Optimization of Thermodynamic Cycles, Control System Innovation, and Reliability Enhancement in Variable Cycle Engines

Yanjun Chen

Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Hong Kong, China

ychenmr@connect.ust.hk

Abstract. This paper examines the design and optimization of Variable Cycle Engines (VCEs) to achieve high efficiency across various flight conditions. By adjusting the bypass ratio, VCEs can optimize performance in both low-speed and high-speed flights, enhancing fuel economy and flight performance. Key areas include optimizing thermodynamic cycles through flexible bypass ratio adjustments and developing advanced multi-parameter control systems for precise and efficient operation. Despite increased complexity and weight, VCEs offer significant performance gains. Future research should focus on lightweight materials, robust control algorithms, and system integration to further improve VCE performance and reliability. These advancements will ensure VCEs play a crucial role in the future aviation sector, driving improvements in fuel efficiency, performance, and safety.

Keywords: VCEs, Thermodynamic Cycle Optimization, Fuel Efficiency, Control Systems.

1. Introduction

The primary power requirements for fifth-generation fighter aircraft are low fuel consumption during cruising and a high thrust-to-drag ratio during combat. These two requirements present significant conflicts in terms of the engine's thermodynamic cycle demands. The Variable Cycle Engine (VCE) theoretically addresses these contradictory needs by adjusting its operating modes to adapt to different flight conditions, thereby achieving optimal performance over a broad range of speeds and altitudes. This operational flexibility is primarily manifested in the dynamic adjustments of the bypass ratio, compressor pressure ratio, and nozzle area, enabling the engine to maintain high efficiency in both subsonic and supersonic conditions.

The VCE operates in two main modes: turbojet mode and turbofan mode. In turbojet mode, the engine is used for supersonic flight, where air is compressed and heated through the compressor and combustion chamber, then expelled at high speeds to generate thrust. The turbojet mode is characterized by a low bypass ratio, suitable for high-speed, high-altitude flight, and capable of providing a high thrust-to-drag ratio. In contrast, the turbofan mode is primarily used for subsonic flight. In this mode, thrust is generated by the low-temperature, low-pressure bypass air and the high-temperature, high-pressure core air, which can either be separated or mixed before being expelled. The turbofan mode can be further divided into dual-bypass and triple-bypass configurations.

The transition between turbojet and turbofan modes is achieved by adjusting the flow distribution between the bypass ducts and the core duct, with the corresponding nozzle adjustments being controlled by variable nozzles to regulate exhaust speed and pressure. The engine dynamically adjusts these parameters under different operating conditions to ensure stability and efficiency during transitions.

From the 1960s to the 1980s, multiple VCE concepts were proposed, including the Variable Pumping Compressor (VAPCOM) engine, combined turbojet and turbofan modes, improved turbojet and turbofan combinations, series/parallel mode VCEs, the three-spool Modulating Bypass (MOBY) VCE, the initial dual-circuit single-bypass VCE, the initial triple-exhaust dual-bypass VCE, simplified single-bypass and dual-bypass VCEs, and further simplified core-driven fan structures.

Although most of these concepts were not practically implemented, they provided valuable experience and lessons for the further development of VCEs. The Selective Bleed Variable Cycle Engine (SBVCE) adjusts the bypass ratio to optimize performance under different flight conditions. In subsonic mode, the engine operates as a fan (low pressure ratio); at Mach 1.6, it operates as a non-afterburning turbojet (high pressure ratio). Variable compressor geometry is a mature technology, while variable high-pressure turbine geometry poses significant risks, and variable low-pressure turbine geometry requires further investigation.

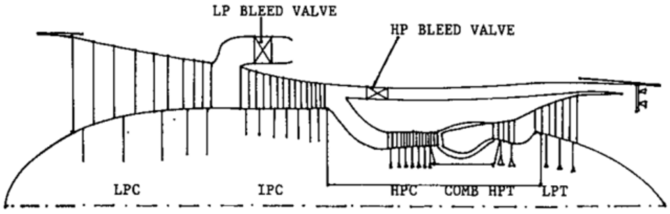

Figure 1. The Selective Bleed Turbofan

The diagram above illustrates the schematic structure of a Selective Bleed Variable Cycle Turbofan Engine. These valves release a portion of the compressed air under various operating conditions to optimize the compressor's performance and efficienc (Figure 1).

