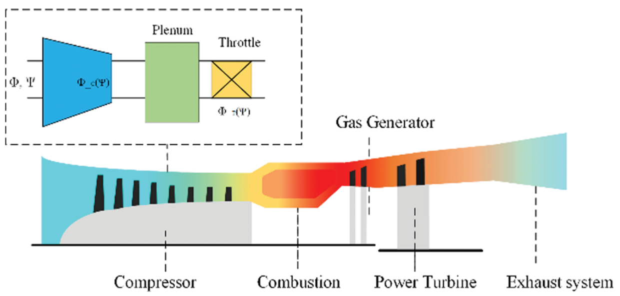

Fig. 3. Structural of the compression system.

The MG model could capture the dynamic characteristics of surge and rotating stall in a compression system, as illustrated in Fig. 3.

It is formulated through three interrelated differential equations:

$$\frac{d\psi}{d\varsigma} = \frac{1}{4B^2 l_c}(\Phi - \Phi_T(\Psi)) \tag{2}$$

$$\frac{d\Phi}{d\xi} = \frac{1}{l_c}\left(\Psi_C(\Phi) - \Psi - \frac{3H}{4}\left(\frac{\Phi}{W} - 1\right)J\right) \tag{3}$$

$$\frac{dJ}{d\xi} = J\left[1 - \left(\frac{\Phi}{W} - 1\right)^2 - \frac{J}{4}\right]\delta \tag{4}$$

where Ψ is the pressure-rise coefficient; Φ is the flow coefficient in the compressor; ζ is the dimensionless time; J is the square of the amplitude of angular disturbance of flow coefficient; H and W are, respectively, the semi-height and semi-width of cubic axisymmetric characteristic; lc specifies the length of compressor and duct; δ is a constant coefficient that reflects the flow hysteresis within the compression system. B is the well-known Greitzer-B parameter defined as:

$$B = \frac{U}{2a_s}\sqrt{\frac{V_p}{A_C l_C}} \tag{5}$$

where U is the tangential speed of the rotor, as is the local sound speed, Vp is the plenum volume, and AC is the cross-section of the compressor.

With the key variables defined above and the system structure illustrated in Fig. 3, the governing equations of the MG model are given as follows:

$$f(\Phi) = \left[1 + \frac{3}{2}\left(\frac{\Phi}{W} - 1\right) - \frac{1}{2}\left(\frac{\Phi}{W} - 1\right)^3\right] \tag{6}$$

$\Psi_C(\Phi)$ is the steady-state characteristic curve of the compressor expressed by the following cubic curve function:

$$\Psi_C(\Phi) = \Psi_{C0} + Hf(\Phi) \tag{7}$$

$\Phi_T(\Psi)$ is the throttle valve characteristic, which can be expressed by the following equation:

$$\Phi_T(\Psi) = \gamma_T\sqrt{\Psi} \tag{8}$$

Let $J = 0$ in Equation (4), which represents the disappearance of the airflow disturbance wave at the inlet of the compressor, and the MG model is obtained:

$$\frac{d\Phi}{d\varsigma} = \frac{1}{l_c}(\Psi_C(\Phi) - \Psi) \tag{9}$$

$$\frac{d\Psi}{d\varsigma} = \frac{1}{4B^2 l_c}(\Phi - \Phi_T(\Psi)) \tag{10}$$

The equations of the MG model provide a compact and efficient representation of surge dynamics in axial compressors.

However, to enhance its applicability in different scenarios, such as accommodating varying system configurations, supporting the implementation of advanced control strategies, or improving modeling accuracy under different flow regimes, numerous efforts have been made to refine and extend the original model. The following works illustrate how subsequent studies have built upon the MG framework to advance both theoretical understanding and practical surge control performance.

In subsequent studies, researchers have continued to refine and extend the MG model to enhance its capability in analyzing and controlling surge dynamics. Xiao [43] quantitatively characterized different types of oscillations in axial compressors based on the MG model, showing that surge and rotating stall can be distinguished through Hopf bifurcation analysis governed by throttle coefficient and compressor geometry. Reference [44] focused on control design by proposing a procedure for synthesizing dynamic output feedback controllers for the surge subsystem. Their approaches simplified the parameter search and provided stabilizing controllers under quadratic constraints. Building on the sensitivity of model parameters, the work in [45] treated the duct length parameter L_c as a variable rather than a fixed value. This study showed that different L_c correspond to distinct surge behaviors, such as deep surge and mild surge, and that the optimal value of L_c varies with mass flow rate. To capture broader system dynamics, an enhanced MG model was proposed in [46], incorporating pipeline acoustics via a transmission line representation. The simulation results show improved agreement with experimental observations, particularly regarding surge oscillation frequency. Reference [47] compared the classical MG model with a modified structure under closed-loop control. Through eigenvalue and bifurcation analysis, it was found that while both models handled small disturbances effectively, the MG model exhibited greater robustness under large perturbations and damping characteristics, even without active control. Recent modeling framework [48] has extended first-principles compressor characteristic formulations from cubic to quintic shapes by incorporating diffuser recirculation, enabling the prediction of both mild and deep surge. When applied to experimental facilities, such models capture stable operation, surge onset, and wave dynamics in pipework with remarkable agreement to measured data, providing valuable physical insight for early-stage turbocharger design. A full-system numerical model [49] incorporating adaptive boundary treatments with open-boundary methods has been developed to predict mild and deep surge behaviors in high-speed centrifugal compressors across different flow regimes. Notably, it captures various low-order oscillation modes and identifies unstable equilibrium points in the supersonic regime with high accuracy, providing a new path to multi-regime surge dynamics. These developments collectively underscore the flexibility and ongoing relevance of the mathematical framework in surge modeling and control.

