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Variable Cycle Engine Concepts and Component Technologies—An Overview

The variable cycle engine (VCE) is of interest for military and supersonic civil platforms due to its improved operational flexibility. However, the increase in design and control degrees-of-freedom results in a more complex engine architecture. Numerous different VCE concepts have been proposed and studied in literature. This paper provides an overview of VCE concepts and technology. A historical outline of important activities, investigated concepts, and technical advancements is given, and the main objectives and use cases of the technology are described. In addition, specific challenges and technical solutions for variable compressors and turbines are discussed in detail. Important VCE concepts are qualitatively evaluated, and their advantages and disadvantages are highlighted.
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Keywords: variable cycle engine (VCE), adaptive cycle engine, selective bleed engine, split-fan, core-driven fan (CDF)

1 Introduction

The interest in variable cycle engine (VCE) technology has grown over the past decades for military and civil supersonic aircraft applications. In these scenarios, the engine has to function efficiently at subsonic cruise and safely in supersonic flight. The VCE takes advantage of variable components to adjust its operating characteristics. The result is a design with fewer performance compromises compared to a conventional engine design.

The variable components and configurations of VCEs are selected to best meet a set of operational requirements. Thus, it becomes challenging to directly compare VCE concepts generated with different optimization goals in mind. At a macrolevel, the variable cycle engine uses adjustable components—typically vanes, nozzles, and mixing systems—to adjust the overall thermodynamic cycle. This ability can offer significant operational advantages, such as a reduction in fuel consumption, installation drag, or infrared signature along with an increase in thrust; see Sec. 2.3. This holistic approach goes beyond the conventional usage of variable compressor guide vanes and variable nozzles to ensure a safe and efficient operation of the individual components.

These variability features are needed for the thermodynamic cycle adjustment and must be appropriately designed. The transition from fixed to variable turbomachinery components is in itself a challenge in terms of practical implementation and component efficiency. Both the potential and challenges must be understood in detail, with a special focus on the compressor and turbine. In summary, the design process of a VCE is a multidisciplinary task, requiring a thorough understanding of its variable components.

Depending on the VCE concept, the compressor may require an additional bypass duct and further geometric variabilities to enable flow modulation. So far, research has mainly focused on addressing the increased system complexity during the design process. This mostly concerns control schedule design and a safe transition between operating modes.

The available literature also provides solutions for increased turbine operating flexibility. This includes maintaining a higher performance in part-load operation with reduced compromises to design point performance [1–3] and a work split adjustment between spools [4,5]. Control is typically applied via variable stator vanes to regulate either the reduced core mass flow or the flow angles. The former has an extensive effect on the engine thermodynamic cycle, and the latter is directed at increasing the turbine isentropic efficiency in a more localized approach. Additional methods for turbine variability can be considered [6–8], albeit with a lower technology readiness level (TRL).

A major challenge for designers arises from the multiple degrees-of-freedom introduced by added variability. The complexity can reach a point where engine behavior becomes nonintuitive. Despite extensive literature on VCEs and their variable components, understanding the implications of each variable feature remains challenging. This problem is targeted by answering two questions. How can variable geometry be implemented in an aircraft engine? What are the implications of this variability?

Using a top-down approach, this review starts with a VCE-level discussion in Sec. 2. Previous research activities and selected VCE concepts are presented. Various operational benefits to the aircraft platform are discussed in Sec. 2.3. The discussion then moves to the

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individual variable compressor and turbine components in Secs. 3 and 4. Local effects and possible design solutions are addressed.

2 Variable Cycle Engine Concepts

2.1 Research Activities on Variable Cycle Engine. Research on VCE technology traces back to the 1960s. Since then, industry and public research institutions have pushed research activities with intensive efforts. The need for this technology arose from the goal of developing an efficient supersonic transport aircraft (SST). An SST requires the operational behavior of a turbofan (low specific thrust) at subsonic flight and the characteristics of a turbojet (high specific thrust) at supersonic flight [9–14]. Specific thrust is defined as engine thrust relative to the engine mass flowrate, $F_N/\dot{m}$. Conventional engines are designed for either high or low specific thrust, leading to significant compromises in the case of an SST. As a result, adaptable specific thrust is a key aspect of VCE research efforts.

With this in mind, General Electric (GE) developed one of the first VCE concepts, the "variable pumping compressor" (VAPCOM). This twin-spool turbofan engine with a variable exhaust mixer and variable turbines is depicted in Fig. 1. The variable components enable a change in bypass ratio (BPR) in the range between BPR ≈ 0 (turbojet) and BPR ≈ 1 (turbofan). This concept reduces fuel consumption by 3–4% when compared to a conventional engine. Increased weight, complexity, and losses caused by mass flow shift between bypass and engine core prevented this concept from moving forward [16]. Nonetheless, additional concepts have been developed for the same application in subsequent technology programs in the U.S. and Europe.

General Electric is a pioneer in VCE technology, having conducted a series of joint investigations with NASA throughout the 1960s and 1970s. The advancements GE made across various concepts are documented chronologically in Ref. [15]. In the early 1970s, the manufacturer attempted again to combine the operating characteristics of the turbojet and turbofan in a successor of the VAPCOM VCE concept, the "turbo augmented cycle engine" (TACE). In a similar fashion, it was designed to switch between operating modes through variable geometries. This concept consists of a turbofan and a turbojet engine arranged in series. Using variable ports, the bypass mass flow can be directed from the turbofan into the turbojet to operate the engine with no bypass mass flow; see Ref. [15]. In the alternative operating mode, only the front turbofan is active. Despite the improved fuel consumption compared to VAPCOM, the significantly higher system weight (about 40% compared to a conventional engine) prevented TACE from being further developed [16].

Later, in the mid-1970 s, GE developed the first double bypass engine concept with the "modulating bypass ratio engine" (MOBY). The fan is divided into a front and a rear part, each feeding a separate bypass duct. Using variable flaps, the ducts can be opened or closed, which enables a redistribution of the flows within the engine from one duct to the other to regulate specific thrust. A further advantage of this redistribution is the flow-independent thrust control, often referred to as flow holding. This enables a reduction in installation drag during engine part-load operation, which in turn leads to a reduction in fuel consumption [15]. The MOBY concept demonstrated that double bypass concepts offer high potential for

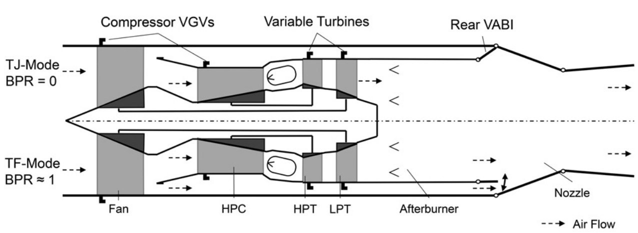

Fig. 1 VAPCOM concept in turbojet mode (upper half) and turbofan mode (lower half), adapted from Ref. [15]

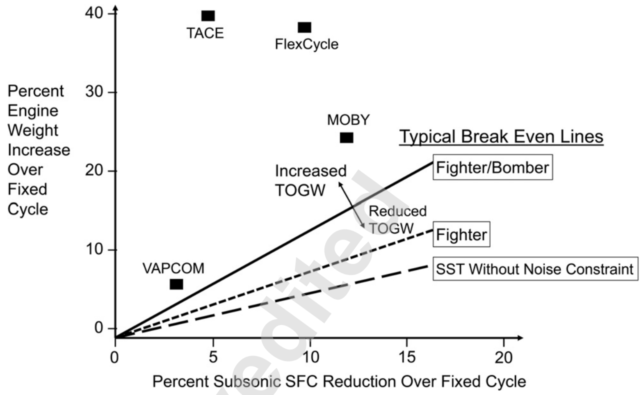

Fig. 2 Break-even relationships between engine weight increase and fuel consumption decrease for various aircraft, adapted from Ref. [16]

supersonic application but need further development due to complexity and (again) high system weight [16].