2. Thermodynamic cycle method

Through thermodynamic relationships and component characteristics calculations, off-design thermodynamic cycles can be analyzed. Assuming flow blockage before each turbine, the high and low-pressure turbines are matched first, followed by the matching of the low and high-pressure compressors. In high-pressure mode (HP mode), the control parameters include the low-pressure compressor stator, fuel flow rate, and nozzle area. In low-pressure mode (LP mode), the control parameters are the two nozzle areas and the fuel flow rate. When transitioning from high-pressure mode (HPM) to low-pressure mode (LPM), the reduction in the dimensionless flow rate of the low-pressure turbine decreases the requirements for variable geometry in the boosting stage but increases the requirements for high-pressure variable geometry. Increasing the bypass ratio improves subsonic fuel consumption and hypersonic performance, outweighing the impact of increased weight and variable geometry complexity.

The Selective Bleed Variable Cycle Engine (SBVCE) avoids approaching surge limits and thrust restrictions, with mode transition times comparable to those of hydraulic systems. Modal uncertainties due to intermediate component volume and shaft inertia limit the transition. An optimized control system reduces engine size. This turbofan engine, through selective bleeding, flexibly responds to various flight conditions, enhancing performance and fuel efficiency. The configuration of low-pressure and high-pressure bleed valves optimizes compressor operating conditions, prevents stall, and increases airflow, making it suitable for applications requiring high performance and high reliability [1-4].

Based on the DBE-GE21 and DBE-GE23 engines, GE developed the YF120 engine, the world's first flight-validated dual-bypass variable cycle engine. However, due to losing the competition to the F119 engine, the YF120 did not advance to the engineering development stage. Variable cycle engine (VCE) technology aims to achieve optimal thermodynamic cycles under various operating conditions by flexibly adjusting the thermodynamic cycle method and control variables. This, however, introduces complexities in structure, such as increased weight, dead weight, control complexity, and increased frontal area, as well as issues with numerous control variables, complex control mechanisms, and high control difficulty (Figure 2).

GE and Pratt & Whitney (PW) each received $427 million in NGAP research contracts and are expected to enter the validation phase with the Y-model flight demonstrator by 2025. The advantages include the use of ceramic matrix composite materials, a 25% improvement in fuel efficiency, a three-stream configuration, a 30% increase in range, a 10% increase in thrust, and advances in additive manufacturing [5].

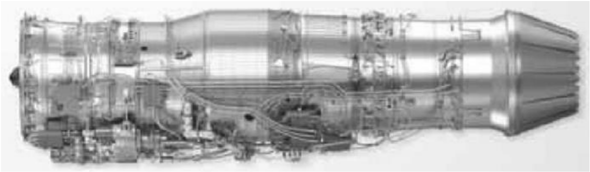

Figure 2. Adaptive Engine Transition (AETP) Program

Clark, R. A., Shi, M., Gladin, J., & Mavris, D. have designed an innovative aircraft Thermal Management System (TMS) capable of dissipating thermal loads into the bypass flow of a low-bypass turbofan engine or into the ram air flow. The TMS comprises an air cycle system similar to the typical air cycle machines used on current military and civilian aircraft. Its operation involves pressurizing bleed air from the compressor and cooling it through a heat exchanger located in the ram air flow or the engine bypass flow, then expanding the cooled air to a low temperature suitable for heat dissipation.

The researchers utilized a numerical propulsion system simulation to model a simple low-bypass afterburning turbofan engine, providing boundary conditions for the TMS system across the entire flight envelope of a typical military fighter aircraft. The study results indicate that the TMS’s maximum heat dissipation capacity is closely related to the engine bleed airflow rate, which is determined by the temperature conditions imposed by the aircraft's cooling system. Notably, the temperature of the engine bypass flow significantly limits the thermodynamic feasibility of designing the TMS using bypass air as a heat sink. By utilizing the cold airflow provided by a variable cycle engine, the TMS can significantly increase heat dissipation capacity while minimizing the impact on aircraft integration and engine performance (Figure 3-4).

This design requires minimal modifications to existing engine systems, preserving their integrity and functionality, with low retrofit costs, making it suitable for widespread adoption and application. Based on mature technology, the system is easy to engineer and quickly deploy, particularly advantageous for retrofitting older engines. It has broad market potential, extending the service life and enhancing the performance of existing engines.

In summary, the proposed TMS system, through innovative thermal management methods and efficient engineering design, demonstrates significant application potential in modern aero engines. It not only optimizes thermal load dissipation but also presents notable advantages in cost, engineering feasibility, and market application, providing important references for future aircraft power system designs [6].