C. DATA-DRIVEN MODELS

While physics-based models such as CFD simulations and mathematical simulation models have become the backbone of surge analysis, they often rely on idealized assumptions. In contrast, data-driven modeling approaches seek to capture system dynamics directly from operational or experimental data, without explicitly relying on first-principles equations. This method has gained increasing attention in recent years due to its flexibility, ability to handle nonlinearity, and suitability for systems operating under complex conditions. Data-driven methods are particularly valuable for identifying early instability features, adapting to system changes over time, and supporting real-time monitoring or control. These models include techniques such as neural networks, support vector machines, autoregressive models, and, more recently, hybrid frameworks that combine data-driven learning with physics-based constraints.

Based on current research, data-driven modeling approaches for compressor surge prediction can be categorized into four major types: recurrent neural networks (RNN), graph-based neural networks (GNN), transformer-based models, and hybrid frameworks that integrate physical constraints. Representative studies under each category are summarized below. Reference [47] proposed a data-driven stall warning method for aircraft engines with inlet distortion using a high-order distortion model and deterministic learning. The system dynamics under normal and stall inception conditions were approximated and stored using radial basis function networks, and an estimator was used to identify early stall based on residual comparison. Reference [51] developed a deep learning model to predict stall and surge in axial flow compressors under distorted inflow conditions. A long short-term memory neural network was trained using dynamic pressure data measured on the casing wall during stall processes. To improve prediction accuracy, model parameters were optimized using the Northern Goshawk algorithm. The model was validated through step-by-step and recursive prediction methods under both uniform and distorted inflow. It was able to predict stall and surge at least one second in advance across different flow conditions. A recent study developed a data-driven early warning system for spike stall using pressure data from axial compressor experiments [52].

Pressure matrices and time-evolving graphs were constructed from sensor readings, and four neural network models: Gated Recurrent Unit (GRU), LSTM, GNN-GRU, and GNN-ConvLSTM were evaluated for spike prediction. The models achieved up to 100% accuracy in detecting stall precursors 30 revolutions in advance. In a more recent study, a stall warning system combining a continuous wavelet transform and a vision transformer was proposed. Time-series pressure data were converted into time-frequency images to train a classifier. A model ranking strategy [53] was used to improve robustness under sensor faults, and the system showed high accuracy and early warning capability in stall experiments.

Moreover, data-driven approaches commonly require large amounts of labeled data under a variety of operating conditions to achieve good performance. This can be challenging in safety-critical systems where fault data are scarce or difficult to obtain. To address this issue, techniques such as transfer learning, synthetic data generation, and physics-informed neural networks are being explored to reduce the reliance on massive datasets while maintaining accuracy and reliability. A comparative summary of various modeling approaches is shown in Table II.

Each modeling approach has its advantages and limitations. CFD models excel in physical detail, mathematical models in control integration, and data-driven models in adaptability and prediction. A promising trend lies in combining these methods to form hybrid surge modeling frameworks that leverage physical methods to form hybrid surge modeling frameworks that leverage physical understanding, efficient structure, and learning capabilities. Such integration may support more accurate and practical solutions for real-time surge monitoring, prediction, and control in modern gas turbine systems.

D. FUTURE TRENDS AND PROSPECTS IN COMPRESSOR SURGE MODELING

Compressor surge modeling still faces challenges in terms of adaptability, real-time performance, and promotion and application under complex working conditions. Future research is expected to make progress in the following directions.

1) MODELING FOR SYSTEM DIVERSITY. As compressors are widely used in gas turbines, aeroengines, and industrial systems, the complexity and diversity of working conditions put forward higher requirements for modeling. Traditional models based on single working conditions and fixed structural parameters are difficult to adapt to practical needs such as multi-working condition switching and high dynamic response. Therefore, future modeling work will pay more attention to the adaptability, scalability, and versatility of the model at the system integration level. In addition, the system dynamic characteristics brought about by factors such as non-steady state, large cavity, and flexible structure are becoming the core influencing variables of compressor surge problems, posing a challenge to the timeliness and robustness of modeling. This requires researchers to develop a modeling framework with stronger expressive capabilities to cope with nonlinear behaviors under complex working conditions.