Reference [16] evaluates the benefit of reduced fuel consumption against the setback of higher system weight for GE VCE concepts up until 1975. The "takeoff ground weight" (TOGW) is the chosen evaluation criterion for this analysis. As shown in Fig. 2, the developed concepts lead to an unreasonable TOGW for all applications (fighter/bomber, fighter, SST). Looking at the break-even lines, the higher VCE weight offset the reduction in fuel consumption.

These developments made by GE later led to the "core-driven fan" (CDF) VCE concept. In this case, the rear fan stage, the core-driven fan, is driven by the high-pressure turbine (HPT). Consequently, the HPT has to provide more power. As a result, the low-pressure turbine (LPT) inlet temperature decreases, and the required cooling air for the LPT can be reduced [15]. A bypass channel is added before and after the core-driven fan. Both streams are mixed and routed via a single duct to the afterburner, as depicted in Fig. 3. When the selector valve is open, both bypass channels are active (double bypass mode). When closed, the total inlet mass flow is directed through the fan into the core-driven fan (single bypass mode). This mode change enables a significant change in the bypass ratio and specific thrust. Studies on the CDF VCE concept have been published for a range of technology levels and application scenarios [17–24].

The CDF VCE was presented by GE as an engine option for the YF-22 and YF-23 within the "Advanced Tactical Fighter Program." To date, it is the only VCE concept tested in flight and fully certified. Due to the higher development risks, production costs, and expected maintenance effort, GE's engine (GE-F120) was discarded in favor of its conventional competitor from Pratt & Whitney (PW-F119) [25].

Pratt & Whitney's research activities in VCE technology began with the need to develop efficient engines for supersonic civil aircraft [26,27]. Like the core-driven fan engine, the "variable-stream-control engine" (VSCE) concept was developed for the government-funded "Supersonic Cruise Aircraft Research" (SCAR) technology project [18]. This concept, shown in Ref. [27], has a

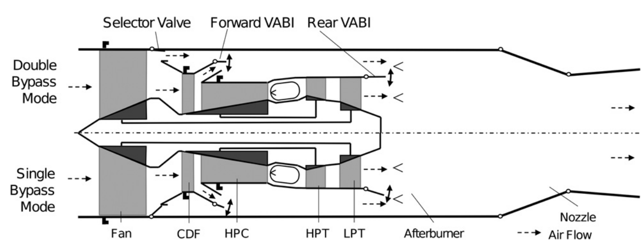

Fig. 3 VCE with a core-driven fan architecture in double bypass mode (upper half) and single bypass mode (lower half), adapted from Ref. [15]

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combustion chamber in the bypass duct and a complex flap system with an ejector at the rear of the bypass duct. These variable components resulted in reduced noise, emissions, and fuel consumption [27,28]. Nonetheless, this concept suffered from problems with flame stability in the bypass burner at low inlet temperatures and high pressure losses [29].

European engine manufacturers Rolls Royce and SNECMA similarly focused their VCE research activities on the application for supersonic transport aircraft (SST) with the perspective of replacing the Olympus engine in a Concorde successor. Both manufacturers eventually merged their individually developed concepts into a joint project.

The "tandem fan engine" concept developed by Rolls-Royce has a similar design to a twin-spool turbofan, albeit with a separate fan in front of the conventional fan [30]. Both are driven by the low-pressure turbine. For takeoff and climb conditions, the engine is operated in increased bypass mode. In this mode, a fraction of the air flow compressed by the front fan is ejected to the outside through a separate nozzle on the side of the engine. Simultaneously, air is fed to the rear of the engine through a side auxiliary inlet door (ejector). For supersonic cruise, the engine is switched to low bypass mode by closing the additional nozzle and inlet, operating like a turbofan.

Snecma developed the "Moteur a cycle variable" (MCV99), a VCE concept intended as a possible successor to the Concorde Olympus engine. Two different configurations of this concept have been published, a two-shaft and a three-shaft variant. While the latter offers slightly greater variability in the working process, it is also considerably more complex and heavier than the former. The principle of the concept is here briefly explained for the two-shaft version, depicted in Ref. [31]. A compressor and turbine are mounted on the first shaft, as in a turbojet. An additional fan, driven by an additional turbine, is mounted on a second shaft. However, there is no combustor between these two additional turbocomponents. The engine operates as a turbofan during takeoff and subsonic flight. Before the primary air mass flow enters the combustion chamber, it is split into two streams. A fraction is bypassed into the secondary turbine driving the secondary cycle fan, the fan turbine. Before reaching the secondary turbine, it is mixed with the air flow drawn in through side intakes and compressed via the secondary cycle fan. Primary and secondary flows are not mixed together but pass through two separate variable nozzles. In supersonic cruise, the side intakes and the HP air bleed are closed, and the engine operates as a turbojet [32].

The cooperation between Snecma and Rolls-Royce later resulted in the "mid-tandem-fan" (MTF) VCE concept [11]. It benefited from the developments of the tandem fan engine and the MCV99. The MTF VCE has a single-stage fan driven by the low-pressure shaft, positioned behind the low-pressure compressor (LPC). It has two flow paths with a BPR > 2 for takeoff and climb. Bypass flow enters the engine through front and side air intakes. This dual flow path provides low specific fuel consumption (SFC) and reduced noise levels due to the moderate exhaust velocity (approximately 400 m/s at the nozzle exit), which is relevant to meet noise regulations. For high specific thrust, the side intake is closed, and the bypass flow is reduced by modulating the mixer and nozzle areas. In addition, the adjustable guide vanes of the midfan are used to reduce the airflow into the bypass duct. The jet velocity in this operation is about 650 m/s at the nozzle exit. The corresponding low BPR of about 0.7 is advantageous for supersonic flight [11]. Closing the side air intakes, used at subsonic speeds to supplement the front air intakes, minimizes air drag during cruise flight. Rolls-Royce claims that the MTF operates up to Mach 0.3 without losses in thrust performance [11,33].