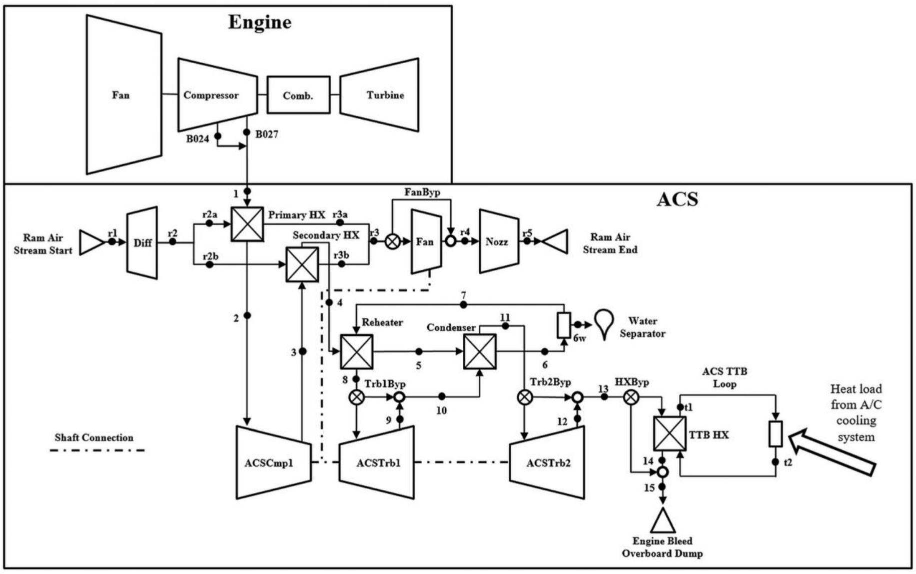

Figure 3. Proposed ram air-cooled TMS architecture

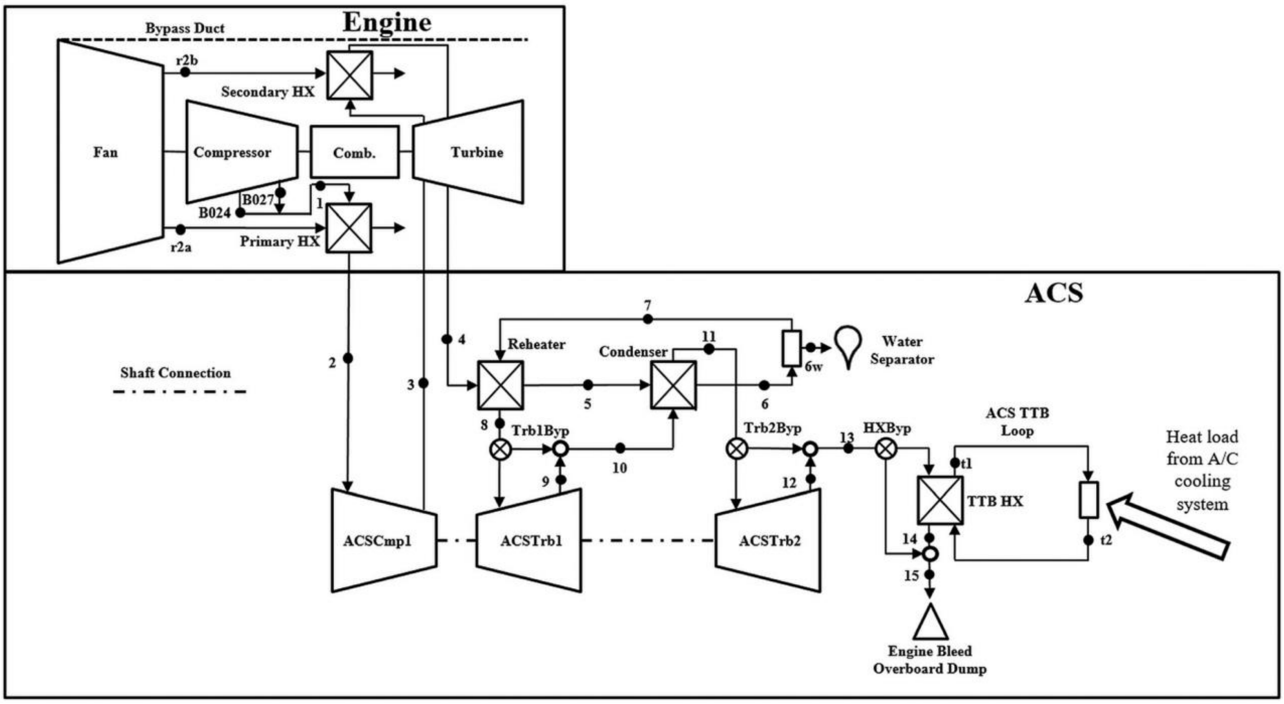

Figure 4. Proposed bypass air-cooled TMS architecture

The increase in turbine inlet temperature and turbine cooling gas temperature in variable cycle turbofan engines leads to reduced cooling effectiveness, thereby constraining engine performance enhancement. To address this issue, Wenqi, Pei Xinyan, Tian Hongyu, and Hou Lingyun utilized supercritical aviation kerosene as a cooling source to reduce the turbine cooling gas temperature through an air-oil heat exchanger. Under high temperature and high pressure conditions, traditional air cooling methods struggle to meet the demands, whereas supercritical aviation kerosene, with its superior thermophysical properties, emerges as a novel cooling source for turbines.

By introducing an air-oil heat exchanger into the variable cycle engine, the turbine cooling gas temperature can be effectively reduced, thereby improving cooling effectiveness. The study results indicate that under takeoff conditions, the performance of the variable cycle engine with an air-oil heat exchanger is significantly enhanced, with a 1.86% reduction in specific fuel consumption and a 0.95% increase in thrust, demonstrating notable economic and environmental benefits.

Supercritical aviation kerosene offers advantages such as high heat capacity, low viscosity, and high heat transfer coefficient in cooling applications. However, further research and optimization are needed in the future, including evaluating the