2) BALANCE BETWEEN MODEL SIMPLICITY AND CONTROLLABILITY. Although existing high-fidelity models (such as CFD) can reflect flow details, their computational complexity is high, and it is difficult to use them directly for real-time control. Future development trends will focus on building a "controllable model" suitable for controller design, while retaining key dynamic characteristics, compressing the model order, and improving computational efficiency.

Table II. Compressor surge modeling approaches comparison.

Modeling approach	Advantages	Limitations	Representative works
CFD Models	High accuracy; detailed flow structure.	High computational cost; not suitable for real-time use.	[33–37]
Mathematical Models	Good interpretability; good real-time performance; suitable for control design.	Simplified assumptions	[40–43,46]
Data-driven Models	Adaptive; can handle complex nonlinear dynamics; suitable for real-time use.	Requires large datasets; lack physical interpretability.	[47,51–53]

This modeling direction requires combining physical modeling with control requirements, such as developing an extended model based on the MG model, a lumped parameter model, a quasi-steady-state dynamics model, etc., while strengthening the physical interpretability of the model structure to provide theoretical support for subsequent control law design and stability analysis.

3) DATA-DRIVEN AND HYBRID MODELING. With the application of high-frequency sensors and edge computing, a large amount of data during the operation of the compressor can be collected and used in real time. Data-driven modeling methods, such as system identification, LSTM, and Gaussian Process Regression (GPR), provide new ideas for understanding complex nonlinear behaviors, especially in scenarios where the model structure is unknown or traditional modeling is difficult.

However, pure data models still have shortcomings in generalization ability, physical consistency, and interpretability. A more promising direction in the future is "gray box modeling" or "hybrid modeling," that is, integrating the first-order physical model with the data learning results, thereby improving the prediction accuracy and practicality of the model on the basis of ensuring physical consistency. This will also become one of the key supports for intelligent control of compressors.

IV. RESEARCH PROGRESS AND PROSPECTS IN ANTI-SURGE CONTROL

Compressor surge control strategies can be broadly classified into passive and active methods. Passive control enhances compressor stability through structural or aerodynamic improvements. Active control uses sensor feedback and actuator intervention to maintain stable operation under varying conditions.

A. PASSIVE CONTROL

Passive control methods aim to suppress surge by modifying the internal flow field or structural response of the compressor. These approaches are typically based on fixed geometric features or fluidic components and do not require sensors. At the same time, with the rise of modern advanced control, the number of related studies on surge passive control from the perspective of compressor structure design is limited. Reference [54] developed a passive surge control method using a hydraulic oscillator based on aero-elastic coupling. A nonlinear lumped parameter model was used to simulate system dynamics and identify optimal control parameters. These parameters guided the design of the control device. Then, experimental tests confirmed its ability to suppress surge as predicted by the simulations. In addition, researchers have explored flow-based passive methods to delay instability onset.

Recent studies have demonstrated the effectiveness of self-recirculating injection (SRI) as a passive surge control strategy. By extracting air from the downstream casing and reinjecting it upstream as a wall, SRI can delay tip leakage flow development and suppress spike-type stall inception (see Fig. 4). Experiments conducted on both single- and multi-stage axial compressors have shown that SRI can improve stall margin by over 13% without efficiency loss

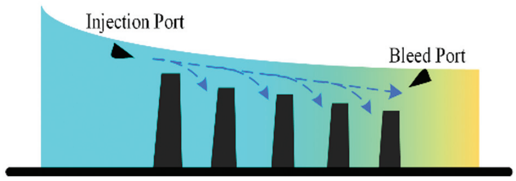

Fig. 4. Schematic of Self-Recirculating Injection.

[55], further enhances applicability by achieving up to 6.12% stall margin improvement [56]. SRI enhances stability by reducing unsteady tip leakage, lowering blade loading, and improving wake recovery behind the rotor. While passive control strategies have shown notable improvements in compressor stability through structural design enhancements, they are often limited in adaptability once the system is in operation.

B. ACTIVE CONTROL

Nevertheless, these structure-based passive control methods often result in increased aerodynamic losses, leading to reduced compressor efficiency and consequently affecting the overall performance of gas turbines. In recent years, the rapid development of embedded computing and real-time sensor systems has accelerated the transformation of surge control solutions from model-based to data-centric. These technologies are able to extract meaningful patterns from noisy or high-dimensional input data, which is critical for early surge detection and mitigation. In addition, cloud-assisted data aggregation and transfer learning have opened up new possibilities for common control strategies across different compressor types or operating modes.

Compared to passive control methods, active control involves real-time adjustment of system parameters through feedback mechanisms, allowing the compressor to maintain stability across a wider range of operating conditions. To better illustrate recent developments in active surge suppression control, this section categorizes representative control strategies based on their underlying control logic architecture, including closed-loop feedback control, model predictive control, robust control, data-driven approaches, and intelligent methods.

1) CLOSED-LOOP FEEDBACK CONTROL. The closed-loop feedback control method dynamically adjusts the controller output by real-time monitoring of key system state parameters, such as the compressor inlet total pressure, static pressure, mass flow rate, or vibration signal, so as to maintain system stability under disturbance or load change conditions. This type of method has the characteristics of fast response speed and strong adaptability, and it is one of the important technical routes for actively suppressing surges.

