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Review

A review on aero-engine inlet-compressor integration and inlet flow distortion in axial compressors

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ABSTRACT

The air intake-compression systems of modern aircraft usually use the aero-engine intake and fan/compressor as the main components. Inlet-engine compatibility has always been the key to the stable and safe operation of the propulsion system, including the influence of inlet distortion on the compressor performance and stall margin. Since 1950, theoretical models and experiments on the flow stability and inlet distortion of axial compressors have been released. After the 1990s, numerical methods became important tools. In the 21st century, the new trends of aircraft propulsion system/inlet integration, blended wing body, and stealth capability led to a new direction for the inlet-engine flow matching problem. This review aims to combine the development of both the inlet and the axial compressor components, and provides an overview of the research history, latest progress, and prospects of compressor inlet distortion in inlet-engine compatibility problems. Analytical or numerical models, experiments, and simulations related to inlet distortion problems are summarized.

1. Introduction

Since the emergence of the aero-gas turbine engine in the 1940s, its performance and configuration have undergone four generations of development, and the thrust-weight ratio has increased from 3 to 10. In the past two decades, advanced configurations of civil or military aircraft engines have been proposed, including the three-spool engine, the geared turbofan (GTF) engine, and the variable-cycle engine configuration. But in most flight conditions (e.g., Mach number $Ma < 3$), the air inlet-compression system remains the inlet-fan-compressor configuration, which means the inlet distortion problem of the inlet-engine compatibility has always been one of the core factors threatening the safety and stability of the propulsion system.

The pursuit of maneuverability and stealth in military aircraft led aero-intakes to a complex environment and compact layout design, which posed a great challenge to the ability to efficiently organize and control the airflow as uniformly as possible and transport it to the aerodynamic interface plane (AIP) downstream. At the same time, the design load and pressure ratio of the axial compressors have been increasing over the past decades, which may lead to serious flow stability problems under these complex inlet distortion conditions. In advanced fighters, the S-shaped airflow duct with a coating of radar-absorbing material has become an important technology for stealth capability [1]. Some subsonic unmanned aerial vehicles (UAVs) and bombers tend to use blended wing body (BWB) or flying wing configurations, where S-duct, half-embedded or embedded inlets, and boundary layer ingestion (BLI) inlets might be adopted [2,3]. Besides, wide-speed-range aircraft, which represent the future development trend, place higher requirements on the flow capture of the supersonic or even hypersonic inlets. Supersonic inlet flow instability was also of concern.

In the scope of civil aircraft, although there has been research and application (i.e., the Tu-144 and the Concorde) of supersonic civil aircraft since the 1950s, subsonic civil aircraft are still widely used due to factors such as cost and noise control. Subsonic pitot-type inlets were widely used as nacelles, and the small length-diameter ratio might cause a stronger aerodynamic coupling among the flow fields of the external environment, the nacelle, and the low-pressure fan. Special inlet distortions may also be induced in special flight conditions. With the update of civil aircraft technical indicators (e.g., specific fuel consumption (SFC), emissions, and noise pollution), new aerodynamic layouts for airframe-propulsion integration are being developed [4]. From the 1990s to the 2020s, some well-known projects (e.g., ERA [5], VELA [4],

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NACRE [6], and ACFA2020 [7]) have been carried out. Aircraft such as the SAX-40 and X-48B adopted the BWB or HWB (Hybrid Wing Body) aerodynamic design and the BLI inlet-engine system. Like some military stealth UAVs, similar challenges in inlet-engine compatibility are foreseeable.

In short, it is possible for both military and civilian aircraft to encounter unique inlet-engine compatibility problems. From the perspective of the air intakes, two main concerns were prominent. The first is to guarantee a sufficient airflow rate for the downstream components (airflow rate matching), and the second is to organize the air flow at the AIP as evenly as possible by using optimized design or flow control techniques (flow field matching). As for the compression components, the main problem is evaluating and increasing the aerodynamic stability of compressors under various distortion conditions. When unsteady numerical simulation had just been applied to the research of turbomachinery, Cousins [8], Bissinger [9], and Breuer [10] overviewed the theoretical and experimental developments of inlet-engine compatibility at that time. More than 10 years later, steady and unsteady Reynolds-averaged Navier-Stokes simulations (RANS, URANS) have become important tools for studying flow mechanisms and inlet-compressor coupling effects. High-fidelity or hybrid-fidelity methods such as detached eddy simulation (DES), large eddy simulation (LES), and direct numerical simulation (DNS) have also been improving.

During the past decades, various kinds of tools with different focuses have been developed that are capable of making trade-offs between fidelity and computational consumption [11], as shown in Fig. 1. This review aims to unite the research on aero-intake and compressor systems, summarize the history and recent progress in inlet-compressor integration, and provide a reference for future trends from the perspective of axial compressors. Internal flow characteristics caused by typical intakes are discussed in Section 2. Theoretical and numerical tools and techniques for evaluating inlet distortion at the AIP, axial compressor performance, and flow stability are reviewed in Sections 3, 4, and 5, respectively.

2. Inlet distortion caused by aero-intakes

The design of aero-intakes is closely related to the purpose of the aircraft. Different types of aero-intakes may cause different internal flow characteristics, resulting in different types of distortions at the AIP.

Classical configurations of military supersonic intakes include axial symmetric intakes (e.g., MiG-21 and F104), two-dimensional rectangular intakes (e.g., MiG-23), and similar wedge-shaped intakes (e.g., MiG-29, F14, F15, etc.). Typical advanced configurations include the Caret inlet used by the F22 fighter and the diverterless supersonic inlets (DSI) used by the J20 and F35 fighters [12]. For advanced wide-speed range aircraft, the typical turbine-based combined cycle (TBCC) propulsion systems include the tandem TBCC (e.g., SR-71) and the over-under TBCC (e.g., SR-72). Unique inlet-engine-nozzle integration and inlet distortion problems were encountered [13]. In higher Mach number conditions, ramjet engines, scramjet engines, and rocket-based combined cycle (RBCC) propulsion systems without compressors are better choices, which is beyond the scope of this review.

For subsonic intakes, classical Pitot-type intakes were applied to the earliest subsonic fighters (e.g., MiG-15) and are still widely applied to the nacelles of conventional civil aircraft. As an optimization, non-axisymmetric drooped and scarfed short nacelles were designed and studied to control the noise [14] and optimize the performance of the engine at high AOA conditions [15]. Advanced S-duct (or serpentine) inlets and BLI inlets are of great concern because of the distortions caused in the AIP. Recently, a new compact S-inlet for supersonic air intake conditions has been proposed and tested [16].

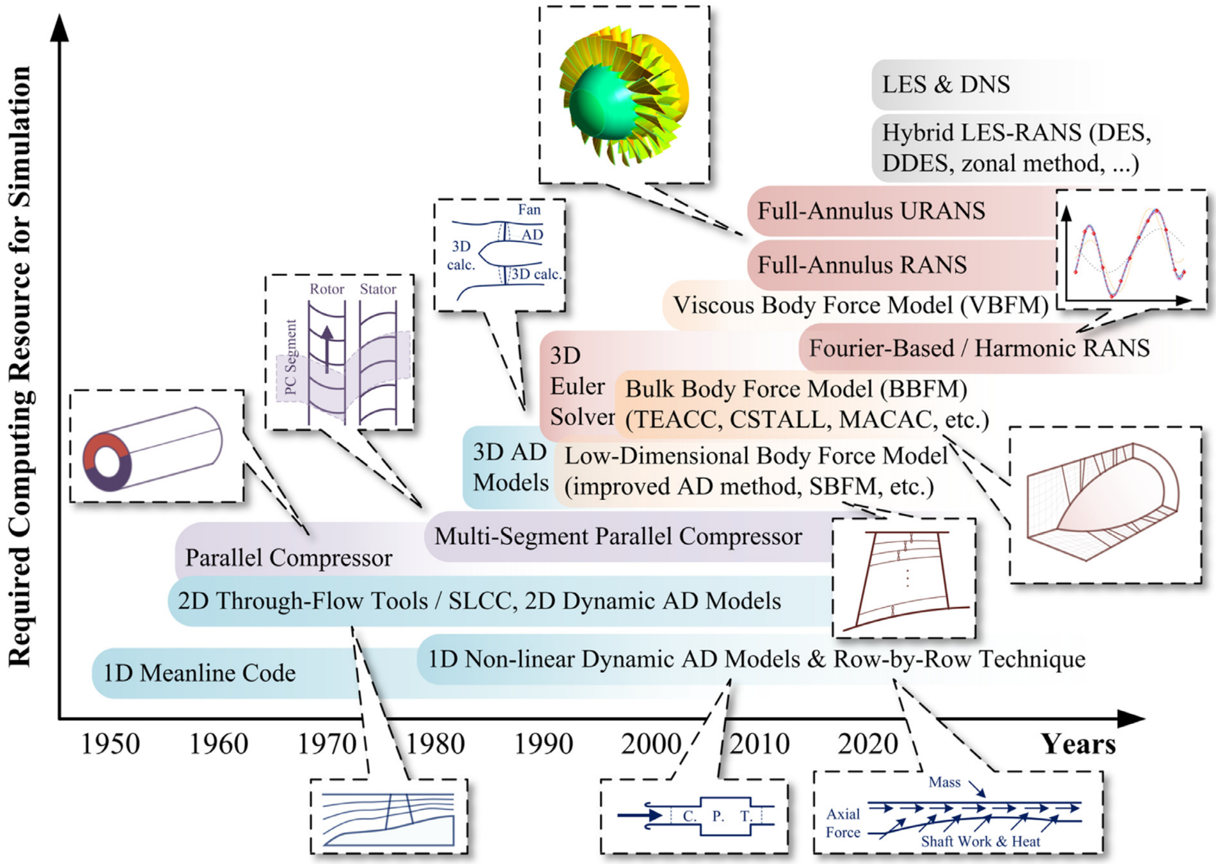

Fig. 1. Models or Simulation Tools with Different Degrees of Simplification, Computational Consumption, and Fidelity [104,116,128,131,135,136,147].