impact of overweight, studying material compatibility, optimizing system integration, and assessing environmental impact. By using supercritical aviation kerosene as a cooling source and incorporating an air-oil heat exchanger into variable cycle turbofan engines, turbine cooling effectiveness can be significantly improved, enhancing engine performance and reducing fuel consumption (Figure 5-6) [7].

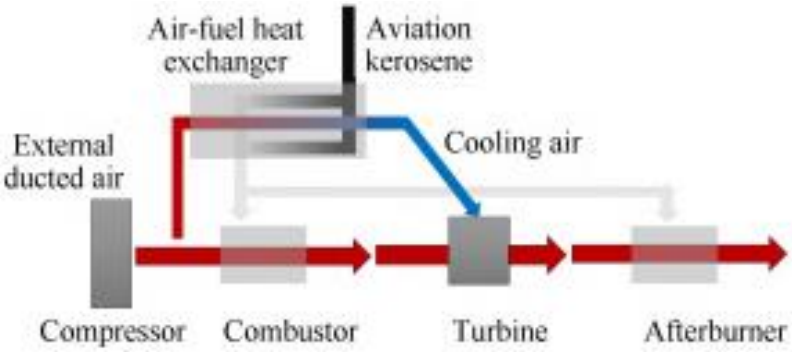

Figure 5. Schematic of the working principle of air-fuel heat

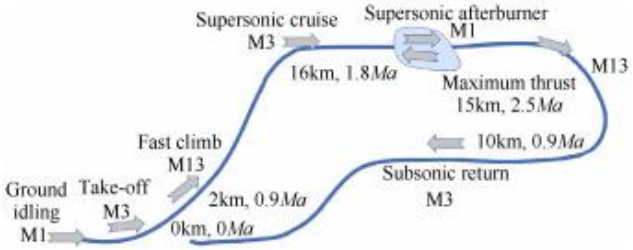

Figure 6. Schematic of main flight conditions

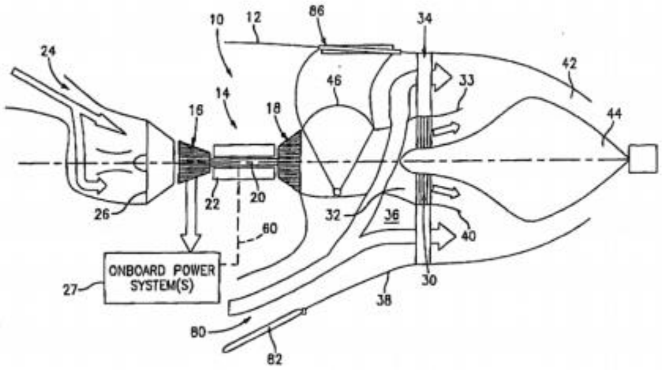

Figure 7. Patent Application Diagram

Eiler's study reveals (Figure 7) that the design of gate 46 plays a crucial role in controlling the airflow path to optimize the thermodynamic cycle of the turbine engine. By precisely adjusting the airflow's speed, pressure, and temperature, gate 46 can effectively reduce energy losses in the free turbine and fan, allowing more fuel energy to be used for thrust generation, thereby significantly improving fuel efficiency. Additionally, the precise control of gate 46 can decrease fuel consumption and emissions, further optimizing engine performance under various flight conditions. This technology enhances the overall adaptability and reliability of the engine by flexibly adjusting the airflow path, particularly excelling in response to varying flight speeds and altitudes. This represents a significant advancement in Variable Cycle Engine (VCE) design, offering substantial operational advantages [8].