In the late 1980s, the "selective bleed engine" (SBE, Fig. 4) was developed at Cranfield University (UK) [34]. In this concept, the fan is divided into a front and a rear block. Each has a bypass duct that can be opened and closed by valves. For high specific thrust operating points, the outer duct is closed and the inner duct is open. The engine is in high-pressure mode because the bypass air is charged by both fan blocks. In this mode, the engine operates as a

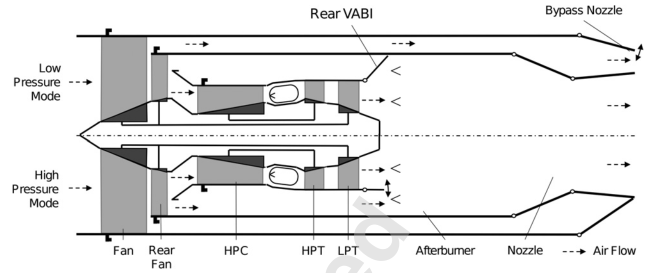

Fig. 4 Selective bleed engine in low-pressure mode (upper half) and high-pressure mode (lower half), adapted from Ref. [34]

low-bypass-ratio turbofan. In low-pressure mode, the outer duct is open and the inner duct is closed. The air mass flow through the outer duct is ejected through a separate nozzle. This second low specific thrust mode is suitable for fuel-efficient part-load operation such as cruise or loiter. In the original concept developed for an advanced short takeoff and vertical landing fighter, the air from the outer bypass can also be used for lift in hover mode. In this case, the bypass air is ejected downwards via lateral nozzles. Despite the variety of publications for various applications, this concept remained at a study level [11,34–42].

Figure 5 shows an overview of selected VCE concepts plotted over a timeline in the upper half and several VCE technology programs in the lower half.

2.2 Current Technology Programs. Through numerous technology programs (Fig. 5 depicts only an excerpt), expertise in the field of VCE has been continuously extended with different concepts, especially in the U.S. With the end of SST, VCE technology has become inadequate for civil aviation. The research focus has since moved to the use case of a combat aircraft and, to some extent, of an unmanned combat air vehicle [5,24].

A VCE is currently under development within the program trilogy Adaptive Versatile Engine Technology, Adaptive Engine Technology Demonstrator, and Adaptive Engine Transition Program (AETP). It is intended as the future standard engine option for an in-service multirole combat aircraft platform (F-35 version A and C). In the most recent AETP, GE and P&W are developing VCE technology for real-condition flight tests. According to published information, the GE XA100 engine is a three-stream engine (double bypass VCE without bypass stream mixing) with an integrated heat exchanger in the outer bypass duct for thermal management [43]. A possible configuration of this concept is shown in Fig. 6. Details on the P&W's XA101 engine are scarce, except that it is also a three-stream engine [45].

The follow-up project to AETP, the "Next Generation Adaptive Propulsion" (NGAP), will investigate VCE engines for an air superiority fighter. It will complement the "Next Generation Air Dominance" (NGAD) aircraft platform project on the propulsion side [46].

In Europe, MTU Aero Engines, Safran, and ITP are working in the EUMET consortium on a propulsion system for the "Next

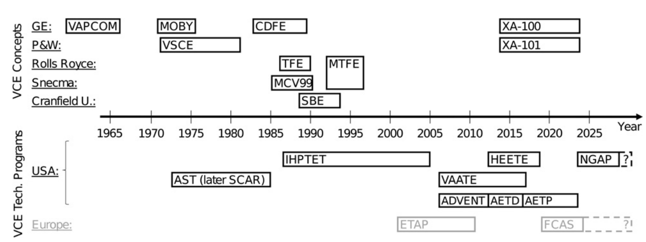

Fig. 5 Time line of VCE concepts (upper half) and technology programs (lower half)

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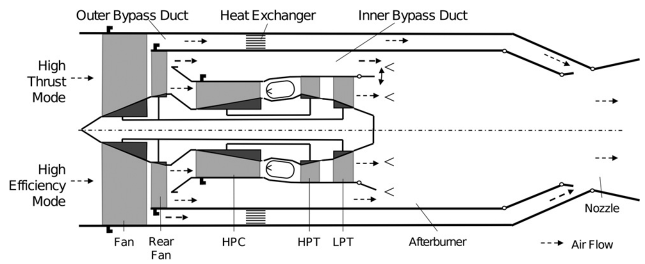

Fig. 6 Possible configuration of a three-stream engine in high thrust mode (upper half) and high efficiency mode (lower half), adapted from Ref. [44]

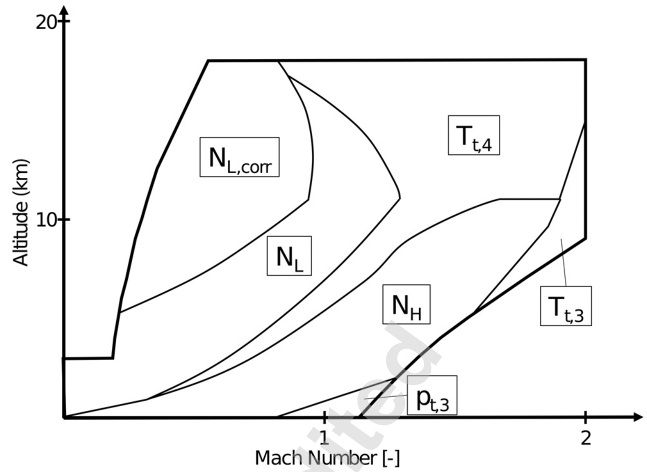

Fig. 7 Typical limiters in a fighter engine flight envelope, adapted from Ref. [48]

Generation Fighter Aircraft." This aircraft is intended as a successor for the Eurofighter and Rafale in 2040 and is being developed as part of the "Future Combat Air System" (FCAS) project. Research is ongoing for this engine within the "Next European Fighter Engine" (NEFE) project, with a focus on VCE technology [47].

2.3 Possible Variable Cycle Engine Optimization Goals. The use of variable components offers the possibility to adapt the operating behavior of the engine. Depending on the requirements, the cycle of a VCE can be optimized to achieve specific benefits in comparison to conventional engines. VCE research from the 1960s to the 1980s focused mainly on the SST use case and later moved to military applications. As a result, the optimization goals discussed in this section are mainly focused on these two use cases.

Quantitative benefits of a VCE are only provided on some studies. These strongly depend on the use case as well as technology level, assumed installation resistances, weight, and additional variable geometry related losses. As an example, when taking variable geometry-related losses into account, Ref. [24] reports a drop in fuel savings from 9% to 3%. Hence, it is essential to describe all boundary conditions as well as the analyzed VCE concept in detail in order to present the saving potentials. The focus here is to provide a literature overview of VCE optimization goals.

2.3.1 Efficiency. The overall efficiency of an engine is the product of thermal efficiency by propulsive efficiency. Increasing either one is therefore desirable. Cycle thermal efficiency is the ratio between net power and the power provided by the fuel. If component efficiencies are fixed, thermal efficiency can be increased with a higher overall pressure ratio. A variable turbine is particularly suitable for this task as it can directly influence the compressor operating line; see Sec. 4.1. Propulsive efficiency relates the usable propulsive power of the engine to the energy at the nozzle. It increases as the difference between nozzle exit speed and flight speed decreases. Hence, the propulsive efficiency is directly dependent on the specific thrust. As described in Sec. 2.1, many VCE concepts focus on specific thrust regulation to achieve optimized values. For several double bypass concepts, this is achieved by redistributing the mass flow within the engine.