2.1. Supersonic inlet flow stability

For supersonic inlets, more attention is paid to the control of the shockwave system, the control of adjustable components, and internal flow instability. Most of these studies are carried out without compression components downstream. Therefore, these decoupling studies mainly concern about the spatial and temporal uniformity of flow parameters at the AIP between the inlet and the engine face. Of the two, the temporal uniformity appeared to be more of a concern, including inlet buzz and other unstart phenomena. Inlet buzz is usually caused by severe subcritical conditions, while severe supercritical conditions might cause the local unstart problem for high-Mach inlets [17,18]. Instability in subcritical conditions is generally of greater concern. When the supersonic inlet and the engine work together, the inlet is usually in a slightly supercritical condition. Typical flow structures in these conditions are shown in Fig. 2. Apart from typical temporal distortions, the inward or outward turns in the duct of over-under TBCC configurations were found to cause extra spatial distortion upstream of the turbine engine [13]. Besides, the spatial non-uniformity induced by the square-to-circular transition and shock waves upstream of the AIP might also be noteworthy in some conditions [19,20].

Inlet buzz was first discovered in the study of missile air intake by Oswatitsch in 1944 [21]. It is now generally considered to be a kind of self-sustaining shock oscillation. The Ferri criterion [22] and the Dailey criterion [23] are two famous mechanisms. The former focuses on the interaction between the shear layers (originating from the oblique shocks and the terminal shock) and the boundary layer of the cowl lip [22], while the latter focuses on the shock-wave boundary-layer interaction (SWBLI) generated by the intersection of the boundary layer and the terminal shock on the ramp surface [23]. Fisher et al. [24] linked the Ferri criterion to little buzz and the Dailey criterion to big buzz, based on detailed experiments. Kumar briefly summarized the progress in the schlieren technique and numerical simulations on inlet buzz [25]. Recently, a new type of “mild buzz” was discovered in the flow stability research of an external-compression supersonic inlet and seemed to link to a different origin [26].

From the perspective of the compressor, the frequency of the flow oscillation at the AIP is important, as it directly describes the characteristics of the sinusoidal-form planar wave inlet distortion. For the dominant oscillation frequency, there seemed to be no direct relationship between the little buzz and the big buzz. In some inlets, the oscillation frequency of both is similar [24,27], while in others, the frequency of the big buzz is much lower [28] or higher [29]. It was believed that in the generation of this self-sustained oscillation, not only does the source of instability need to propagate downstream, but also the feedback mechanism upstream is required to form a closed loop. The upstream-propagate pressure wave satisfies the latter condition and results in a typical acoustic resonance. Therefore, the possible buzz frequency could be quickly estimated based on the one-dimensional standing wave theory [20,28,30].

Supercritical instability was more considered in the hypersonic inlets of ramjets, scramjets, or RBCC configurations. However, the inlet-engine compatibility problems should not be discussed for these high Mach number configurations, as the hypersonic inlet itself should be considered an important part of the thermodynamic circle. Therefore, the problem concerned here should be limited to the turbine engine mode of the TBCC configurations (Ma < 3), where a serpentine duct is usually combined with the supersonic inlet due to space constraints. There are few related studies on the supercritical flow characteristics of

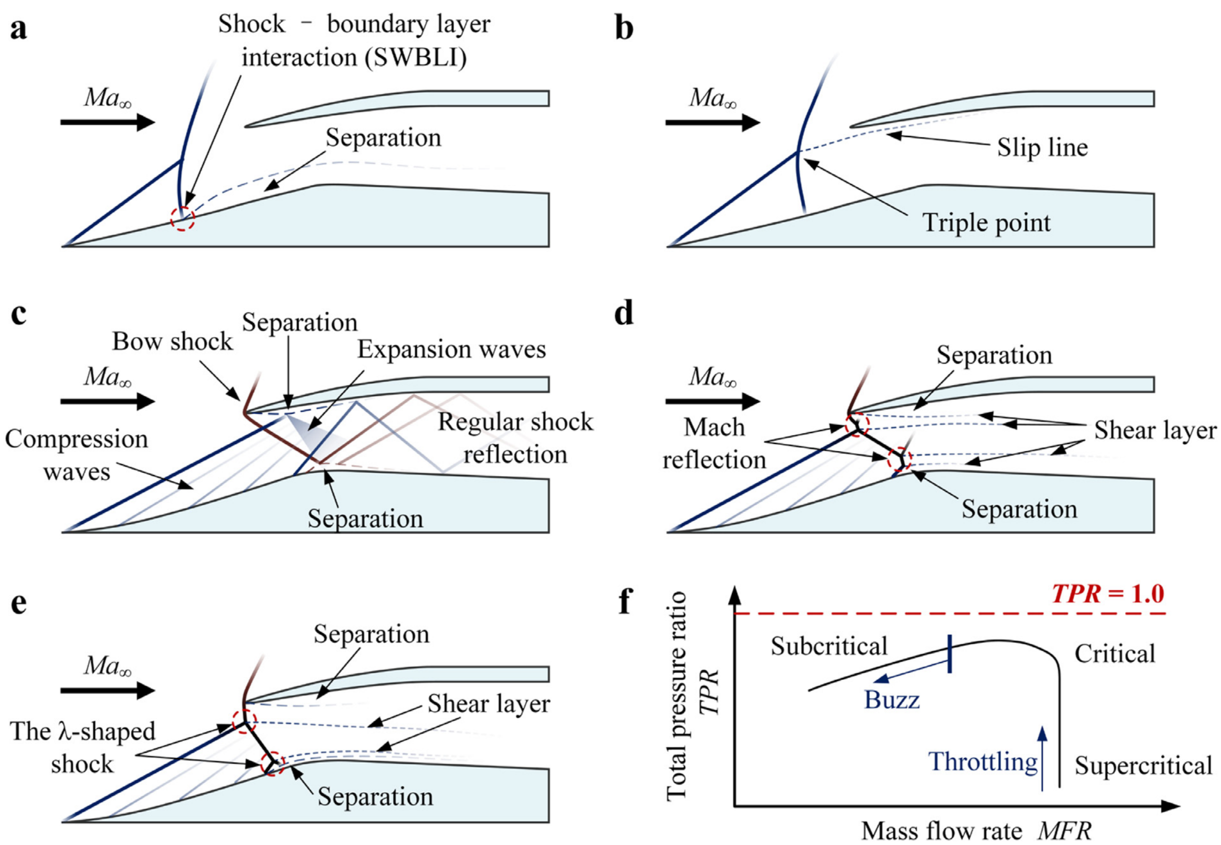

Fig. 2. Typical Flow Structures of Some Supersonic Inlets in Off-Design Conditions. (a) The Dailey criterion of subcritical buzz conditions [23]. (b) The Ferri criterion of subcritical buzz conditions [22]. (c) Regular shock reflection of an external-compression supersonic inlet at a small throttling ratio (TR) [31]. (d) Mach reflection of an external-compression supersonic inlet at medium TR [31]. (e) The lambda-shaped shock structures of an external-compression supersonic inlet at large TR [31]. (f) Typical performance curve for supersonic inlets in different operating conditions [32].

these supersonic inlets. But in hypersonic inlets, previous studies concluded that typical instabilities might be related to the shock reflection transition from overall regular reflection (ORR) to overall Mach reflection (OMR) near the cowl lip [17,31]. Local unstart can cause a significant decrease in the flow coefficient at the AIP, and the compressor components, if present, are sensitive to the sharp drop in the mass flow rate.

Overall, the internal flow in the supersonic intake is rich in detail. Inlet buzz has been the central concern for years. Plenty of studies have been carried out in buzz detection, mechanistic experiments, flow simulations, flow instability analysis, shock wave-boundary layer interaction (SWBLI), and optimized design. However, the compression system is concerned with the spatial and temporal uniformity of the inflow. It seems that not enough research has been done on the supersonic intake-compression system as a whole.

2.2. Nacelle intakes

Before coupled nacelle-fan numerical simulations were carried out in the 21st century, there were related studies on measurements, flow visualization experiments, and simplified numerical analysis. Notable experiments include the research of boundary layer separation (BLS) at pitot-type intakes with different geometric details [33] and surface oil flow visualizations with vortex-generator-based flow control methods [34]. Most of the early numerical methods were based on the potential flow method [35], inviscid Euler equations [36], and Navier-Stokes (NS) solvers with actuator disk models [37].