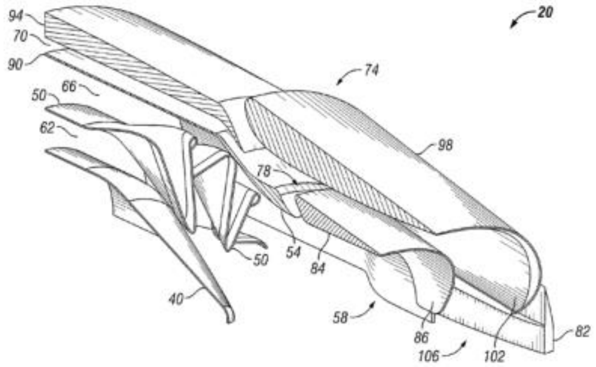

Figure 8. Local Iso-Axial Cross-Section Diagram of a Supersonic Contraction-Expansion Nozzle System [9]

According to the research by Jagdish S. Sokhey and Anthony F. Pierluissi, the design of the nozzle system is crucial for airflow control and thrust generation. The nozzle system design can be categorized into two types: those with ambient free stream and those without. The nozzle system with ambient free stream introduces a third airflow, enhancing the nozzle's suction effect, optimizing exhaust conditions, and significantly improving thrust and efficiency. On the other hand, the nozzle system without ambient free stream, although relatively simpler in design, may be slightly less efficient and have lower thrust output due to the absence of the assisting ambient free stream (Figure 8).

This technology demonstrates an effective method for enhancing thrust and improving internal flow conditions within the nozzle by introducing a third airflow, providing important technical support for nozzle system design [10].

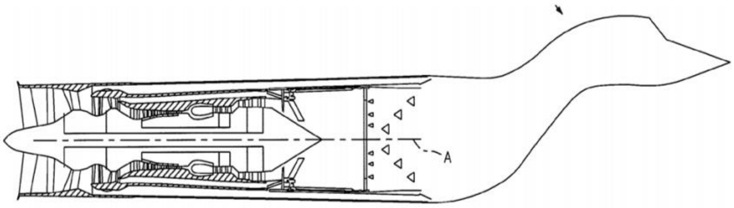

Figure 9. Rectangular S-Shaped Mixed Exhaust Nozzle System

The research by Felix Izquierdo and Timocy J. McAlice indicates that the rectangular S-shaped mixed exhaust nozzle system improves thrust and efficiency by mixing engine exhaust with bypass air through an S-shaped path design before emission. The S-shaped path increases the flow path length, balances pressure distribution, reduces vortices and flow separation, and optimizes flow characteristics. The mixed airflow within the S-shaped path optimizes temperature and velocity distribution, enhancing the nozzle's thermal efficiency and thrust efficiency while reducing noise. However, the system is structurally complex and has higher design and manufacturing costs (Figure 9).

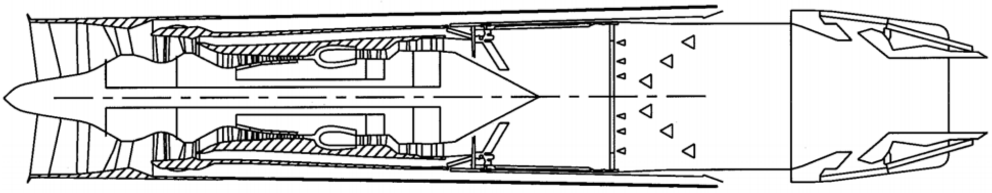

Figure 10. Rectangular Separate Exhaust Nozzle System

The rectangular independent exhaust nozzle system uses a straight exhaust path, where engine exhaust and bypass air are expelled through separate nozzles. This design simplifies the airflow path, reduces flow resistance, and increases exhaust velocity. However, the independent exhaust design may increase wake vortices, leading to less uniform thermal efficiency and noise control compared to mixed systems. Despite this, its simple design, low manufacturing, and maintenance costs make it suitable for applications requiring a straightforward structure (Figure 10).