One typical method is to install total pressure sensors at the compressor inlet and configure an electric control valve at the outlet of the plenum chamber to achieve pressure feedback control through a proportional-differential controller. In order to ensure the effectiveness of the controller under different operating conditions, the researchers also established a nonlinear lumped parameter model with time lag factors to simulate the dynamic behavior of the system and optimize the control strategy. The results show that the control method can effectively suppress surge under a wide range of unstable conditions while avoiding actuator saturation, and has feasibility and stability margin [57].

Another study proposed a feedback indicator based on correlation measurement to detect the repeatability of pressure fluctuations in the rotor tip area, thereby identifying the risk of rotating stall or surge at an early stage. This parameter is integrated into the margin management module of the aircraft engine control system, enabling the control system to adaptively adjust the operating margin according to the actual state. Tests on a turbofan engine simulation platform show that this method can effectively improve the stability and safety of system operation under various operating conditions [58].

Some studies have explored surge feedback control strategies based on piston actuators. The researchers designed a nonlinear backstepping controller based on full-state feedback and a linear feedback controller that depends on the plenum pressure and piston speed. The former can achieve global asymptotic stability of the system, while the latter can also achieve effective stability in local areas despite its simpler control structure. Simulation analysis shows that both methods have good anti-disturbance performance and can be implemented according to actual system requirements [59,60] built a surge control framework for centrifugal compressors based on the Greitzer model. Through the relationship between tip clearance and compressor performance, a Proportional-Integral-Derivative (PID) controller based on flow feedback was designed. Combined with the low-frequency tracking capability of the active magnetic bearing on the rotor, effective tip clearance regulation was achieved. The experimental platform verified the control effect at different speeds and throttle valve openings. The results showed that the speed had little effect, while the opening change had a significant effect on surge control.

2) MODEL PREDICTIVE CONTROL. Model predictive control predicts future system behavior through online optimization and generates control strategies in real time. It is suitable for processing complex systems with nonlinear, constrained, and multi-variable characteristics. Reference [61] studied the nonlinear Model Predictive Control (MPC) method for centrifugal compression systems, with pressure ratio and surge margin as the main control objectives. Then, a contractive nonlinear MPC is proposed to ensure system stability by enforcing Lyapunov function descent, alongside alternative offset-free linear and nonlinear MPC formulations to manage disturbances and modeling uncertainties. Simulation studies, executed on a realistic test bench and implemented on an industrial PLC, demonstrate that both SQP-based and full nonlinear MPC methods deliver superior performance in surge margin preservation and reference tracking, while maintaining acceptable computational efficiency. In addition, in order to improve industrial feasibility, the study also compared the performance of controllers based on the SQP, which reduced the computational effort while maintaining control accuracy.

Another study further extended the MPC strategy to a compression system that considers the influence of pipeline acoustic coupling. By introducing the nonlinear model of the compression system and the dynamics of the close-coupled valve (CCV), a more engineering-practical compressor model was established. The designed nonlinear MPC controller significantly expanded the operating area of the compressor while meeting the CCV valve operation constraints and system state restrictions, and improved the control system's regulation capability. The results show that this strategy can still effectively suppress surge and achieve stable system operation [62]. Building on extended models, **adaptive Nonlinear Model Predictive Control (NMPC) scheme** [63] incorporating a nonlinear disturbance observer and optimization has been proposed to achieve simultaneous surge/stall suppression with improved tracking accuracy and reduced computation time. The results prove that nonlinear MPC has good robustness and real-time performance, and it is a powerful tool for surge suppression control of future industrial compression systems.

3) ROBUST CONTROL. Robust control methods emphasize maintaining control performance and stability in the presence of system parameter uncertainty or external disturbances. Reference [64] By comparing the control strategies of a single-stage compressor supported by magnetic bearings, it was found that the load suppression capability of traditional PID control in the range of 10–100 Hz is limited. In contrast, the H∞ controller with a multi-input multi-output structure can not only effectively deal with system uncertainty, but also achieve load suppression performance two to three times that of PID in the same frequency range.

Other studies further reveal the impact of control strategies on the dynamic robustness of compressors by comparing the stability performance of the MG model and its improved version under different disturbance amplitudes. Reference [65] designs an optimal controller based on Linear Quadratic Regulator (LQR) to achieve active control of surge and rotating stall near the peak of pressure rise. Simulation results show that the controller can stabilize small disturbances in both models, but performs differently in the case of large disturbances: the MG model has strong damping characteristics in the negative slope region and can automatically attenuate even if the disturbance is severe; while the improved model can more realistically predict the evolution of disturbances, and will show an unstable trend when the disturbance exceeds a certain intensity. This comparative analysis emphasizes the importance of controller robustness in the presence of model differences and large disturbances, and also confirms the ability of LQR to balance disturbance suppression and system stability in engineering applications. In industrial centrifugal compressors, anti-surge protection is critical under fast transients such as start-up, shutdown, or pressure fluctuations. An advanced anti-surge control (ASC) strategy [66] based on split PID control has been proposed and validated using HYSYS simulation and plant data, showing significant improvements in surge prevention performance compared to conventional PID controllers.