In crosswind or high AOA conditions, the separation and reattachment of the nacelle boundary layer is an important source of dynamic distortion at the AIP. This is possible to cause the fan to remain stalled even if the inlet condition returns to clean (locked in stall). In 1999, Freeman recorded this flow oscillation experimentally and concluded that it was due to the delay between the fan flow and the inlet response [38]. Hall and Hynes measured the delay effect of the boundary layer separation and reattachment in crosswind, plotted the hysteresis loop, tested the ground and crosswind effects, and pointed out that the change of the crosswind angle is the main determinant [39].

URANS and experiments have confirmed that the effect of the fan usually alleviates the steady-state inlet distortion of the nacelle in crosswind and high AOA conditions [40–42]. Although this appears to be beneficial to the stall margin, a recent URANS simulation suggested that the unsteady disturbances of the fan propagating upstream might increase the boundary layer separation downstream of the intake throat and the unsteady SWBLI upstream of the engine face, making the boundary layer more sensitive to the crosswind conditions [43].

Ground-vortex ingestion is another concerning phenomenon. Its intensity and position change have been fully studied and associated with changes in environmental wind speed, wind direction, and flight conditions. Recent URANS simulations have mainly focused on its unsteady performance and the stall margin loss [44]. Experiment results based on the Particle Image Velocimetry (PIV) technique were also carried out [45]. Related mechanisms and previous studies in detail were reviewed by Chen [44].

As for the flow control techniques in the nacelle, common active and passive control methods include the air-jet vortex generators [34], the plasma actuators [46], boundary-layer trips [34], and aerodynamic air bleed [47].

The latest short nacelle intakes have a trend towards non-axisymmetric drooped and scarfed designs for noise control [14] and optimization of high AOA performance [15]. However, simulations showed that boundary layer separation might be more likely to occur under crosswind conditions [48]. Design guidelines for related fan blades have also been gradually proposed in the past decade [15].

In conclusion, the crosswind or high AOA conditions usually cause local circumferential time-average total pressure loss (usually less than 120°) and might tend to expand towards the mid-blade sections. Dynamic distortions may be caused by boundary layer separation and reattachment at the nacelle lip or unsteady disturbance of the fan blades. The local tightly wound vortex and paired vortices were usually caused by crosswinds and ground vortex. Besides, wing-tip or fuselage-induced vortices may produce a diameter-scale bulk swirl distortion at the AIP, accompanied by an overall increase or decrease in compressor performance. Regardless of the above forms, previous studies have confirmed that there are two main sources of distortions: vortex ingestion and lip boundary layer separation. The former is mainly affected by the external environment, flight speed, and distance from the ground, while the latter is mainly affected by crosswind and AOA. Both of the two factors can result in a significant loss of stall margin. Besides, optimization of the fan's position may not only reduce the distortion intensity, but also reduce the aerodynamic loss of the nacelle.

2.3. S-duct inlets or serpentine inlets

Significant total pressure and swirl distortion at the AIP can be caused by S-inlets due to the curvature of the duct and the boundary layer separation (BLS) regions. Much attention has been paid to the steady or unsteady internal flow structures and flow control methods, especially for some newly designed serpentine BLI inlets. The radial and circumferential velocity gradients and static pressure gradient on the cross-section can induce secondary swirl flow, and the streamwise static pressure gradient near the solid wall may induce boundary layer separation.

In the early design and internal flow mechanism analysis, the S-ducts were usually simplified as variable-diameter round ducts with curved centerlines (e.g., the polynomial designs [49] and the double arc designs [50]). The swirl patterns at the AIP were measured early by Bransod [51] and Guo [52] in the 1980s. Later, the oil flow visualization technique was used for the BLS regions inside [53]. In the 1990s, RANS solvers started to be applied to isolated S-duct inlets to simulate the BLS regions and distortion at the AIP [54]. Some classical or well-studied S-inlets were designed and investigated, including the M2129 inlet [55,56], the IFCPT S-duct [57,58], and a recent supersonic compact serpentine air intake [16].

However, both numerical and experimental works showed the complexity of separating flows, which posed a serious challenge to the accuracy of the turbulence models required for RANS simulation. Take the M2129 inlet as an example; the loss and swirl predicted by the S-A turbulence model might be larger [55], and the RNS3D solver (based on an eddy viscosity turbulence model) seemed to be inaccurate in predicting the start of BLS at high Mach numbers [56]. Due to this complexity, the 3rd and 4th propulsion aerodynamic workshops (PAW03, PAW04) summarized and compared the calculations of dozens of different RANS solvers for a specific S-inlet (the IFCPT S-Duct) and found that the Spalart-Allmaras (SA) or shear stress transport (SST) models appeared to have good performances for this kind of flow [57,58]. Besides, turbulence models based on the Reynold stress model (RSM) also showed consistency with experiments to some extent [59,60].

Recent high-fidelity simulations, such as the DDES (delayed detached eddy simulation) [61] and LES [62], for isolated S-inlets became possible. Experimental techniques with higher temporal and spatial resolution, such as Doppler global velocimetry (DGV) [63] and stereoscopic particle image velocimetry (SPIV), have also been applied [61]. Modal analysis methods such as proper orthogonal decomposition (POD), its spectral variant (SPOD), and dynamic model decomposition (DMD) are optional to analyze the form and switching of unsteady modes [61,64].

For flow control techniques, classical micro-vanes and synthetic jets were widely researched. New flow control technologies include the active method based on sweeping jet actuators (SJAs) [65], plasma actuators [66], and bio-inspired passive surface treatments [67].

As the compact aerodynamic layout of some S-duct BLI inlets results in a stronger coupling of the inlet and engine, the boundary conditions of isolated S-inlets might deviate from reality. But the coupling research may encounter some special difficulties below.

Numerically, (U)RANS calculations require fine boundary layer mesh elements near the fan blades and the blade passages, which means that the results usually take weeks or months to be obtained. To overcome this disadvantage, in the 2010s, Chima simulated the Versatile Integrated Inlet Propulsion Aerodynamics Rig (VIIPAR) of the NASA Glenn Research Center (GRC) by using the CSTALL body force model program [68]. This was possible to avoid the large number of elements by using body force source terms instead of blade rows, with the sacrifice of precision. As far as academic research is concerned, coupled (U)RANS calculations were not completely impossible and have been carried out on the propulsion system of some S-duct BLI intakes and investigated the evolution of inlet distortion [69]. However, during the iteration and design phases, if the performance of the inlet-compressor system in inlet distortion conditions needs to be evaluated, the resource consumption is too high.

Experimentally, the size of the compressor limits the size of the inlet, though the full-scale coupled experiments are much more demanding on equipment and space than the scaled isolated inlet experiments. One low-cost solution is to use special swirl distortion screens (or other distortion generators) to replace the full-size S-inlet [70], but the dynamic distortion patterns might deviate from true S-inlet configurations. Recently, a few full-size coupled tests have been recorded, notably the research from NASA [71] and the tests of the MexJET turbofan engine in Germany [72].

In conclusion, previous studies confirmed that the S-ducts may cause one-per-rev, two-per-rev, or sometimes three-per-rev total pressure distortion patterns according to different designs, and the scales of these deficit regions are comparable to the radius of the AIP. Aggressive designs usually lead to multi-per-rev patterns. A pair of counter-rotating vortices may appear near the main distortion region, and a weaker pair of vortices can sometimes be found on the other side of the AIP. Complex unsteady modes are mainly related to the streamwise vortex structure caused by boundary layer separation.

3. Types and assessments of inlet distortion at the AIP

The temporal and spatial non-uniformity of the flow at the AIP pose challenges to the efficient and stable operation of the compressors. In addition to the typical distortion forms discussed in Section 2, more general inlet distortions can be described and assessed according to standardized compressor experimental guidelines. Total temperature distortions under special conditions will also be discussed below, as they can also endanger the flow stability of the compressor significantly.

The basic idea of the distortion assessment is to extract one or more indices that have the most significant impact on compressor performance, efficiency, and stability from the AIP as indicators. Well-established distortion assessment indicators can be used for decades, and their calculation expressions have been introduced in detail in some reviews on compressor testing [9,10] and guidance documents shown below.

3.1. Total pressure distortion

Total pressure distortion is the most classical form. The earliest studies mainly focused on the time-average (or steady-state) patterns and simplified the features into circumferential distortion, radial distortion, and the combination of the two. However, the tests of the F111 [73] and the B70-J93 inlet-engine system [74] found that the increase in turbulence intensity may also lead to stalls, even if the steady-state distortion remains at an acceptable level. In the late 1960s, as a result, dynamic total pressure distortion also became a concern.

In the 1970s, NASA recorded abundant experiments on the effects of total pressure distortion on the pressure-rise characteristics and stability of axial compressors [75,76]. For dynamic total pressure distortion (temporal non-uniformity), Bowditch [74] reviewed the study of inlet-engine compatibility and inlet distortion from the perspective of the 1980s and compared some classical methods for evaluating dynamic distortion, including the Jacock method, the Melick method, and the Motycka/Steven series method. The Jacock method is based on the extreme value theory (EVT). It attempts to estimate the maximum distortion level caused by dynamic distortion [77]. The Melick method is an evaluation for a limited number of dynamic pressure measurement points, aimed at the tradeoff between the test cost and data accuracy [78,79]. The Motycka/Steven series of methods introduces random numbers to estimate dynamic distortion peaks [80]. For dynamic distortion, special dynamic responses can only be induced when the distortion frequency is within the sensitive range (which may be approximately $1\% \sim 100\%$ rotor shaft speed suggested by Breuer[10]) of the compressor. Fluctuation frequencies that are too low can be approximated to be quasi-steady-state for the engine, while extremely high-frequency dynamic distortion cannot be kept up by the compressor due to the inherent aerodynamic delay.