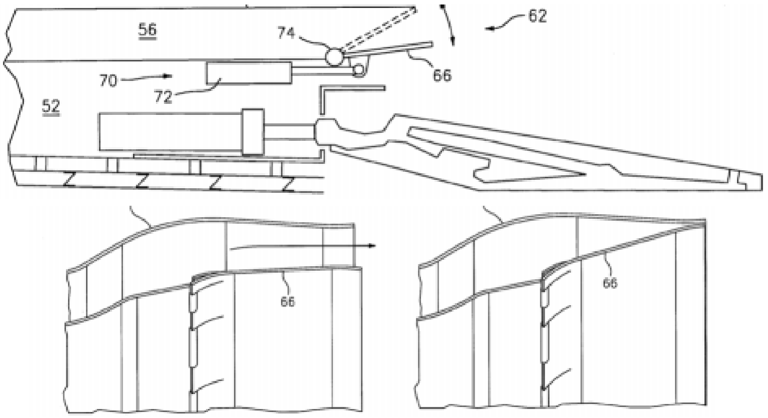

Figure 11. United Technologies Nozzle Patent

The patent US 20140165575A1 by Felix Izquierdo and Timocy J. McAlice describes a nozzle adjustment system that optimizes the thermodynamic cycle of a gas turbine by adjusting the openings of the non-primary flow path and the secondary flow path nozzles (Figure 11). The system includes a mechanism to change the nozzle cross-section by adjusting the position of adjustment component 66, thereby controlling the opening of the non-primary flow path. This control optimizes the temperature and pressure distribution of the airflow, enhancing the efficiency and thrust of the gas turbine. Additionally, by overlaying nozzle adjustment tabs, the system can further fine-tune the opening of the non-primary flow path to better match the operational requirements of the gas turbine, thereby further optimizing the thermodynamic cycle [11].

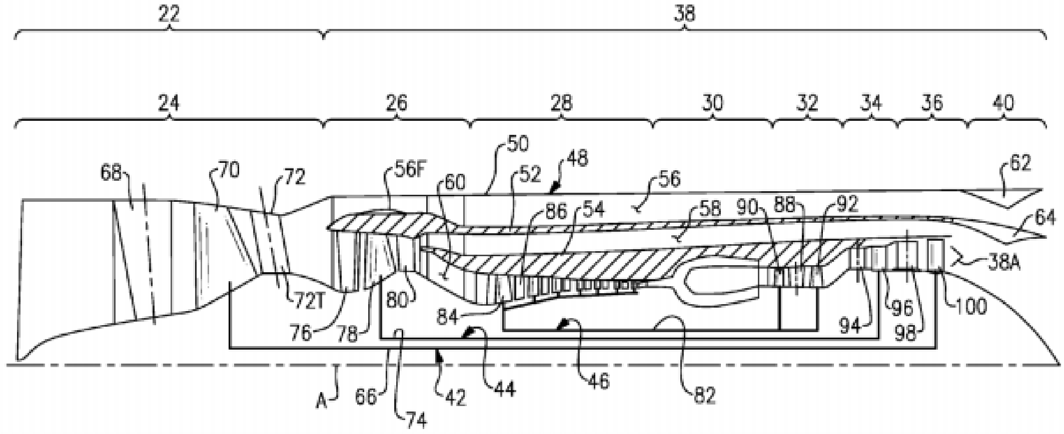

Figure 12. United Technologies Adjustable Turbine Patent

The research by Daniel Bernard Kupartis (patent US 20160186667A1) describes a sophisticated gas turbine system that optimizes thrust output and combustion efficiency across different flight stages through multiple adjustment mechanisms. This system includes a by-pass (outer bypass) fan and a first-stage fan for initial air compression, followed by a single-stage intermediate pressure compressor and a seven-stage high-pressure compressor that progressively compress the air to enhance combustion efficiency. The combustion chamber performs the combustion process, converting chemical energy into thermal energy. A two-stage high-pressure turbine extracts energy from the high-temperature, high-pressure gases to drive the high-pressure compressor. An intermediate pressure turbine and a low-pressure turbine further extract energy to drive the intermediate and low-pressure compressors, optimizing energy utilization. The turbine guide vanes adjust the airflow direction and speed by changing the blade angles, optimizing turbine efficiency (Figure 12).