2.3.2 Thrust. The maximum thrust of an engine is limited by various engine-specific operating limits. These are usually mechanical, aerodynamic, or thermal. The limits on thrust for a conventional engine depend on altitude and airspeed. The typical flight envelope of a fighter aircraft is illustrated in Fig. 7 with the respective operating limit for maximum thrust. Multiple operating limits are rarely reached at the same time, offering a thrust increase potential that VCEs can exploit. By adjusting the variable components, the cycle can be adapted to achieve aerodynamic, mechanical, and thermal limits simultaneously.

2.3.3 Engine Integration. Reducing thrust-dependent installation drag is a relevant benefit of VCE technology. On a conventional engine, the flowrate decreases directly with thrust. Drag forces increase at the inlet and nozzle in comparison to maximum airflow operation. This results in lower overall efficiency during part-load operations. However, with variable components, the inlet mass flow can be maintained at a maximum, even in part-load operation—a feature known as flow holding. This capability has been demonstrated in a series of VCE studies [23,44,49]. The corresponding reduction in drag leads to a lower engine thrust, F_N, requirement and to a direct reduction in fuel consumption, since $\dot{m}_{\text{fuel}} = \text{SFC} \cdot F_N$. The potential savings in fuel consumption at subsonic cruise due to the reduction in installation drag can reach 10% for a fighter application [50]. Thermal and power management are additional aspects that may benefit from mass flow regulation. This is especially relevant in modern combat aircraft due to the demand for power-intensive electronic components, such as directed energy weapons [51]. These demand high levels of electrical power for a short period of time that must be delivered via generators. How VCE can support this increased demand has not yet been conclusively evaluated. Nonetheless, the heat generated by these electronic components must be dissipated. One solution is to use the continuous air mass flow of the engine as a heat sink. The principle is to integrate a heat exchanger in the bypass duct to remove the waste heat from the electronic systems. Some VCE concepts have several bypasses and are capable of adjusting the mass flow split between them. This offers the potential to provide a continuous air mass flow to the heat exchanger [52,53].

2.3.4 Infrared Signature. The infrared signature of the aircraft platform is essential for its survivability. It is mainly dependent on engine exhaust nozzle temperature and nozzle area. Using variable geometries, a VCE can control these parameters within certain limits, thus providing a benefit when compared to a conventional engine variant. However, when optimizing for minimum infrared signature, care should be taken to avoid performance disadvantages such as increased fuel consumption [54]. So far, Ref. [55] provides the only report on a VCE optimized for reduced IR signature.

2.4 Variable Area Components

2.4.1 Variable Area Bypass Injector. For reasons of weight and installation space, individual bypass ducts can be avoided by mixing the bypass flows. For certain mixing conditions however, undesirable reverse flows from the second bypass port to first can occur [56]. This must be avoided, as it can compromise stable engine operation. Mixing imposes an additional design constraint which influences the engine matching. Including a mechanism that allows adjusting the mixing areas and static pressures of the mixing flows helps to avoid reverse flow. The area adjustment can also influence the mixing mass flow ratio and therefore have a significant impact on the ability of a VCE to adapt the cycle.

2.4.2 Variable Area Nozzle. The variable throat area (A_8) of a variable area nozzle (VAN) has a major influence on the engine

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Table 1 Comparison and qualitative evaluation of selected engine concepts

Engine concept	Bypass	Rear fan shaft	Qualitative evaluation criteria: Cycle adaptation capability	Complexity (concept/control)	Weight	Installation drag	Heat management	Subsonic cruise SFC	Supersonic cruise SFC	Spec. thrust (sizing)	TRL
Mixed turbofan	Single	—	o	o	o	o	o	o	o	o	9
Selective bleed	Double separate	LP	+	−	− −	+	−	++	o	−	3
Core-driven fan	Double mixed	HP	++	− −	−	++	o	++	+	o	8
Three-stream	Double separate	LP	+	−	−	++	++	++	−	o	7

flowrate. The flow at A_8 is choked (Mach = 1) at almost all operating points. Thus, the flowrate can be controlled by varying A_8. This has a significant effect on the operating condition of the fan. By de- or increasing A_8, the fan can be throttled or dethrottled, moving its operating point toward higher or lower pressure ratios, respectively. This change of the fan pressure ratio has a major influence on the engine's specific thrust and SFC. Variable thrust nozzles have been used in engine technology since the introduction of afterburners. With an unchanged A_8, afterburning would act like a strong throttling of the fan causing it to stall. This is avoided by increasing A_8.

2.5 Variable Cycle Engine Concept Comparison. A comparison of published VCE concepts is only possible on a qualitative basis, especially as the studies differ in terms of application, assumptions, accuracy, and design objectives. Furthermore, the disadvantages of increased complexity and weight are often not covered in detail. Table 1 provides a qualitative assessment by the authors of selected engine concepts in comparison to a conventional mixed turbofan engine. These concepts have been examined in many studies and therefore provide a good basis for comparison. The table serves to highlight the main advantages and disadvantages of typical design approaches for VCEs.

By splitting the fans onto two shafts, the core-driven-fan engine concept offers an efficient way of adapting the specific thrust and thus the cycle. In addition, the front bypass can be closed or opened by using the selector valve. These features make this concept highly adaptable, which would be beneficial for aircraft that need to operate at very high Mach numbers while providing low SFC at subsonic cruise at the same time. However, this comes at the cost of complexity in terms of design and control due to the number of variable geometries. This concept has already been tested in flight with the F120 engine from General Electric and therefore has a very high TRL.

In contrast, the selective bleed engine has so far only reached the level of a concept study. Nevertheless, it has been investigated in many studies, as its control is comparatively simple. This concept can operate in two modes—as a mixed flow turbofan with a small BPR and high fan pressure ratio and as a separate flow turbofan with medium BPR and small pressure ratio. As the bypass flows are routed in separate ducts and separate nozzles, the SBE is rated as heavier.

The three-stream engine could be regarded as an extension of the SBE, as it has separate bypasses, but both have continuous flow. By eliminating the separate nozzle and valves that control the discrete flow conditions, the concept is further simplified, and the weight increase is reduced. Another important aspect of this concept is the use of the outer and colder bypass flow as a heat sink for the waste heat from the aircraft. Such a concept is currently being tested by the U.S. Air Force in flight trials. For this reason, this concept is assigned a high TRL. The concept has a lower ability to modulate the flow as compared to the CDF concept which suits platforms with smaller flight envelope. Due to its decreased complexity, it also comes with reduced risk.

It is very difficult to determine which VCE type is suitable for a certain aircraft. The best engine concept (including VCE and conventional) for a particular aircraft depends on a series of criteria, a selection of which is listed in Table 1. How the criteria are weighted depends on both the manufacturer and the costumer. The favored architecture also depends on further criteria, such as the flight mission or financial and strategical considerations. For a final evaluation, the overall picture is needed. Focusing on values such as SFC or thrust alone is not enough.

3 Variable Compressor Technologies

3.1 Requirements. A major requirement of a VCE is flow modulation, achievable through geometrically variable components and an additional bypass duct. With it comes the capability of flow holding. As discussed in Sec. 2.1, flow holding enables a flow-independent thrust control for reduced spillage and drag. As thrust reduces, core mass flow is increasingly bypassed from the compressor to side channels to maintain a constant intake.

Further compressor requirements arise from the demands of future aircraft and, although not limited to VCEs, can be crucial for the design. The thermal management and high power extraction discussed in Sec. 2.3.3 are two aspects.