For the assessment of the time-average total pressure distortion (spatial non-uniformity), in 1972, the SAE International Aerospace Council Divisional Technical Committee S-16 (S-16 Committee) was formed. Later, the publication of the Aerospace Recommended Practice 1420 (ARP1420) became a milestone in the total pressure distortion assessment, and the newest related guidelines were released as ARP1420C [81]. The evaluation paradigm (measurements, indicators, and empirical quantitative estimation of compressor performance and stability degradation) for engineering was gradually established. In 1983, Aerospace Information Report 1419 (AIR1419) summarized the important progress related to total pressure distortion in the 1970s, and the latest version of this guideline was released in 2023 as AIR1419D [82]. Calculation examples of the total pressure distortion indicators $\Delta PC/P$ (or circumferential distortion indicator, *CDI*), $\Delta PR/P$ (or radial distortion indicator, *RDI*), and *MPR* (Multiple-Per-Rev), as well as the integrated scaled test methods with aircraft components and aero-intakes, were introduced in detail. Besides, the ARP6420 [83] provided similar guidelines for pressure, temperature, and planar wave distortions in 2021.

Apart from the indicators above, aero-engine research institutes and manufacturers have also proposed other indicators based on their methods, such as the earliest $\Delta P/P_{ave}$ index (applied to F111 first) [73]; *DC60* and *DC90* of the Rolls-Royce; *DI, IDC*, and *IDR* of the General Electric Company (GE); K_θ and *KRA* of the Pratt & Whitney; and the W, $\Delta\sigma_0$, and ϵ_{av} indices used in Russia and China. Pecinka [84] and Campbell [85] compared these total pressure distortion indicators.

These basic forms of spatial distortions have brought abundant research directions with practical and engineering backgrounds. Typical distortion patterns for the inlet-compressor interaction are shown and explained in Fig. 3. In terms of axial compressors, especially in distortion conditions, studies related to tip clearances, stall mechanisms, stall warning, stall margin enhancement, and unsteady rotor-stator interaction have also been of great concern.

3.2. Total temperature distortion

In the mid-1960s, the impacts of time-variant and steady-state temperature distortions on aero-engines were noticed. As a classical form of time-variant temperature distortion, the total temperature ramp is usually the result of the ingestion of hot exhaust gasses from weapons, and is also likely to cause the engine to stall, as the F86 and F94C fighters experienced [86]. The temperature rise rate is the main indicator of the temperature ramp. Besides, it was also concluded by the S-16 committee that in the conditions of exhaust gas or steam ingestion, the temperature ramp might not be the predominant factor. In addition to the influence of the spatio-temporal non-uniformity of the total temperature, the URANS simulations of Yao et al. indicated that total temperature distortion could be induced by total pressure distortion in some multi-stage axial compressors. In these studies, a phase difference (approximately

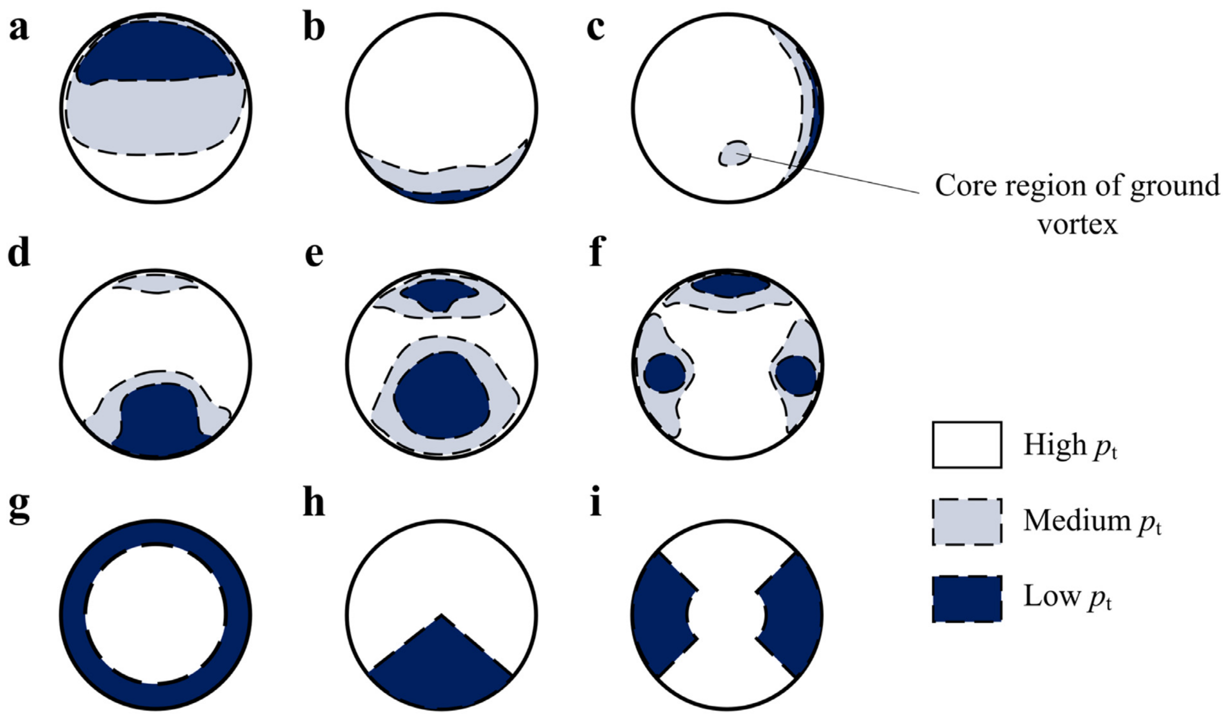

Fig. 3. Typical Total Pressure Distortion Patterns at AIP. (a) Inlet spatial p_t distortion characteristics of an over-and-under TBCC configuration [13]. (b) Nacelle-induced pattern in high AOA conditions [40,41]. (c) Nacelle-induced pattern in crosswind and ground vortex conditions [43,44]. (d) Typical one-per-rev pattern induced by S-ducts with low curvatures [55]. (e) Typical two-per-rev pattern induced by S-ducts with high curvatures [59]. (f) Typical three-per-rev pattern induced by aggressively designed S-ducts [57]. (g) The idealized radial distortion pattern [82]. (h) The idealized one-per-rev circumferential distortion pattern [82]. (i) A two-per-rev example of idealized combined radial and circumferential distortion [82].

90°) between the total pressure and the total temperature distortion in the circumferential direction was found [87,88].

The S-16 committee issued the ARD50015 document in 1991, which was replaced by the AIR5867 document in 2017 [89], providing guidelines for classification, experiments, and evaluations for total temperature distortion. Like the guidelines in AIR1419, the distortion descriptors $\Delta TC/T$, $\Delta TR/T$, and sensitivity coefficients K_C and K_R were defined to evaluate the influence on the loss of pressure ratio and stability margin comprehensively.

In the last century, related experiments were carried out on some turbojets, turbofans, and turboshaft engines (e.g., J85, TF30, and T700) [89]. Hydrogen burners or hot air jets were usually used as heat generators. Recently, a few related numerical studies on the propagation and evolution of temperature distortion were carried out. Besides, the hot gas ingestion (HGI) problem of the vertical and short take-off and landing (V/STOL) aircraft has attracted attention in the past decades [90]. But on the whole, more attention has been paid to the combined total pressure-temperature distortion.

3.3. Swirl distortion

In the 1970s, the impacts of swirl distortion on engines were first shown during the tests of the Tornado fighter [9]. Later, the tests of the Tomahawk missile and the F-35B fighter both encountered swirl distortion problems. Typical swirl distortions were often generated by vortex ingestion, inlet total or static pressure distortion, and S-duct inlets.

Most swirl indicators are based on the swirl angle. The indicator first used was τ_{87} (the ratio of the circumferential velocity component and the axial velocity component on the 87% radius of the AIP) [91], which was later developed by Peng into a combination of $\tau_{87,average}$ (the intensity of the bulk swirl), S_{cb} (the coefficient of the bulk swirl), τ_{ct} (the intensity of the paired swirl), and S_{ct} (the coefficient of the paired swirl) [92]. They were defined as:

$$\begin{cases} \tau_{87,average} = \bar{\tau}_{87} = \frac{\sum_{i=1}^{N} \tau_{87,i}}{N}, & S_{cb} = \frac{\bar{\tau}_{87}}{|\tau_{87}|_{\max}}; \\ \tau_{ct} = \frac{\tau_{87,\max} - \tau_{87,\min}}{2}, & S_{ct} = \frac{\tau_{ct}}{|\tau_{87}|_{\max}}. \end{cases} \tag{1}$$

In the above equations, the index i means the i^{th} locations of different circumferential measurement points, and the N means the total number of measurement points.