The system features a Variable Cycle Engine (VCE) that adjusts the bypass ratio and turbine guide vane angles to optimize thrust output and combustion efficiency during different flight stages (such as takeoff and cruise). The bypass ratio adjustment increases the bypass ratio during takeoff to enhance thrust and decreases it during cruise to improve combustion efficiency. The adjustment of turbine guide vane angles precisely controls the airflow direction and speed, reducing energy losses and improving turbine efficiency. Although the system complexity and weight increase, leading to higher manufacturing and maintenance costs, these fine-tuning mechanisms significantly enhance performance and efficiency [12].

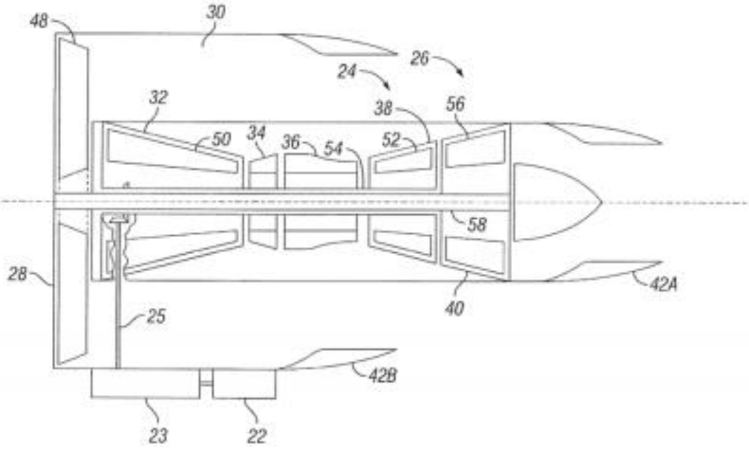

Figure 13. Rolls-Royce North America Auxiliary Turbine Patent 1

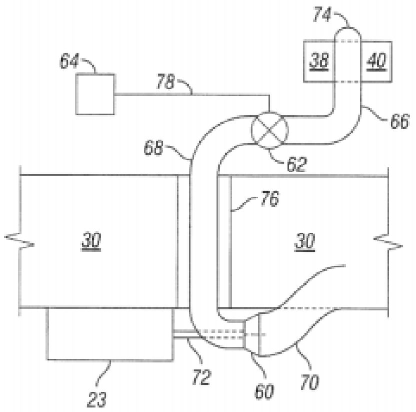

Figure 14. Rolls-Royce North America Auxiliary Turbine Patent 2

From the design model example by Rolls-Royce, it can be seen that during aircraft takeoff, the thrust output of the engine system 20 is enhanced through an auxiliary turbine system 22. Specifically, when valve 62 is opened to increase the flow capacity of the auxiliary turbine, part of the core engine gases are directed through auxiliary turbine 60. Auxiliary turbine 60 extracts power from these gases and transmits it to the compressor 32 via gearbox 23, thereby increasing the compressor's output and ultimately enhancing the overall performance of engine 20 (Figure 13).

Additionally, the gases discharged from auxiliary turbine 60 are introduced into the outer bypass 30, contributing to the output of engine 20. The opening of valve 62 can be adjusted according to actual conditions to meet different flight requirements, achieving optimized control of thrust output (Figure 14).

This design significantly increases the thrust output of the engine during the takeoff phase through the intervention of the auxiliary turbine system, while ensuring efficient use of the gases. However, the complexity and increased weight of such a system may lead to higher manufacturing and maintenance costs, and the additional dynamic adjustment components also introduce reliability risks.

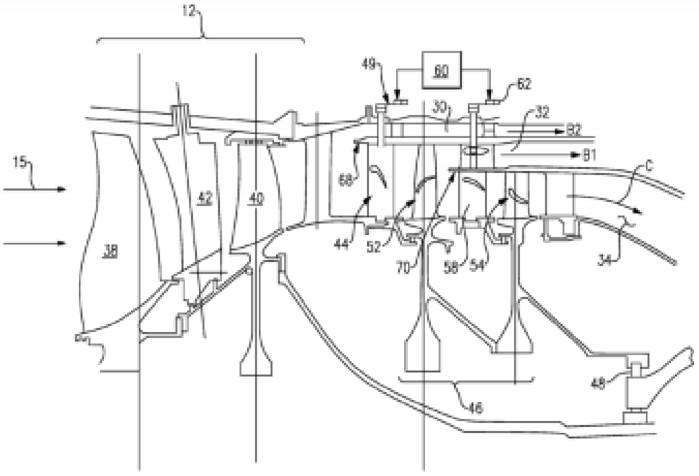

Figure 15. United Technologies Shroudless Fan Patent

In the gas turbine system proposed by Daniel Bernard Kupartis, the core airflow C is directed and compressed by a second-stage fan 52 driven by a second-stage (cold) turbine 54. The first-stage variable stator vanes 44 control the direction of the airflow entering the second-stage fan 52, while the second-stage variable inlet guide vanes 58 adjust the speed of the second-stage (cold) turbine 54, thereby affecting the states of the core airflow C and the bypass stream B1. The stator vanes and guide vanes alternately fix and rotate, with the fixed stator vanes bearing structural loads (Figure 15).