4) DATA-DRIVEN CONTROL. With the rapid development of sensor, data acquisition, and real-time processing technology, data-driven control strategies have gradually emerged in the field of active compressor control. Unlike the traditional method that relies on system physical modeling, data-driven methods can use historical data and real-time signals to construct control logic through pattern recognition and feature extraction, which is particularly suitable for highly nonlinear and complex systems.

Reference [67] proposed an active surge control method based on blade load distribution adjustment, which mitigates the instability trend by monitoring the system operating conditions and adjusting the blade force distribution. The method was verified on a compressor test platform. Although a simplified model was introduced in the control strategy, its core control logic mainly relies on rule response based on sensor data. For a micro gas turbine system coupled with a large cavity component, reference [68] proposed a surge prediction and suppression strategy based on subsynchronous vibration characteristics. The experimental results show that when the system approaches the surge boundary, the subsynchronous frequency component is significantly enhanced. The control system can monitor the signal in real time and actively open the bleed valve to avoid the occurrence of instability. This method realizes closed-loop control from feature extraction to active intervention, verifying the practical feasibility of data-driven in early fault perception and response.

In addition, data-driven methods have also begun to merge with deep learning algorithms to explore the problem of early prediction of compressor instability. Reference [69] further expanded the data-driven control form and proposed a fuzzy logic controller for surge suppression of axial flow compressors. The controller makes decisions based on the changing trends of pressure rise and mass flow, without the need for known surge lines or system equilibrium points, significantly reducing the reliance on system modeling. Simulations show that this method can effectively suppress surge under various operating conditions and exhibit good adaptability and robustness. Reference [70] explored the application of deep learning methods in stall prediction. Based on the real operating data of a 100 kW micro gas turbine compressor, the researchers trained a LSTM network model to identify compressor stall trends in advance. The results showed that the model can give an early warning 5-20 ms before the stall occurs. If combined with a fast controller with high time resolution, active intervention can be achieved, significantly improving the dynamic response capability and operational safety of the system. The data-driven control method shows good system adaptability and real-time performance by identifying and responding to key signals during compressor operation.

With the development of artificial intelligence and high-speed controllers, this type of method will play an important role in the intelligent surge suppression of complex gas turbine systems in the future, and is expected to be deeply integrated with traditional model methods to build an adaptive control framework with more self-learning capabilities.

In summary, active control strategies provide a more flexible framework for compressor surge suppression than passive control methods. By leveraging real-time sensing, feedback loops, predictive modeling, and intelligent decision-making algorithms, these methods can maintain system stability under a variety of operating conditions, including highly transient and uncertain conditions. Closed-loop feedback control provides fast response and robustness against disturbances by dynamically adjusting system parameters based on pressure, flow, or vibration signals. MPC extends this functionality by predicting system behavior and optimizing control actions within defined constraints, especially for nonlinear and multivariable environments. Robust control methods such as H∞ or LQR emphasize performance reliability in the presence of modeling uncertainty or parameter changes, ensuring surge suppression even under extreme conditions. Meanwhile, data-driven control methods open up new avenues by leveraging historical and real-time data to build adaptive control logic. From fuzzy logic systems that require no equilibrium knowledge to deep learning models that predict surge occurrence milliseconds in advance, these approaches have significantly reduced reliance on traditional physical modeling. The increasing integration of artificial intelligence with real-time control hardware also highlights the potential of hybrid strategies that combine physical insights with learning-based adaptability. In summary, advances in active control not only improve the safety and efficiency of gas turbines but also lay the technical foundation for intelligent and autonomous turbo-machinery systems in future energy infrastructure.

Each active control approach has its own advantages and scope of application. Closed-loop feedback control is suitable for fast-response scenarios with clear system feedback, while model predictive control is well-suited for multivariable constrained systems requiring optimal performance. Robust control methods are particularly useful in situations with high uncertainty or extreme operating conditions. In contrast, data-driven control offers flexibility and self-learning capabilities, but it depends on the quality and quantity of data.

By comparing these strategies clearly demonstrates that no single approach fully meets all application requirements, and future research may focus on hybrid integration for specific compressor systems. To provide a clearer overview, Table III summarizes the key features, advantages, and limitations of representative active surge control strategies.

C. ENGINEERING CONSIDERATIONS

Various control strategies have been proposed to suppress compressor surge. These methods vary in complexity, adaptability, and suitability for practical deployment. This section summarizes the main features of representative passive and active control methods and discusses the challenges they face in practical applications.

Table III. Compressor surge active control strategy comparison.