With future fighter aircraft producing increasing amounts of heat, a continuous bypass stream flow may be required for cooling purposes [44]. Furthermore, a thermal management system that uses a second bypass stream as a heat sink can significantly benefit from its colder stream. In this scenario, bypassed air does not heat up through multiple stages of fan compression, allowing for a higher temperature gradient at the heat exchanger than in a conventional engine [57].

The short-term high power extraction required for directed energy weapons is limited by the compressor surge margin [51]. This transient behavior must be simulated and accounted for in the design process.

Hypersonic flight may require a combination of VCE and ramjet configurations [58–60]. In ramjet mode, the fan must be capable of windmilling.

3.2 Design Aspects. Numerous concepts of VCEs can be found in literature, e.g., Refs. [12,13,19], and [61]. There is also a significant number of patents on VCE design with details on the compression system [62–65].

Some early concepts, such as the VAPCOM depicted in Fig. 1, do not require changes to the compressor. This single bypass VCE is a low bypass turbofan with a variable area bypass injector (VABI) in the turbine discharge section [19,66]. The rear VABI balances exhaust static pressure of turbine and fan, allowing the fan to operate at high flow even when the compressor speed is reduced at part-load.

More sophisticated concepts introduce a second bypass stream and variable geometries in the compressor section to further increase the flow modulation ability. The flow through the second bypass duct can either be kept separate from the first bypass stream or mixed with it, as depicted in Fig. 3. The first bypass duct separates the fan into two blocks and the second bypass duct starts after the fan. The last fan stage, located between the two bypass ports, plays a critical role in the design of a VCE compressor. It can either be driven by the low-pressure spool as in conventional engines (split-fan

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configuration) or by the high-pressure spool (core-driven fan stage), as schematically depicted in Fig. 8. Furthermore, this fan stage has to accept significant differences in mass flow and is often equipped with a variable inlet guide vane (IGV).

Additional geometric variability is needed to control the mass flow split between the two bypass ports and adjust it according to the flight conditions. Injector valves and adjustable vanes provide the necessary variability. The complexity of the variable components can vary between VCE concepts with implications on the control system and engine maintenance.

Sections 3.2.1–3.2.4 discuss particular aspects of compressor design for different VCE configurations.

3.2.1 Double Bypass. A supersonic cruise requirement leads to fans with two or three stages and high pressure ratios. The multistage fan allows for the additional bypass between two fan blocks [19], as in the CDF concept. This double bypass configuration leads to improved engine flow modulation and can be seen as the main feature of advanced VCE concepts. However, a double bypass adds cost and complexity [66]. In addition to the rear VABI, a forward VABI is required to match the static pressure of the two bypass streams.

In terms of engine weight and exhaust nozzle complexity, it is preferable to mix the two bypass streams instead of keeping them separate, as in Fig. 3. On the other hand, additional requirements such as the heat sink discussed in Sec. 3.1 might force the two bypass streams to be kept separate.

3.2.2 Split-Fan. The split-fan configuration enables a larger front fan block in comparison to a conventional turbofan with the same core size [61]. The result is a higher airflow and increased bypass ratio capability [19].

The rear fan block is sometimes termed aft fan stage if it is driven by the LPT [67].

3.2.3 Core-Driven Fan. The rear fan block can also be driven by the HPT in a CDF configuration [17,19,22,48,56,68,69]. The different operating modes lead to significant variations in mass flow through the CDF. As a result, the IGV must be tolerant to a wide incidence angle range to avoid high pressure losses. Hence, a CDF stage can benefit from a variable IGV [22]. This may come in the form of a split-type IGV, with either an adjustable front or rear blade section [70,71].

A CDF VCE has more independent design variables and requires additional design choices. The pressure ratio toward the CDF hub influences the pressure ratio required from the high-pressure compressor (HPC). It can be regarded as a primary design parameter and should be chosen carefully [48]. A CDF is challenging to design because of its higher shaft-speed and relatively low design pressure ratio [67].

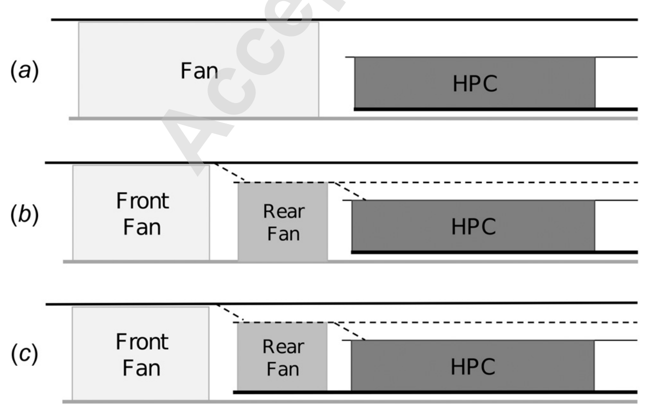

Fig. 8 Schematic comparison of conventional compression system (*a*) versus split-fan (*b*) and core-driven fan (*c*). Dashed lines show possible variable geometries and a potential subdivision of the bypass flow.

3.2.4 FLADE. The FLADE (fan on blade) concept employs an auxiliary fan mounted on the fan tip in its own separate flow stream [67,72–77]. This additional stream provides increased air flow at takeoff and can be deactivated at supersonic cruise to reduce drag.

Shortcomings of the FLADE configuration include the added weight and complexity of the auxiliary fan and the large fan diameter. Due to the high Mach numbers at the FLADE inlet, a positive preswirl is needed to reduce the shock intensity and associated losses [78]. Combining a FLADE with a double bypass VCE essentially yields a triple bypass engine with multiple operating modes, termed by some authors as "adaptive cycle engine" [68,79,80].

3.3 Design and Evaluation. Evaluating different VCE concepts and finding the most suitable for a specific application requires accurate performance prediction and preliminary component design. The compressor surge margin is an especially critical constraint.

The performance analysis has to account for the additional geometric variabilities [67,81,82]. Different performance prediction methods for VCEs are approached in the literature. These include stage-by-stage and parallel flow path compressor models [83], interpolation methods [82], or a combination between reliability analysis and performance analysis using artificial neural networks [84]. Performance prediction methods are increasingly combined with optimization techniques to help improve the performance of VCEs [44,75,77].

Component matching becomes more challenging in a VCE due to the added component variability [68,79,85]. The front and rear fan stages need matching [86], as well as the rear fan stage or CDF stage and the HPC [87].

Designing the control schedule for the variable features in a VCE is far more complex than for a conventional engine. A schedule for the different VCE variabilities must be established for each flight mode.

Research has been conducted on handling the increased complexity of the system and optimizing the control schedules of the variable components [44,80,82,85,88]. When the design parameters of an engine change, the control law has to be redesigned. Generating control law in an automated manner to speed up the design process using optimization techniques has become a relevant field of research [89–91].

A final relevant aspect is the transition process between operating modes, for instance, from subsonic cruise to supersonic cruise. A series of studies report on this aspect [19,76,92,93].