However, these early indicators above only used parameters on the 87% radius ring of the AIP because they were designed for flight conditions. For ground tests, more detailed measurements can be carried out, and the generality of the above indicators is limited. Another early indicator, *SC60*, was proposed and tested, and it was defined as the ratio of the maximum average circumferential velocity component over a sector area of 60° to the axial velocity component in the center of the AIP. For a detailed evaluation of the swirl pattern and intensity, in 2010, AIR5686 recommended the *SS* (Sector Swirl), *SI* (Swirl Intensity), *SD* (Swirl Direction), and *SP* (Swirl Pairs) as combined indicators [93], though the selection of AIP location might affect the results of the swirl evaluation.

In addition, four categories of swirl distortion were defined by the AIR5686 guideline (i.e., bulk swirl, tightly wound vortices, paired swirl, and cross-flow swirl). The bulk swirl can cause the compressors' angle of incidence (AOI) to increase (i.e., counter-rotating bulk swirl) or decrease (i.e., co-rotating bulk swirl) in all circumferential positions, thereby causing the overall rise or fall of the characteristic line. For counter-rotating bulk swirl, the increased AOI means a significant rise in mass flow rate at the stall boundary. The paired swirl and cross-flow swirl distortions are characterized by positive and negative changes in swirl angle at different circumferential positions, which means the AOI fluctuates dynamically with an approximate frequency range of 1–3 times the rotor shaft speed. This might cause the total pressure characteristic line and stability margin to drop dramatically, as discussed in ref. [94]. The tightly wound vortices are mainly related to the ingestion of ground

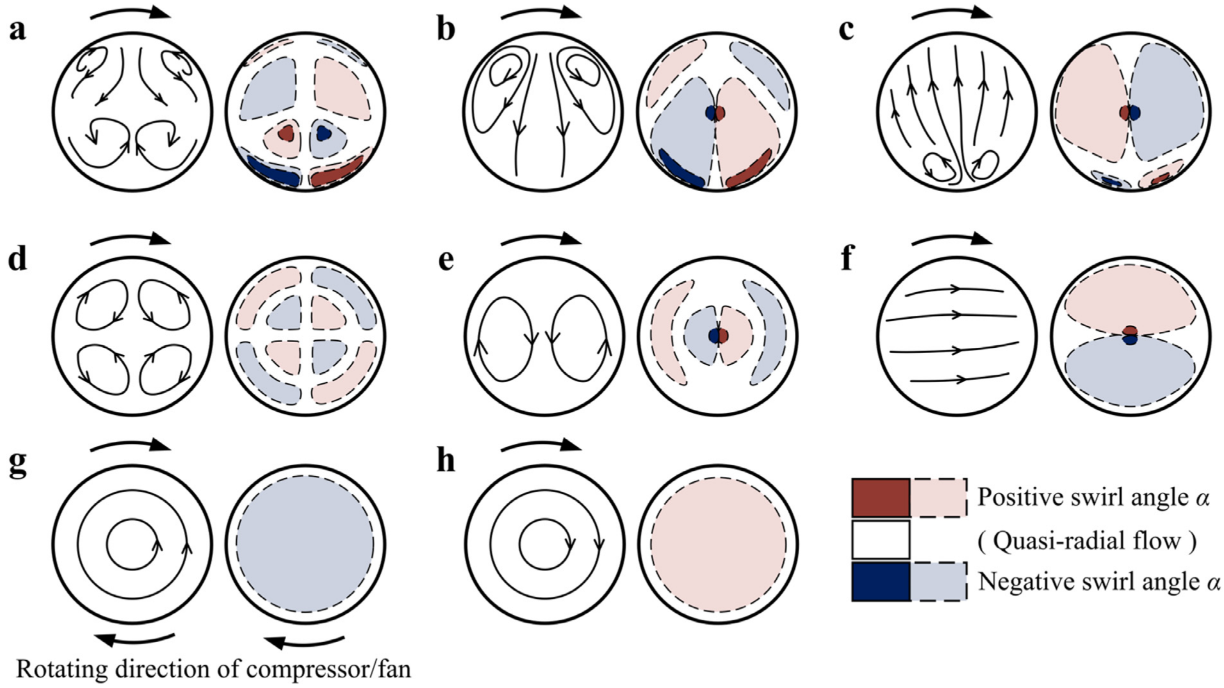

Fig. 4. Typical Swirl Distortion Patterns and Circumferential Swirl Angle Distribution Patterns. (a) A typical two-pair swirl pattern caused by S-duct inlets [61,62,99]. (b) A typical one-pair swirl pattern caused by S-duct inlets [61,99]. (c) A possible swirl pattern downstream the nacelle in high AOA conditions [42]. (d) Ideal two-pair counter-rotating swirl distortion [93]. (e) Ideal one-pair counter-rotating swirl distortion [93]. (f) Cross-flow distortion [93]. (g) Ideal counter-rotating bulk swirl [93]. (h) Ideal co-rotating bulk swirl [93].

vortex or wing-tip vortex. The influence region is usually accompanied by local total pressure distortion, and may be dynamic.

Experimentally, adjustable guide vanes [95], delta-wing vortex generators [96], chamber swirl generators [97], and specially designed stream vanes [98] have been applied as swirl generators to produce typical swirl patterns in place of real swirl patterns.

Typical swirl patterns and swirl angle distributions associated with nacelles and S-inlets are shown in Fig. 4. Related theoretical and numerical modeling, as well as compressor stability assessment and enhancement under swirl distortions, have been the main development directions in recent decades [99,100].

3.4. Planar wave distortion

The ideal planar wave distortion is a kind of one-dimensional, unsteady total pressure oscillation with no spatial non-uniformity. It can be simply described and classified by using the time-domain total pressure fluctuation curve and the frequency-domain power-spectral density (PSD)-frequency curve. Simplified dynamic analysis models are easily suitable for evaluating the dynamic response of such distortion to the compressor.

Steenken [101] and Ball [102] summarized its basic process of measurement and classification. Usually, dynamic total pressure data at the AIP is obtained and spatially averaged, before the PSD analysis is done to obtain the frequency-domain information. In 2021, the AIR5866A guideline classified the planar wave distortions into four categories, each corresponding to different wave sources. Inlet buzz, which is closely related to the supersonic inlet-engine compatibility, features a single-peak sinusoidal planar wave [103]. Dynamic total pressure assessments might also be applicable, but in some cases, the temporal non-uniformity caused by inlet buzz is strong enough that the effect of spatial non-uniformity is almost negligible [9,10].

The planar pressure pulse generator (P^3G) and air jet distortion devices are commonly used as planar wave distortion generators [103]. Recently, there has been little research on planar wave distortion. It is generally believed that it should be avoided during the design process of the propulsion system, including the control of the supersonic inlet flow stability.

3.5. Static pressure distortion

The static pressure distortion has less effect on compressor characteristics than other inlet distortions. It is usually caused by the curved centerline of the inlet duct, accompanied by swirl or total pressure distortion, such as the flow in S-duct inlets. Based on a simple streamline curvature analysis, one can infer that a long and straight duct is likely to weaken the static pressure non-uniformity quickly. Apart from the S-duct inlet configurations, unique static pressure distortion might occur in some newly designed drooped and scarfed nacelles, but more attention seems to have been paid to the effects on noise control [43].

4. Theories and models of compressor performance and stability

In addition to the experimental guidelines above, many theoretical and numerical models with different simplifications have been developing in the past decades. Some physical simplifications were verified by experiments, showing their reliability and rationality. Different from the full-annulus (U)RANS simulations or high-fidelity LES, these simplified methods have significant advantages in terms of computational and time costs. It is important to have an understanding of the origins of these methods because it determines their basic ideas and potential applications. Therefore, brief comments are also given in each subsection.

4.1. Low-dimensional performance simulation tools

In the early years, Mean-Line Code (MLC) and Streamline Curvature Code (SLCC) were developed as rapid and important simulation tools for the initial design of compressors. Low-dimensional simplifications prevent them from being applied to complex inlet distortion problems directly. However, they can form the basis for other numerical models and theories. In addition, improved versions of these rapid design tools continue to play an important role in the early stages of modern compressor design.

MLC is a row-by-row model that uses the semi-actuator disk to replace the effects of blades [82], and can quickly estimate the compressor characteristics in the one-dimensional design stage of the compressor. SLCC considers the flow to be axisymmetric, inviscid, and ideal, so it can only be applied to distortions with obvious axisymmetric features (e.g., radial distortion and bulk swirl) [82]. As a two-dimensional model, some geometric details of the meridian plane can be contained.

The accuracy of both methods directly depends on the accuracy of the relational database input between the loss and deviation of the blade rows. Therefore, abundant experiments or simulations might be needed to build up the database. As through-flow design methods, they are usually not used in the case of inlet distortion, and it is difficult to assess the stall boundary accurately and directly, but empirical indicators such as the de Haller number or the diffusion factor (D factor) can help with this.

4.2. Dynamic response models

Dynamic models consider the inlet and the engine as a whole system, and can examine the nonlinear dynamic response of the system before and after stalling.