Control Strategy	Advantages	Challenges	Representative works
Closed-loop Feedback Control	Fast response; easy to implement; good stability.	May be sensitive to noise; performance depends on sensor placement.	[57–60]
Model Predictive Control	Handles constraints; suitable for nonlinear systems.	High computation load; model accuracy dependent.	[61,62]
Robust Control	Tolerates uncertainty; ensures stability under extreme conditions	May be conservative; requires careful design.	[64,66]
Data-driven Control	No need for full model; supports early prediction.	Needs large datasets; generalization may be limited.	[67–70]

Passive control methods rely on structural or pneumatic improvements. Their advantages are simplicity and low maintenance. After installation, no feedback signals or active components are required. However, passive methods have limited flexibility. Their effectiveness is determined by design and may not adapt to changing operating conditions. Self-circulating injection is an example. Under certain conditions, it can improve stall margin without affecting efficiency, but it cannot respond to transient changes or system failures. Another example is the use of hydraulic oscillators, which are simple and effective in specific settings, but lack the ability to dynamically adjust after installation.

Active control methods offer greater flexibility. They can adapt to changing operating conditions and suppress a surge in a more targeted manner. Control strategies such as model predictive control and fuzzy logic have been tested in simulations and experiments. Some methods use pressure sensors and actuators to regulate mass flow. Other methods use more complex models to predict system behavior and take corrective actions.

Although active control strategies have great potential, they still face engineering challenges. First, real-time control requires fast and reliable sensor data. Pressure or flow sensors may be affected by noise, delays, or calibration drift. In many compressor systems, sensor locations are limited by physical constraints. Improper sensor placement can reduce the effectiveness of the control algorithm.

Second, the actuator and bandwidth are crucial. Exhaust valves, guide vanes, or pistons must respond quickly enough to comply with control commands. In high-speed systems, actuator latency can reduce control accuracy. Some research has proposed the use of magnetic bearings or piston-based flow control. These approaches offer fast response times but increase system cost and complexity.

Third, robustness is crucial. In real systems, operating conditions vary, components wear out over time, and unexpected disturbances can occur. A control method that works well in simulation may not be reliable under real-world conditions. Robust design methods such as gain scheduling or adaptive control can help, but they also increase design complexity.

Finally, testing and validation remain challenging. Many control strategies have been demonstrated on simplified test benches or simulation platforms. To achieve practical application, these approaches must be validated on full-scale compressor systems. This requires hardware, a real-time control platform, and robust safety mechanisms to address control failures.

D. FUTURE TRENDS AND PROSPECTS IN COMPRESSOR SURGE CONTROL

While various passive and active strategies have demonstrated effectiveness in suppressing surges, future development still faces several challenges. These include improving adaptability to varying operating conditions, reducing energy consumption, and enhancing control reliability under uncertainty. To address these challenges, future research may focus on the following directions.

1) MULTI-DIMENSIONAL COORDINATION OF CONTROL OBJECTIVES. The goal of compressor surge control is gradually expanding from a single stability guarantee to a comprehensive optimization of performance indicators such as stability, efficiency, and response speed. At present, many control systems still take delaying the occurrence of a surge as the primary goal, but in actual engineering, maintaining efficient operation of the compressor is equally important. Future control methods will focus more on reducing performance losses and improving overall operating quality while ensuring safety.

In order to achieve this goal, research is gradually moving toward multi-objective optimization control strategies, striving to maintain a balance between system stability and energy efficiency under different load changes and operating disturbances.

2) FUSION OPTIMIZATION OF CONTROL METHODS. Traditional surge active control relies on preset models and fixed control logic and has limited adaptability. With the improvement of algorithms and computing power, intelligent methods such as fuzzy control, adaptive control, and neural networks have begun to be applied to actual compressor control tasks. These methods can adjust the control strategy in real time according to the actual operating status and improve the system's adaptability to nonlinear and time-varying characteristics.

The future development trend will be to combine data-driven algorithms with traditional control methods, use historical and real-time data for pattern recognition and trend prediction, and thus improve the control system's autonomous decision-making ability and regulation effect.

3) SYSTEM RESPONSIVENESS UPGRADE. The execution effect of active compressor control is limited by the response speed and accuracy of the hardware system. Problems such as sensor delay and slow valve response often limit the performance of the control algorithm. Therefore, improving the real-time response capability of the control system is an important direction for future development.

Research is exploring new hardware such as high-speed pressure sensors, solenoid valves, and piezoelectric actuators to improve the detection frequency and adjustment accuracy of the system. At the same time, closer software and hardware collaborative design will become a trend, so that the control strategy and the execution system form an efficient linkage mechanism.

Overall, surge control strategies are expected to evolve toward more integrated, intelligent, and robust systems. These developments will support more efficient and stable operation of gas turbines under increasingly complex and dynamic environments.

4) CONTROL SYSTEM INTEGRATION. As the complexity of the compressor system increases, it is difficult to accurately reflect the system status by relying solely on a single signal feedback. Multi-source signal fusion and multi-module coordinated control are becoming key directions. For example, the combined analysis of pressure, vibration, temperature, and other information can more comprehensively identify unstable operating conditions.