A simultaneous adjustment of the variable components is required to maintain thrust and compressor surge margins during transition. Switching between cycle modes or even a slight cycle adjustment to varying flight conditions requires the VABIs and variable vanes to be adjusted accordingly. The control process must be designed carefully to guarantee a safe and smooth transition. Furthermore, back-flow from the second to the first bypass duct must be avoided. Numerical simulations of the forward VABI during mode transition can help analyze the flow field and improve the control method [56,94].

If the control schedule is appropriately optimized, a mode switch can be carried out safely, and the response time of the hydraulic actuator system becomes the limiting factor [95,96].

4 Variable Turbine Technologies

A variable turbine enables the adjustment of flow angles and reduced core mass flow. The latter approach is often used in stationary gas turbines for power generation to maintain a higher turbine inlet temperature at part-load. It can also control the work split between spools in aircraft engines with implications for compressor efficiency, installation drag, or engine response. This comes at the expense of variable geometry-related pressure losses.

4.1 Reduced Mass Flow Control. The approach discussed in this section focuses on adjustable turbine vanes with a variable

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stagger angle, γ. This adjustment is reflected in the throat area and reduced core mass flow, with implications for the thermodynamic cycle of the engine.

Adjusting the vanes of a turbine row affects a change in its throat area, as shown in Fig. 9. An open configuration with a positive stagger angle change, $\Delta\gamma > 0$, leads to a larger throat area and $\Delta\gamma < 0$ to a smaller one. The change in throat area can be assumed linear for a small $\Delta\gamma$ [2], but the same is not necessarily true for the reduced mass flow. If the variable vane row is adjusted to an open position, the downstream blade row may eventually be the one to choke. The same may happen on the variable vane row itself for a closed configuration. In short, the reduced mass flow is expected to reach a plateau at both high and low stagger angles [97,98]. In the literature, the change in stagger angle ranges between −15.0 deg and 108 deg with mean values from −6.5 deg to 10.0 deg; see Table 2. The corresponding reduced mass flow ranges between 74% and 118% of the design values, estimated from Ref. [48].

Reduced mass flow control is generally implemented through a variable geometry vane row, referred to as a VAN. The mechanism is usually built into the first stage of a low-pressure turbine or power turbine. The concept is extensively described in the literature for a recuperated gas turbine with industrial, marine, and land vehicle applications. As the turbine load is reduced, the VAN is set to a closed position to regulate the fuel–air ratio in the combustor and maintain a higher turbine inlet temperature. The resulting higher thermal efficiency and lower SFC are reported in Refs. [1,3,98,103,105], and [122].

Part-load SFC and thermal efficiency improvement is also documented for aircraft propulsion. The cumulative studies of Refs. [2,115,117], and [120] discuss a similar increase in thermal efficiency and SFC reduction for a miniature gas turbine, adequate for an unmanned aerial vehicle. In Ref. [117], as the load is reduced, the potential for SFC improvement increases. An SFC reduction of up to 2.5% is reported for a closed VAN position, $\Delta\gamma < 0$. References [124] and [125] also test this variability for recuperated aero-engine concepts. Again, the VAN is used to lower the reduced core mass flow during cruise and increase the engine thermal efficiency. The SFC is reported to decrease by as much as 2%. In short, an optimized control schedule can maximize thermal efficiency and minimize SFC at one operating point without compromising the rest of the operating range, where the vanes return to their original position.

Besides the heavily studied turbine inlet temperature increase, regulating the reduced core mass flow can have additional implications for the engine operation, depending on its configuration. In a single-spool turbojet configuration, Eq. (1) can be used as an approximation for off-design performance [126]. Closing the VAN at the turbine inlet and reducing $\dot{m}_{\mathrm{red},4}$ at constant T_{t4}/T_{t2} moves the operating point to the left-hand side of the compressor map. If however, the $\dot{m}_{\mathrm{red},4}$ is reduced while also increasing T_{t4}, the pressure ratio Π_C should increase and the surge margin should drop

$$\Pi_C = k \cdot \frac{\dot{m}_{\mathrm{red},2}}{\dot{m}_{\mathrm{red},4}} \cdot \sqrt{\frac{T_{t4}}{T_{t2}}} \qquad (1)$$

In a twin-spool engine, a VAN at the LPT inlet is valuable to control the work and pressure split between spools, along with their

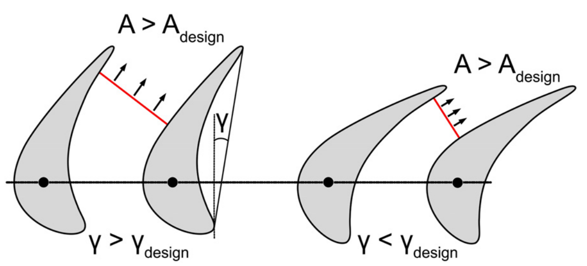

Fig. 9 Throat change with stagger angle

shaft-speed [101,127]. Closing the VAN increases the work and shaft-speed of the LPT while reducing those of the HPT. The HPC pressure ratio and capacity are subsequently reduced, eventually bringing the LPC to an increased pressure ratio and lower surge margin, with a noticeable effect on component efficiency [5].

Apart from the added freedom during the engine design process, this pressure split regulation can provide additional advantages. For once, Ref. [4] reports on the possibility to reduce the engine response time. In this study, the LPT VAN area is increased by 20% at part-load with constant shaft-speed. As a result, the pressure ratio and speed of the HPT at part-load increase and ΔN_{HPT} decreases in a 10–100% acceleration maneuver. The increased reduced mass flow and lower turbine inlet temperature result in an increased surged margin and allow for a higher excess power. The result is a reduction in response time of 24.5% for this particular setup. From an opposite perspective, Refs. [1] and [98] discuss the concept of active aerodynamic braking through flow interaction between the VAN and the downstream blade row, forcing an abrupt shaft-speed deceleration that may be desirable to prevent overspeed damage to the turbine in case shaft failure. In another study, Ref. [128] combines the LPT VAN with a variable exhaust nozzle to maintain a constant LPT and LPC operating point at any given flight condition, effectively reducing installation drag. Finally, to a certain extent, the regulation of the pressure split may also affect the reduced core mass flow and the turbine inlet temperature, albeit only indirectly as this is typically set by the HPT.

Despite the benefits discussed in this section, reduced mass flow control typically results in additional pressure losses through the turbine. This ultimately affects the turbine isentropic efficiency and finally the engine thermal efficiency. References [97,113], and [108] report a reduction in turbine isentropic efficiency when the variable vanes move away from the design position. Also, Ref. [3] documents the impact of the isentropic efficiency reduction on the engine thermal efficiency for a power-turbine with a VAN. Taking this effect into consideration cuts the thermal efficiency improvement from +3.8% to only +1.8%. This indicates the importance of the aerodynamic performance of variable components. As a possible explanation, a control schedule focused on reduced mass flow optimization might lead to a blade incidence angle far from ideal, resulting in a pressure loss increase. The vane gap to the annulus wall and the variable distance between the vanes and the downstream blades are additional factors to consider. A deeper understanding of the dependency between turbine efficiency and airfoil stagger angle is mandatory to ensure that the potential benefit of a VAN is not nullified. Variable geometry-related losses are further discussed in Sec. 4.3.