The Greitzer model is a classical one-dimensional dynamic model [104]. The compressor and the throttle sections are simplified as actuator disks. The momentum equations for the inlet and outlet pipes and the mass conservation equation of the cavity are conducted to obtain the dimensionless parameter “B” of the system. A small “B” corresponds to a degenerative rotational stall process, while a large “B” implies that a limit ring or surge may occur after the compressor stall.

The combination of the one-dimensional model and stage-by-stage (or row-by-row) technology has given birth to analysis models of multistage compressor dynamic characteristics, represented by the dynamic turbine engine compressor code (DYNTECC) [105]. As a part of the Aerodynamic Turbine Engine Code (ATEC), DYNTECC solves Euler equations with source terms derived from the inputs of the blade row characteristic in quasi-steady states, taking the mass exchange, blade force effect, and axial work into consideration. In 2003, another inlet-compressor coupling model was developed. The inlet was solved by a three-dimensional solver, and the compressor was modeled with a similar one-dimensional model [106]. Apart from this work, Zhang and Hu combined the row-by-row and actuator disk methods, proposed a two-dimensional nonlinear model, and analyzed the dynamic characteristics of large hub-to-tip ratio multistage axial compressors [107].

Although these one-dimensional models can consider some unsteady distortion processes (e.g., planar wave and temperature ramp), they are not suitable for spatial distortion problems. In 1986, Moore tried to expand the original one-dimensional Greitzer model into a two-dimensional incompressible model, known as the famous M-G model [108,109]. It was assumed that most of the unsteady flow characteristics caused by circumferential non-uniformity can be preserved even if the flow is considered to be inviscid. The M-G model was able to characterize the rotational stall phenomenon in circumferential distortions, and theoretically predicted the existence of the large-scale modal waves, which was confirmed experimentally [110]. The higher-order distortion improvements to this model were later studied by Mansoux [111] and Lin [112].

Apart from the extended work of the Greitzer model, the DYNTECC model can also be combined with the parallel compressor method to investigate the influence of circumferential distortion on compressor performance [105,113].

In summary, these models were mainly developed from an explanation of the stall process in the 1980s. At the same time, these tools are precisely needed for the simulation of the overall dynamic simulation of the propulsion systems. At that time, various interesting forms of compressor stalls had not yet been fully discovered. Most of these models were initially based on uniform inflow conditions, and were later improved to handle simple inlet distortion forms. Dynamic response models provide a rapid but crude tool for qualitative behavior prediction after stalling.

4.3. Actuator disk and semi-actuator disk modeling methods

As classical and simple modeling methods for blade rows, the actuator disk (AD) or semi-AD methods were often incorporated into other models in Sections 4.1, 4.2, and 4.6. In the AD method, a blade row is reduced to a no-thickness disk with given flow parameters changing on both sides, while in the semi-AD method, an inertial distance was considered, simulating the flow information inside the blade rows to a certain extent.

4.3.1. (Semi-)AD-based numerical models and simulations

In addition to the applications in the low-dimensional tools above, in the 1980s and 1990s, three-dimensional Euler equations were usually solved in the bladeless regions, while AD or semi-AD was used in the blade regions. Billet’s model [114] assumed that the flow followed a series of one-dimensional channels (obtained from through-flow calculations) in the blade row area. The comparison with the experiments showed it could roughly predict the total pressure distribution downstream of the rotor row, but the one-dimensional assumption made it difficult to deal with boundary layer separation accurately. In a later report from SNECMA, a similar method was also adopted to simulate a multi-stage axial compressor [115]. Joo [116] reviewed the development of these methods on turbomachinery in the 1980s and 1990s, and calculated the interaction between an inlet-fan configuration. A RANS solver was first used instead of the previous Euler solver, but its result still could not be considered as a simulation with viscosity because of the coarse mesh elements near the boundary layer. After 2000, NS equations solved in the bladeless region started to develop in a real sense [117]. Recently, AD-related methods are usually considered only in large simulations, such as the integration of internal and external flow of BLI inlets or BWB aircraft, to simulate the suction effect of the engine with a lower computational cost [118].

4.3.2. (Semi-)AD-based flow stability assessments and stall models

Early in 1959, the AD method was used in the analysis of distortion waves and compressor rotational stalls [119]. In 1972, a nonlinear model describing the rotational stall was established based on the semi-AD method by Takata [120], and the stall mechanisms were clarified qualitatively but not quantitatively. After the M-G model was proposed in the 1980s, Hynes proposed a new nonlinear analysis model (H-G model), which aimed to evaluate the stability margin loss of large hub-to-tip ratio compressors with inlet distortions [121]. Further experimental verification by Longley [122] showed that the unsteady behavior of the rotor in circumferential distortion could be captured. However, the source of the flow instability was usually difficult to capture by using these time-advancing approaches. To capture the flow instability mechanisms, Sun [123,124] developed a three-dimensional analytical model for compressor stability analysis under uniform-intake conditions by combining the linear stability theory with the semi-AD method. Recently, Gu [125] combined this kind of analytical model with the parallel compressor modeling method, confirmed the ability to deal with the circumferential distortion problem, and showed the potential capability of dealing with other complex distortion problems.

4.3.3. Current situation of AD methods

AD-based models also take the performances of the compressor blade rows as input, which is similar to the methods in Sections 4.1, 4.2, and 4.5. Since 2010, the computational advantages of the AD and semi-AD methods have been diminishing compared to BBFM. This is why their applications for traditionally simulating compressor performance have rarely been carried out nowadays. However, it still has certain advantages in the iterative design, optimization, and internal-external flow co-simulation processes.

Although Section 4.3.2 indicates its import applications on stall margin evaluation theories, there has been little progress in recent decade, largely because the flow in newly designed axial compressors is too complex. Simplified theories have limited benefits compared to abundant numerical simulations. In general, these theories can only be used as a reference for estimating stability margins in the low-dimensional design processes of a new axial compressor, or to provide some qualitative analysis.

4.4. Parallel compressor theory

As a simple model, the parallel compressor (PC) theory provided an important analytical tool in the early years for the response and performance of the compressors in circumferential distortion conditions, while the radial distortion problems can be easily handled by 2D through-flow calculations. The combination of both techniques laid the foundation for body force models in Section 4.5.

In 1959, Pearson and McKenzie proposed the earliest parallel compressor model, supposing the sub-compressors worked independently with the same outlet static pressures [126]. It had many disadvantages, including but not limited to inaccurate outlet static pressure modeling, as well as the neglect of dynamic effects and circumferential secondary flow. Later, the improvements on the critical distortion angle, multiple segments, and unsteady corrections were proposed [127–129]. Finally, the work of Davis [130] and Longley [122] showed that reasonable stall margin loss predictions could be made based on PC theory.

Generally, the criterion for the stability boundary of the parallel compressor model is that the mass flow rates in any subregions reach the unstable flow rate of the compressor. The criterion mentioned in AIR1419D is when the character lines of one or more blade rows show zero or positive slopes. However, these criteria are sometimes not accurate enough. A more accurate stability analysis usually requires a combination of experimental results [82].

After 1990, the parallel compressor model evolved towards complex distortion conditions. In addition to the combination with the DYNTECC, Davis and Hale combined the parallel compressor model with the MLC model to investigate the effects of 5-degree co-rotating and counter-rotating bulk swirls on two compressors named Rotor1B and HTSC [94]. In 2011, Davis [131] demonstrated the possibility of handling various forms of combined distortions by showing five engineering cases related to PC models. It can assess the compressor's performance in inlet distortion conditions quickly during the design and test phases. However, its accuracy is limited, especially for radial distortion problems. Recently, Zhao proposed a modified circumferentially averaged method (CAM) based on the parallel compressor theory, verified it with numerical and experimental results, and analyzed the transmission of the distortion along the compressor interior [132]. Benichou developed a local PC approach for the preliminary design phase of BLI configuration, and compared the results with high-fidelity simulations and experiments, showing a relatively high degree of consistency [133].

It should be noted that the PC method was originally proposed to investigate the effect of inlet distortion on compressor performance and flow stability. After 2010, PC-related work was rarely carried out in isolation. Nowadays, its modeling ideas tend to be more theoretical than practical. Its main application is to quickly assess the ability to resist distortion in the compressor design process. A few decades ago, however, its combination with dynamic response modeling used to be the underlying theory in the scope of compressor inlet distortion.

4.5. Body force models

Body force models (BFM) can make a good tradeoff between accuracy and computational cost. Different technical routes have been proposed since 1990. Its basic idea is to use the body force source terms to replace the effect of blade rows. The amount of the calculation can be reduced significantly by replacing the fine boundary layer mesh elements with coarse mesh. Meanwhile, it means the modeling accuracy of the source terms is crucial.

Depending on the levels of simplification, body force models can also be divided into low-dimensional body force models (e.g., streamline BFM, or abbreviated SBFM), bulk body force models (BBFM), and viscous body force models (VBFM).

The basic idea of VBFM was proposed by Xu [11,134]. Only the boundary layer regions of the blades were modeled as source terms, leading to much greater computational consumption than other low-dimensional BFM methods. Comparatively, the quasi-three-dimensional BBFM and low-dimensional BFM have become research hotspots since the 1990s.