At the same time, compressor surge control is gradually evolving from local control to system-level control. In the future, the control system will not only be limited to the compressor itself, but also need to consider the synergy with combustion, exhaust, cooling, and other subsystems, and improve the stability and efficiency of the entire power system through integrated control strategies.

In summary, compressor surge control is developing in the direction of multi-objective optimization, intelligent control, high-speed response, and system integration.

With the continuous increase in the complexity of engineering systems, a single control method can no longer meet the multiple requirements of stability, efficiency, and safety in practical applications. Future research will pay more attention to the integration of models and data, the coordination of control strategies and execution systems, and the unification of local control and system-level management, so as to build a comprehensive control framework with high reliability, adaptability, and real-time performance. This will not only improve the operating performance of the compressor itself, but also provide a more solid technical guarantee for the safe and efficient operation of the entire gas turbine system.

V. DISCUSSION AND OUTLOOK

Despite the growing use of various sensor-based techniques, multiple factors continue to limit early detection and reliable warning. At the same time, accurate modeling and effective control are critical for suppressing surge and ensuring compressor stability. However, the intrinsic complexity of surge dynamics, combined with real-time implementation constraints, presents significant technical challenges. This section identifies and analyzes the major obstacles in surge monitoring, and further discusses the fundamental modeling issues and control limitations that hinder practical application.

A. CHALLENGES IN SURGE MONITORING

1) AMBIGUITY OF PRECURSOR SIGNALS. One of the primary challenges in surge monitoring is the ambiguity of precursor signals. While surge is often preceded by low-frequency pressure oscillations and localized instabilities, these symptoms are typically weak, noisy, and highly variable across different engine types and operating conditions [71]. In certain situations, such disturbances may resemble normal fluctuations during startup or transient maneuvers, making it difficult to distinguish real surge precursors from reasonable dynamics [72,73]. Moreover, there is currently no universally accepted set of features that can reliably indicate an impending surge across a wide range of compressors. A commonly used approach is to determine the occurrence of a surge based on the surge boundary, as illustrated in Fig. 5.

However, the lack of robust and generalizable warning features limits the effectiveness of traditional threshold-based detection methods. Therefore, it is necessary to introduce the concept of stall. Aerodynamic instability in compressors often begins with local disturbances and gradually develops into global flow breakdown. Stall usually appears first as airflow separation or small-scale oscillations near the blades. If not controlled, these local disturbances can expand and intensify, eventually leading to an axisymmetric surge with large-scale flow reversal [74]. Several experimental studies have shown that signal ambiguity often leads to false positives or missed detections in test-rig environments, especially under transient load or during engine startup phases [75,76]. This highlights the practical difficulty in defining universal early-warning thresholds.

2) DISTURBANCES UNDER STRONG COUPLED OPERATING CONDITIONS. Modern gas turbines typically operate in a tightly coupled system, where the compressor interacts closely with the combustor, turbine, and fuel control system. In such an environment, it becomes extremely difficult to effectively isolate surge-related anomalies from other transient processes within the system. For example, a sudden change in fuel flow or a rapid adjustment of rotor speed may induce pressure fluctuations that resemble surge behavior. In addition, external disturbances such as inlet distortion [75], thermal stratification [78], and ambient turbulence can further mask the true surge characteristics. These complex coupling effects pose significant challenges to rule-based or data-driven monitoring strategies, as such approaches usually assume that signal patterns are independent and distinguishable.

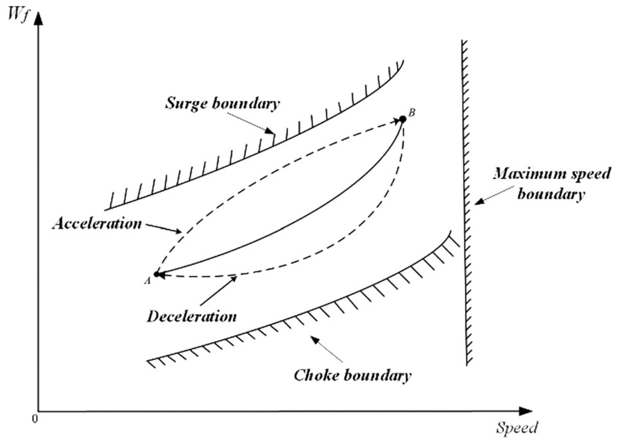

Fig. 5. Engine safe operating range.

3) TIME DELAY AND SYSTEM RESPONSE UNCERTAINTY. The development of surge is highly nonlinear, and real-time monitoring systems are limited by factors such as sensor delay and signal processing delay [79] and actuator response times. Many currently used pressure sensors have limited bandwidth and are unable to capture the rapid dynamics associated with surge onset. Even when high-performance sensors are employed, the data transmission and filtering process may cause extra time delays, which hinder the timely detection of anomalies [80]. Furthermore, actuators such as bleed valves or variable guide vanes often exhibit response lag, which reduces the likelihood of timely intervention once a surge is detected. Then, the accumulation of these delays and uncertainties would severely limit the implementation of fast control strategies and the realization of highly reliable surge prevention control technologies.