4.2 Blade Incidence Angle Control. An alternative to reduced mass flow control is blade incidence angle control, i [6,121]. A departure from design incidence angle, $i/i_{\mathrm{design}} \neq 1$, in part-load leads to an increase in pressure loss [129] and ultimately to a reduced turbine and thermal efficiency. A loss increase at off-design may be partly avoided either through β_1 or β_{1M} where $i = \beta_1 - \beta_{1M}$ [48]. The inlet swirl angle, β_1, is dependent on the upstream vane position, while the inlet metal angle, β_{1M}, is dependent on the blade's own position.

Studies on this approach are mainly restricted to the improvement of a tilt-rotor aircraft variable speed power-turbine performance by Refs. [6,121], and [130]. The incidence angle on the power-turbine rotor blades ranges from 5.8 deg in cruise to −36.7 deg in takeoff. In Ref. [121], the potential of incidence angle control is demonstrated for this power-turbine in off-design conditions. By rotating the blades clockwise, β_{1M} approaches β_1, lowering the blade incidence angle and reducing the pressure losses. Reference [6] reports similar results where a correction in stagger angle of $\Delta\gamma = -10$ deg leads to a 5% increase in turbine efficiency at off-design.

The studies mentioned in this section also discuss a more unconventional approach where both vane and blade rows are adjustable. To achieve a certain correction of the blade incidence angle, the necessary adjustment is distributed between vanes and

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blades, resulting in a smaller throat area variation for each of the two rows. This may be beneficial to partially decouple incidence angle from reduced mass flow variation when needed.

4.3 Related Losses. As briefly introduced in Sec. 4.1, a variable geometry may lead to a reduction in turbine isentropic efficiency, the exception being the group from Refs. [6] and [121]. This section approaches different aspects related to this turbine efficiency reduction.

The effect of geometry variation is experienced by both the load coefficient, Ψ, and the reaction degree, R. The load coefficient, $\Psi = c_{ax}/U \cdot (\tan\beta_1 - \tan\beta_2)$, is dependent on the flow deflection. As the VAN closes and the stagger angle is reduced, $\Delta\gamma < 0$, the flow is further deflected and the inlet swirl angle of the downstream blade, β_1, increases. The resulting increase in load coefficient typically leads to a lower turbine efficiency [131]. Reference [103] documents on a five-stage power-turbine with a VAN at the inlet. The load increase and turbine efficiency reduction are predominant in the first stage, and the effect becomes negligible downstream. Hence, the impact on the overall turbine efficiency is expected to decrease with an increasing number of stages [113].

Opposite to the load coefficient, the reaction degree, $R = 1 - c_{ax}/2U \cdot (\tan\beta_1 + \tan\beta_2)$, decreases as the VAN closes [2,97,109]. In a closed setting, the vanes act increasingly more as a convergent nozzle leading to a higher flow acceleration, higher pressure drop, and a lower reaction degree. An excessive adjustment and drop in static pressure in the vane row can lead to an adverse pressure gradient and flow separation in the downstream blade row, partly explaining the reduction in turbine isentropic efficiency [97].

Clearance between the variable vanes and the annulus wall further contributes to higher pressure losses, especially if it is dependent on the VAN position. To ensure a constant clearance, the annulus wall and vane tip may be locally spherical and concentric [122]. Nevertheless, small leakage losses are still present despite the resulting constant tip clearance [113]. A counter-rotating turbine can attenuate this problem. The flow deflection in the VAN is reduced along with the pressure difference between both sides of the vane, ultimately resulting in reduced leakage losses [103].

At last, the position of the VAN rotating axis determines the dependency between stagger angle and vane-to-blade axial gap. Setting the rotation axis at the vane trailing edge results in a constant axial gap, but from a safety perspective the rotation axis should be placed toward the leading edge [1]. In case of mechanism failure, the VAN moves automatically to an open position, preventing an uncontrolled temperature rise in the turbine. The subsequent variation in axial gap changes the interaction between vane wake and the blades, affecting stage losses and ultimately turbine efficiency [1,132,133].

4.4 Mechanism and Actuator. The concepts from Secs. 4.1 and 4.2 require both an actuating mechanism which, apart from being able to withstand the operating temperatures, must also be light and compact enough. Vanes may be adjusted through a unison ring [116] or a geared ring [107], powered by an actuator. High-temperature electromechanical actuators [134] can be susceptible to jamming, which would freeze both the vanes and the engine cycle into position [135]. Electrohydrostatic actuators are lighter in comparison to a centralized hydraulic actuator systems. Nevertheless, the hydraulic fluid is generally limited to an operating temperature of 440 K (too low). For a blade row, the level of complexity increases. Shape-memory alloy [6] or magnetostrictor [136] actuators could be placed within the disk and connected to the blades at the hub. Despite being compact, these technologies face strong temperature and TRL limitations [137,138]. Integrating a variable turbine mechanism in an aero-engine is strongly dependent on solving these challenges. This problem could be bypassed with alternative fixed geometry concepts like jet flaps [7,139] and plasma actuators [8,140–143]. The main issue in this case is the very low TRL.

5 Summary and Conclusion

The volume of published literature demonstrates the significant effort that both research institutions and industry have dedicated to VCE technology, in the past and continuing today. The main operational advantages of VCEs compared to conventional engines are increased efficiency, increased thrust, reduced infrared signature, and improved integration. In the last few decades, the focus has shifted from commercial supersonic platforms to military platforms. As a result, research on VCE technology has declined. Thus, recent advances in variable compressor and turbine technologies cannot be fully covered.

Over many years of research, mainly in the U.S., numerous VCE concepts have been developed and investigated. The developments led to concepts that allow a mass flow redistribution via two bypass ducts to separate outlet nozzles. While these concepts offer higher potential than conventional approaches, they also lead to a considerable weight increase due to additional ducts and nozzles. For this reason, concepts like the core-driven fan engine have been developed in which the bypass flows are mixed and routed together within the engine. However, bypass flow mixing is constrained to certain limits, slightly restricting design flexibility.

A key operating parameter for characterizing a turbofan engine is the fan pressure ratio. For a conventional engine, the design point fan pressure ratio largely determines the specific thrust and specific fuel consumption throughout the flight envelope. In concepts with several bypass ducts, the fan component is split into a front and a rear block. With variable area mixers, such as front or rear VABIs and variable nozzles, it is possible to influence the fan pressure ratio. Being able to control engine off-design operation in this way allows increased flexibility in engine design. VCEs can be designed with low FPRs efficient for subsonic cruise and high FPRs for thrust-intensive supersonic flight points, utilizing its variable components.

The aerodynamic realization of this flexibility is a challenge for the compressor system, especially for the rear fan block. Located between the bypass ducts, it has to operate safely and efficiently at highly different mass flows. Depending on the degree of mass flow modulation, the requirements for the aerodynamic design of this component are very demanding. A major influence on the design of the compressor system plays the choice of the shaft from which the rear fan is driven. Depending on whether it is driven by the high- or low-pressure shaft, different aerodynamic design constraints arise, which also affect the design of the surrounding compressor components and may require that not all compressors can operate at their optimum circumferential speed.