The BBFM is usually based on the average-passage method, assuming infinite blades for each blade row. By replacing all blade regions with coarse annular meshes, it is possible to quickly obtain the steady or even unsteady flow characteristics of the whole annulus under distortion conditions. It can be noticed that the BBFM has two main parts. The first is the full-annulus flow field solver. Euler solvers were widely used in the 1990s before being replaced by RANS solvers in the 21st century. The second part is the algorithm for extracting source terms from the blade row characteristics. Early algorithms were usually based on through-flow calculations (e.g., SLCC) or AD models. Nowadays, the single-passage RANS simulation of quasi-steady-state compressor characteristics is optional, which might only take a few days or hours.

Over the past few decades, BFM has achieved great success in the field of rapid simulation of coupled inlet-compressor configurations and flow distortion problems, and it is pardonable for BBFM to encounter some fidelity-related challenges below. The first shortcoming is that the passage-scaled flow details are covered up. Secondly, the blockage of the blades' thickness cannot be considered directly, causing an inaccurate prediction of the choke point. This can be improved by using a cross-section reduction factor or by adding extra source terms. Thirdly, quasi-steady-state axisymmetric characteristics are used to infer the blade row characteristics in the unsteady state. This requires modeling the dynamic characteristics of the blade row, which can be an important source of error. Taking the widely used first-order delay relationship as an example, the time delay factor usually needs to be confirmed carefully according to the design of the compressor.

In 1994, the famous TEACC (Turbine Engine Analysis Compressor Code) was developed by the Arnold Engineering Development Center (AEDC). Hale analyzed a single-stage compressor [135], a multi-stage compressor [136], and assessed the inlet-engine compatibility of a fuselage-intake with a three-stage fan configuration [137]. The NPARC Euler solver was used and later replaced by the WIND2.0 solver. Modified SLCC was finally used to model the source terms, though there was an early study based on DYNTECC.

Since the discovery of the spike-type stall precursor in 1993, spike-type stall precursor has become the focus of compressor research [138]. The bulk body force model developed by Gong [139] aimed at capturing and analyzing the initiation and development of these short-wavelength stalls on the four-stage compressor of the General Electric Aerodynamics Research Laboratory. In this model, the body force was decomposed into a force component that only turned the flow and another component that raised the total pressure. After this work, optimizations for the blade force coefficient were ongoing [140–142]. Its applications in inlet-fan interaction have also been tested [141].

Chima also proposed the famous CSTALL program and calculated the coupled inlet-fan-nozzle system VIIPAR in the NASA Glenn Research Center [68] based on the SWIFT CFD solver. Other early BBFM-related work includes the quasi-three-dimensional model carried out by Lindau and Owen [143].

Recently, BBFM has been gradually applied to the rapid simulation or optimization of BLI intakes and the flow analysis of inlet distortion. New models for complex inlet distortion problems are also developing. In the mix-fidelity model developed by Guo [144], the Koch pressure coefficient was modified as the stability criterion. The influences of complex combined inlet distortion on compressor flow stability and performance were also simulated.

Apart from BBFM, faster and lower-dimensional BFMs have also been developing since the 1990s. Escuret and Garnier developed a joint model using three-dimensional calculation in the bladeless regions and through-flow calculation in the blade regions [145]. The most simplified BFM developed by Longley [146] used two-dimensional calculations in the non-blade regions and a one-dimensional model in the blade regions. It can also be classified as a modified AD-based model. Recently, Cui [147] and Li [148] developed a new streamline body force model for simulating the BLI effect on BWB configuration, as a tool for quickly integrating simulations.

Recently, low-dimensional BFM has been in a similar situation to the AD and PC methods. BBFM has become a popular tool, and dozens of similar methods have been proposed by many research teams. In terms of the computer performance at the beginning of the 21st century, it can obtain rich three-dimensional unsteady flow results in a reasonable time. The origin of BBFM can be regarded as a more refined improvement of the AD-based and PC-based methods. Besides, because it is theoretically related to the basic idea of immersion boundary methods, one of these modeling methods is also known as IBMSG (immersed boundary method with smeared geometry). As a relatively refined modeling method, it has been combined with many engineering problems, including but not limited to the design of aircraft-propulsion system integration, the degradation of compressor performance in complex inlet distortion conditions, and the rapid assessment of unsteady interactions between the inlet and compressor.

4.6. Linear perturbation stability models

The idea of linear stability analysis can be traced back to the flow stability research paradigm pioneered by the Orr-Sommerfeld equation. Many modal or non-modal stability analyses were carried out in other fluid dynamic fields, among which detailed reviews were available [149,150]. Unlike other simulation tools, linear stability models, as methods for evaluating flow stability inside the compressor components, focus only on the precursor of the instability. It tries to analyze the flow stability of the compressor from the mechanism, and aims to supplement the empirical and numerical methods with new theoretical and mechanical flow stability analysis tools.

In 1955, Emmons and Stenning both developed the earliest compressor stall prediction models based on small disturbance methods for two-dimensional incompressible plane cascades, and gave some stability criteria based on the AOI or pressure-rise coefficient [151,152]. Later, two-dimensional incompressible and compressible models, as well as three-dimensional incompressible and compressible models, were proposed by Nenni [153], Bonnaure [154], Gordon [155], and Sun [123], respectively. By adjusting the acoustic impedance of the shroud, it is possible for Sun's analytical model to take the effect of casing treatment into consideration. Based on this, analytical models for transonic compressors and multi-stage compressors were proposed by Sun [124] and Cheng [156]. However, all models above are limited to uniform intake conditions, until Gu combined this model with the PC method and harmonic method, and achieved the new progress of linear stability models on the problem of circumferential distortion [125].

Apart from the analytical tools, numerical stability models were also proposed to take more geometric details into consideration. In 2013, Sun et al. [157] proposed the general theory of compressor flow stability. According to different levels of simplification, the streamline model and meridian model were developed, and the effects of the blade design and radial inlet distortion on flow stability were evaluated [158,159]. Flow stability studies on blade cascades were also carried out recently, but the radial wall boundary conditions and the spanwise change of the blade profiles need to be carefully handled before applying to real compressor configurations [160]. Generally, the axisymmetric assumption is still necessary to consider it as a bi-global analysis. In the scope of basic flow instability theories, the tri-global work was limited, mainly due to the storage and eigenvalue solving of the large matrix, and only ideal cases (e.g., isolated airfoil flow and flow around the sphere) have been studied recently, and it is still a long way before it can be applied directly to the inlet circumferential distortion conditions of real compressors.

5. Simulation tools for inlet distortion conditions

Although (U)RANS simulations were applied more than ten years ago, until now, the simulation of the full-annulus multi-stage compressors still required weeks or months, which makes it difficult to participate in the rapid iteration and optimization process required for engineering designs and tests. So far, high-fidelity tools are usually used for extra flow details.

Generally, numerical methods are divided into (U)RANS, LES, DNS, and some hybrid-fidelity methods, such as hybrid RANS-LES or LES-DNS methods. Abundant reviews related to the theories of these methods and their application to axial compressors can be found [161–163]. For inlet-compressor flow field matching problems, abundant flow details can be resolved, which provides a powerful tool for studying the stall mechanism and the interaction between the inlet distortion and the compressor component.

5.1. DNS, LES and hybrid RANS-LES methods

High-fidelity simulations are particularly suitable to obtain flow details that cannot be fully resolved by (U)RANS and BFM methods. The smallest turbulence scale determines the length scale of the mesh in DNS, and the number of nodes can be generally estimated as proportional to $Re^{37/14}$ for three-dimensional problems. Therefore, only low-Reynolds-number cases, rather than the complex internal flow in compressors, can be solved easily. However, simplified calculations at the mechanistic level are possible, including tip leakage flow [164] and blade flutter [165]. Although LES can reduce the computation to a lower level than DNS, usually its near-wall mesh scale is still similar to the scale of DNS. A series of hybrid RANS-LES models represented by Detached Eddy Simulation (DES), Delayed DES (DDES), and Improved DDES (IDDES) have made progress in the simulation of wake-type separated flows. Zonal methods can also be used adaptively in LES or RANS in specific flow regions. The details of these high-fidelity algorithms are not discussed, as the applications of the inlet-compressor flow distortion are of more interest here. Related reviews of the hybrid RANS-LES [163] and LES [166] used in turbomachinery are recommended.

Noteworthy studies related to the simulation of the inlet component includes some LES and POD results of flow in the isolated S-inlet [62] and the isolated supersonic inlet [167]. In compressors, LES was mostly used on planar cascades or single-passage calculations [168]. Up to now, it is still rare to see LES simulations used in simulating the full-annulus compressor stage in distortion conditions, but advances in algorithms and computers are making it possible to be applied in academic research in the next decade.

5.2. RANS, URANS and rotor-stator interface processing

The Reynolds-averaging-based simulations are computationally inexpensive compared to LES and DNS. Turbulence models are used to modulate vortex structures at almost all scales. With the computing resources of the 2020s, steady-state RANS has been able to meet some simulation requirements related to inlet distortion. The main challenge is the accuracy of turbulence models, especially when boundary layer separation occurs. For the integrated intake-compressor simulations, URANS has the highest fidelity among all the methods available today in the engineering sense.

The earliest URANS work on the full-annulus calculation without inlets was carried out by Yao [87] and Fidalgo [169] around 2010. Later calculations started to focus on real coupled inlet-compressor configurations, especially for nacelle-fan configurations. For coupled supersonic inlet and compressor configurations, Chima simulated an axisymmetric external compression supersonic inlet coupled to a Rolls-Royce fan in 2010 by using the coupled AVCS and SWIFT solvers [170].