B. COMPLEXITY IN SURGE MODELING AND CONTROL

1) MULTI-SCALE DYNAMICS OF SURGE. Compressor surge is inherently a highly nonlinear and multi-scale phenomenon, characterized by the rapid reversal of flow, significant pressure oscillations, and complex aerodynamic interactions. The system dynamics involve both fast-scale transient behaviors and slow-scale evolutions. Capturing this complex behavior in mathematical models is a persistent challenge. Classical models, such as the MG model, offer valuable insights but tends to oversimplify certain dynamic features, while high-fidelity CFD models are computationally prohibitive [81,82] for real-time applications. To support modeling efforts, several experimental studies have focused on capturing multi-scale surge dynamics through vibration-based measurements. For instance, blade-mounted strain gauges[83], casing accelerometers, and rotor probes have been employed to observe transient structural responses during surge events, providing valuable data for validating and refining low-order models [84,85]. These experimental insights help bridge the gap between physical models and actual surge behaviors observed in gas turbine hardware.

2) TIME-VARYING PARAMETERS AND OPERATING CONDITIONS. Surge behavior is highly sensitive to time-varying system parameters and fluctuating operating conditions, such as variations in compressor geometry, rotational speed, fuel flow, and guide vane angles. Environmental factors, including inlet distortion and atmospheric changes, further exacerbate this variability. These time-varying changes make static models unreliable and require adaptive or robust modeling methods that can handle real-time changes. If these dynamic changes are not considered, the accuracy of surge prediction and control effectiveness will be seriously affected.

3) BALANCING MODEL ACCURACY WITH REAL-TIME FEASIBILITY. A central challenge in surge modeling and control is the trade-off between model accuracy and real-time feasibility. While detailed physical models can achieve high prediction accuracy, their computational complexity often exceeds the real-time constraints required for active control. Conversely, simplified models with lower computational loads may fail to capture critical surge dynamics. Achieving an optimal balance calls for the integration of reduced-order modeling, data-driven techniques, and real-time optimization algorithms. Such hybrid approaches can offer both sufficient accuracy and acceptable response speed, enabling practical deployment in safety-critical systems like aero-engines and industrial gas turbines. However, this hybrid modeling requires a lot of calculations and verification, which will greatly increase research costs and extend the development cycle.

In summary, the complexity of surge modeling and control arises from the interplay of nonlinear multi-scale dynamics, time-varying parameters, and the pressing need to reconcile model fidelity with real-time implementation constraints. Addressing these challenges requires multidisciplinary efforts combining aerodynamics, control theory, and artificial intelligence.

C. RESEARCH OUTLOOK AND FUTURE DIRECTIONS

This review highlights the current status and recent advances in compressor surge monitoring, modeling, and control. A clear trend is a shift from isolated strategies to more integrated approaches that combine real-time sensing, control-oriented modeling, and intelligent control techniques. Signal-based monitoring methods have proven effective in detecting early surge precursors, while simplified dynamic models, particularly those based on the MG framework, continue to provide valuable insights into system behavior. Simultaneously, control strategies are evolving toward greater adaptability and performance through model-based and data-driven design.

Despite these advances, several key challenges remain. Existing monitoring techniques are often limited by sensor location constraints, weak interference immunity, and insufficient response speed under harsh industrial conditions. Many existing models lack the flexibility to handle multi-parameter coupling and real-time parameter changes. In terms of control, the gap between simulated performance and practical robustness remains significant, especially in the presence of disturbances, component degradation, and varying operating conditions. Table IV provides a consolidated summary of key issues and future trends across surge monitoring, modeling, and control.

Table IV. Comparative overview of compressor surge research directions

Aspect	Key challenges	Promising Trends
Monitoring	Weak precursor signals; sensor placement limitations; noise sensitivity	Multi-sensor fusion; AI-driven anomaly detection; acoustic/vibration integration
Modeling	Limited adaptability; time-varying system parameters	Hybrid modeling; real-time parameter identification
Control	Real-time constraints; model uncertainty; lack of robustness	Hierarchical and adaptive control; data-informed predictive control

To address these limitations, future research should focus on:

a) Developing **hybrid modeling methods** that could combine physics-based with data-driven adaptability;
b) Creating intelligent monitoring systems that integrate multi-source sensing (such as acoustics, pressure, and vibration) with machine learning;
c) Designing unified hierarchical control architectures that combine predictive, robust, and adaptive strategies while balancing real-time feasibility and complexity.

In addition, several open research questions remain unresolved:

a) Real-time hybrid modeling under uncertainty: How can physics-based and data-driven models be effectively combined to handle real-time dynamics and unknown disturbances?
b) Transferable machine learning models across compressor types: Can learning-based approaches generalize or effectively adapt to different compressor architectures without retraining from scratch?
c) Sensor fusion for robust early detection: How can acoustic, pressure, and vibration signals be optimally combined to improve fault detection in noisy environments?

Ultimately, these research directions will contribute to more stable, efficient, and intelligent operation of compressors under increasingly demanding conditions.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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