Variable turbines can strongly affect the engine cycle and offer high potential benefits. However, they seem to have received less priority in aviation and are more difficult to realize than variable compressors. Turbines operate in a thermomechanically more challenging environment. A mechanism to actuate variable guide vanes would have to withstand high temperatures, large thermal expansions, and be compact enough to be integrated in parallel to the complex secondary air system. The level of complexity further increases for variable blades, since the mechanism must be placed within the disk. The challenge of finding a light and compact mechanism that can operate at high temperatures seems to be the main reason why variable turbines are not the focus of current VCE concepts. Nonetheless, the potential and interest on a variable turbine for aviation purposes are noticeable, with recent studies on combined cycles and recuperated engines.

Reducing the weight and complexity remains a key technical challenge and a development focus of VCE technology. This is evident in the progress of VCE technology over recent decades. The complexity of variable components has been reduced over time in an effort to minimize the drawbacks of VCE technology. Given the substantial advantages of VCEs and ongoing reductions in weight and complexity, operational VCEs are likely to be realized in the near future.

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Data Availability Statement

No data, models, or code were generated or used for this paper.

Nomenclature

Latin Letters

c_{ax} = axial velocity (m/s)
F_N = net thrust (N)
i = blade incidence angle (rad)
k = constant
$\dot{m}$ = mass flow (kg/s)
$\dot{m}_{red}$ = reduced mass flow (kg/s)
N = shaft-speed (1/s)
p = pressure (Pa)
P = power (W)
p_t = total pressure (Pa)
R = reaction degree
T_t = total temperature (K)
U = rotor peripheral velocity (m/s)
x_{gap} = stator/rotor axial distance (m)

Greek Symbols

β = blade swirl angle (rad)
β_M = blade metal angle (rad)
γ = blade stagger angle (rad)
η = efficiency
Π = pressure ratio
Ψ = load coefficient

Superscripts and Subscripts

C = compressor
corr = corrected (by the root of the total temperature)
H = high pressure
L = low pressure
1 = blade inlet
2 = blade outlet, compressor inlet station
3 = compressor outlet station
4 = turbine inlet station

Abbreviations

BPR = bypass ratio
CCE = combined cycle engine
CDF(E) = core-driven fan (engine)
FLADE = fan on blade
HPC = high-pressure compressor
HPT = high-pressure turbine
IGV = inlet guide vane
LPC = low-pressure compressor
LPT = low-pressure turbine
MOBY = modulating bypass ratio engine
MTF = mid-tandem-fan
SFC = specific fuel consumption
SST = supersonic transport aircraft
TACE = turbo augmented cycle engine
TOGW = takeoff ground weight
TRL = technology readiness level
VABI = variable area bypass injector
VAN = variable area nozzle
VAPCOM = variable pumping compressor
VCE = variable cycle engine
VSCE = variable-stream-control engine

Appendix: Turbine

Table 2 Publications on variable geometry turbine for flow control

				$\Delta\gamma$ (deg)		$\dot{m}_{red}/\dot{m}_{red,design}$		
Source	Nation	Type	Year	Minimum	Maximum	Minimum	Maximum	Comment
[99]	US	Patent	1967	—	—	—	—	VAN at low-pressure turbine inlet
[97]	US	Experimental	1969	—	—	—	—	VAN on single-stage turbine
[4]	CA	Numerical	1975	—	—	—	—	VAN at low-pressure turbine inlet
[98]	US	Numerical and experimental	1977	−6.0	108.0	0.784	—	VAN at power-turbine inlet with aero-dynamic braking
[100]	US	Experimental	1981	—	—	—	—	VAN on low-pressure turbine of CDF VCE
[1]	US	Experimental	1990	−6.0	80.0	0.784	—	VAN at power-turbine inlet
[101]	UK	Numerical	1990	—	—	—	—	VAN at turbojet and power-turbine inlet
[102]	US	Conceptual study	1995	—	—	—	—	Variable turbine concepts for tilt-rotor aircraft
[103]	UK	Experimental	1995	—	—	—	—	VAN at power-turbine inlet
[60]	JP	Numerical and experimental	1998	—	—	—	—	VAN at low-pressure turbine inlet of turboram CCE
[40]	UK	Numerical	1999	—	—	—	—	VAN at low-pressure turbine inlet of selective bleed VCE
[104]	JP	Report	2000	−10.0	10.0	0.600	1.196	VAN at low-pressure turbine inlet of turboram CCE
[105]	BR	Numerical	2004	—	—	—	—	VAN at power-turbine inlet
[106]	IT	Patent	2004	—	—	—	—	Mechanism for variable turbine stator blades
[107]	US	Patent	2006	—	—	—	—	Mechanism for variable turbine stator blades
[3]	KR	Numerical	2006	—	—	—	—	VAN at power-turbine inlet
[108]	CN	Numerical	2009	—	—	—	—	VAN at single- and four-stage turbine inlet
[109]	US	Numerical	2010	0.0	11.0	1.000	1.205	VAN at single-stage turbine inlet for tilt-rotor aircraft
[110]	DK	Numerical	2010	—	—	—	—	VAN at power-turbine inlet
[111]	FR	Patent	2011	—	—	—	—	Mechanism for variable turbine stator blades
[112]	CN	Numerical	2011	—	—	—	—	Aerodynamic design approach for VAN stage of VCE
[113]	CN	Numerical	2015	−6.0	8.0	0.784	1.173	VAN at single-stage turbine inlet with spherical end-wall

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Table 2 (continued)

Source	Nation	Type	Year	Δγ (deg) Minimum	Δγ (deg) Maximum	$\dot{m}_{red}/\dot{m}_{red,design}$ Minimum	$\dot{m}_{red}/\dot{m}_{red,design}$ Maximum	Comment
[114]	CN	Numerical and experimental	2016	−6.0	10.0	0.784	1.196	VAN cascade
[115]	PL	Numerical	2016	—	—	—	—	VAN at turbine inlet of miniature turbojet engine
[116]	IT	Numerical	2016	—	—	—	—	Analysis of VAN kinematic chain
[5]	DE	Numerical	2016	—	—	—	—	VAN at high- and low-pressure turbine inlet
[117]	PL	Numerical	2017	−7.0	4.0	0.741	1.102	VAN at turbine inlet of miniature turbojet engine
[48]	DE	Book	2018	−5.0	10.0	0.824	1.196	Effect of VAN on turbine capacity and efficiency
[118]	US	Patent	2018	—	—	—	—	Mechanism for variable turbine stator and rotor blades
[6]	US	Numerical	2018	−10.0	0.0	0.600	1.000	Turbine stage with variable stator and rotor blades
[2]	PL	Numerical and experimental	2019	−7.0	4.0	0.741	1.102	VAN at turbine inlet of miniature turbojet engine
[119]	CN	Numerical and experimental	2019	—	—	—	—	VAN on power-turbine inlet
[120]	PL	Numerical and experimental	2020	−7.0	4.0	0.741	1.102	VAN at turbine inlet of miniature turbojet engine
[121]	US	Numerical	2020	−15.0	66.0	0.326	—	Turbine stage with variable rotor blades
[122]	CN	Numerical and experimental	2020	−10.0	20.0	0.600	1.194	VAN at power-turbine inlet with spherical end-wall
[123]	CN	Review	2022	—	—	—	—	Review on challenges for a variable turbine
Mean values				−7.0	10.0	0.741	1.184	

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