There are also a series of fidelity levels between the steady-state RANS and URANS from the perspective of rotor-stator interfaces. The problem of data exchange at the rotor-stator interface is tricky, especially in the simulation of wakes and inlet distortions. Classical mixing plane methods smoothed out the circumferential non-uniformity on the interface, while the frozen rotor model allowed the effects of wake and distortion to pass through the blade row. As a steady-state RANS simulation with the lowest cost, the frozen rotor method shows a roughly reasonable but physically unsatisfying steady-state flow structure. The sliding plane method was widely applied in URANS [171], consuming much more time and computing resources on the initialization and iteration steps.

Apart from the above methods, harmonic-based numerical methods have also been developed, which have found a good balance between unsteady and steady simulation. The unsteady flow field is decomposed into the perturbations represented by the time-averaged flow and Fourier series. Related methods were initially developed by He et al. [172,173], and improved by Hall et al. [174]. Recently, Huang [175] developed the time-space spectral method based on this principle to develop it into the application of multi-row compressors, and reviewed the application of harmonic-based methods in calculation. Du and Ning applied a kind of harmonic balance method to simulating quasi-periodic turbomachinery flows [176]. These methods can reconstruct the approximate effect of a full-annulus RANS calculation within the time of several-passage calculations. However, problems of convergence and accuracy might occur in the near-stall or BLS conditions, as the quasi-periodic characteristics might be weakened.

Recent work based on immersed boundary methods (IBM) is also noteworthy. The concept of IBM was first proposed by Peskin in the 1970s [177]. Its basic idea is to characterize the effect of the wall as force source terms, and its solution is usually based on a Cartesian coordinate. Related theories and recent progress in detail were presented by Griffith [178] and Verzicco [179]. It has a huge time advantage in mesh generation when considering moving boundary problems, thus having the potential to overcome the problem of relative motion of the rotor and stator blade rows. But before that, problems caused by the high Reynolds number need to be solved. When it comes to the scope of turbomachinery, Chen [180] applied it to the unsteady rotor-stator interaction (RSI) problems recently, which has become a new numerical route. Besides, the mixed-fidelity method proposed by Ma [181] used LES to calculate the separation for higher fidelity and used IBM to model the fan blades for a lower computational cost. The inlet-fan interaction on the Darmstadt transonic rotor was chosen as a case, showing the potential of mixed-fidelity methods applied to inlet-compressor interaction modeling. In fact, the concepts used in these two studies represents the two different ways of using IBM. The method of Ma is essentially equivalent to a combination of BBFM and LES, while the method of Chen is a more classic IBM approach to real geometry that combines adaptive mesh refinement.

6. Summary and outlook

6.1. Summary from the perspective of aircraft propulsion system design

Inlet-compressor compatibility has been noted since the 1950s. Different applications and requirements of aircraft have given rise to different propulsion system design directions, which greatly enriches the connotation of the flow field matching problems in inlet-compressor integration. Three main configurations (typical supersonic inlets, nacelles, and curved/submerged inlets for BWB, HWB, or BLI designs.) were discussed in Section 2 above.

The mechanism and detection of inlet buzz, flow stability analysis, and optimization methods for axisymmetric and two-dimensional supersonic inlets have been studied for decades. The DSI inlet (or the bump inlet), as a more advanced design, is usually combined with a Y-shaped or serpentine duct based on the layout of the aircraft. The optimal design and flow control of the inlet distortion in this configuration have attracted attention in the 21st century.

For the nacelle configuration, the classic problems are lip boundary layer separation and ground vortex ingestion. Specifically, this includes: the effects on fan performance and flow stability; the correlation of these distortions with the external atmospheric environment and flight conditions; and specific flow structures such as the shockwave on the lip and its dynamic interaction with the fan.

The major advantage of the new BWB or HWB aircraft and BLI propulsion system is to improve propulsion efficiency through boundary layer ingestion. Therefore, a lot of research has focused on the design and benefit evaluation of this concept since the 1990s. At the same time, the studies on its inlet distortion and flow control have been another focus, as it is an important application for the subsonic S-duct inlets. The former requires a faster iterative efficiency to calculate the coupling flow among the aircraft, inlet, and fan, which gives rise to fast numerical models represented by SBFM and AD. The latter focuses on the details of the flow inside the inlet and the inlet boundary condition of the fan, thus providing the need for the BBFM and (U)RANS methods.

6.2. Outlook from the perspective of aircraft propulsion system design

Different types of propulsion system design have shown different potential directions of development. For supersonic inlets, the overall research direction still does not seem to be closely integrated with the basic research on compressors. The requirement for stealth has promoted the development of the DSI inlet and Y- or S-shaped inlet ducts. This trend places higher demands on the basic research between the two components, especially in the investigation of both transient and time-averaged inlet distortion on the compressors. Recently, some studies on the testing of supersonic S-inlet-induced distortion have been published. More research on the coupling mechanism of the supersonic inlet and fan flow is expected.

In terms of the flow inside the nacelle, previous work has confirmed its sensitivity to the external environment. The design trend towards short, drooped, and scarfed inevitably creates a stronger interaction between the internal and external flow. The mechanism of unsteady interaction between the lip shockwave and fan, the new time-averaged and transient performance of the lip boundary separation in these new designs, and the impact on ran performance and stable operation, are all issues worth paying more attention to.

For the emerging BLI configuration, the challenge posed by the S-duct inlet boundary layer separation is obvious, and the studies on its steady-state distortion are not new. Dynamic distortion and the dynamic response of the fan have become cutting-edge topics. Recent dynamic measurements and high-fidelity numerical simulations have focused on the transient performance of the flow, but have not worked with fans. Whether the coupling configuration will elicit a different dynamic flow? How much stall margin loss does this dynamic distortion induce compared with time-averaged distortion? How does the flow downstream of the inlet and inside the blade rows interact dynamically? These are questions worth exploring.

6.3. Summary from the perspective of inlet distortion analysis methods in compressors

Numerical methods, fluid mechanics theory, and experimental technology related to the inlet distortion problems of axial compressors have been coupled and iterated in the past eight decades. In the 1960s, basic experiments and mechanic modeling started. Among these reduced-order modeling methods, the BFM method in the 21st century has replaced the AD and PC methods in the 20th century. Numerically, the (U)RANS in the 21st century has replaced the Euler solvers in the 20th century.

Among today's numerical techniques, URANS will be irreplaceable for a long time in the future. Harmonic methods overall are successful, especially in improving the computational efficiency of simulating complex inlet distortion and rotor-stater interaction problems, though there might be some difficulties in numerical convergence. The application of direct IBM to turbomachinery is in its infancy. In fact, IBM was first developed to study other problems such as fluid-structure interactions (flutter) and motion-induced vocalization, but a well-established IBM-based solver also has its own unique advantages in inlet distortion analysis. Overall, it is still difficult to apply LES and DNS directly to multi-blade-row inlet distortion problems, but there has been some progress in the application of hybrid-fidelity models such as hybrid LES-RANS and hybrid LES-IBMSG to inlet distortion problems, revealing more details of unsteady flow.

6.4. Outlook from the perspective of inlet distortion analysis methods in compressors

In general, the above methods have been established in different fields and applied to the field of the inlet distortion analysis of axial compressors. The versatility of these methods also allows them to be applied to other fields such as acoustics, fluid-structure interactions, external flow, etc.

AD, PC, and low-dimension BFM, as leading methods, can handle large-scale calculations beyond the capabilities of today's simulation, especially for a quick estimate of the performance of multi-stage compressors. Meanwhile, BBFM or IBMSG methods have been extensively researched and improved. These are of great engineering significance for the design process of the new configuration compression system (e.g., wide velocity domain design and variable cycle design) in the future.

In the process of applying IBM to the real geometry of the axial compressor, it is still tricky to solve the problem caused by the high Reynolds number, but the combination of the hierarchical refinement technique and turbulent wall model has become a possible solution. LES is expected to be applied to the unsteady interaction between the inlet and the compressor more widely in the next decade, but it is relatively more feasible to use hybrid fidelity models nowadays. Among them, the development of wall-modeled LES (WMLES) and its potential application in the field of turbomachinery simulation are also worth noting.

Measurement techniques with high spatial resolution have great potential for inflow measurement in inlet distortion conditions. These surface or volume measurement methods, such as 3D3C PIV and PSP (pressure-sensitive paint), are usually based on non-contact optical principles. But the optical path arrangement in the narrow internal space of the compressor and the new generation of image processing algorithms need to be further considered. For supersonic inlet internal flow measurement, the latest development of quantitative measurement and reconstruction algorithms for 3D schlieren imaging is worth paying attention to.

In terms of flow stability analysis tools, apart from the empirical criteria based on flow details, the development of computer hardware and algorithms is gradually making it possible to solve more complex tri-global problems in the field of basic flow instability, which might also bring a new solution to the flow stability theory of inlet-compressor flow field matching problems.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

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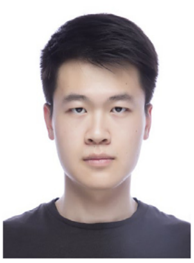

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