The variable speed of turbine 54 introduces reverse pressurization into the core engine's air, lowering the inlet temperature of the compressor and preventing the high-pressure compressor from overheating. At low flight Mach numbers, both the first-stage variable vanes 44 and the second-stage variable guide vanes 58 are in the open position, reducing the core airflow C and minimizing the energy extracted from core airflow C by turbine 54. This allows compressor 26 to operate at maximum capacity, reducing the energy entering bypass stream B1, thereby improving the core thermodynamic cycle efficiency and reducing bypass thrust.

At high flight Mach numbers, the reverse pressurization of core airflow C is maximized, helping to control the inlet temperature of compressor 26 and reduce the outlet temperature T3, while increasing the energy of bypass stream B1. The third rotor 46 and the cold turbine 54 maintain the compressor temperatures within acceptable ranges and maximize fuel efficiency, enabling the gas turbine engine to adapt to changing operating parameters and provide high performance [12].

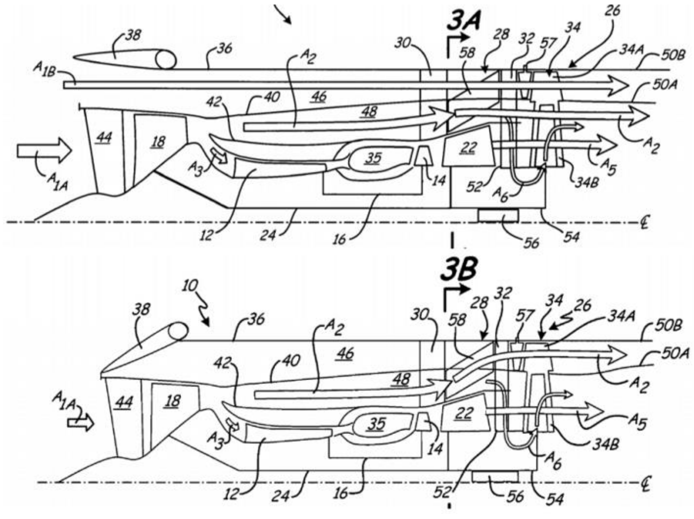

Figure 16. United Technologies Thrust Reverser Patent

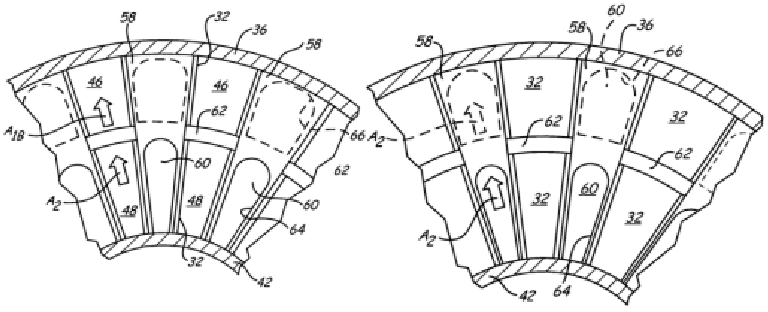

Figure 17. Joint Computational Thrust Reverser Patent

Gary D. Roberge proposed a VCE propulsion system that enhances the operation of low-speed subsonic engines by introducing an auxiliary turbine and an auxiliary fan, thereby increasing the effective bypass ratio in low-speed modes. The low-pressure turbine (LPT) 22 drives the blades 34 through gearbox 56, accelerating the intake A1B to generate thrust. The intake A1B and the bypass flow A2 mix to produce a combined bypass flow that flows around the core airflow, increasing the bypass ratio and thrust (Figure 16).

During high-speed operation, engine 10 generates a higher overall pressure ratio and exhaust velocity, enhancing performance. The outer ring 34A of blades 34 pressurizes the bypass flow A2, improving propulsion efficiency. To ensure the combustion stability of combustion chamber 50 and to prevent surge or blockage in the high-pressure turbine (HPT) 14, low-pressure turbine (LPT) 22, and propulsor 26, the flow proportions of each airflow must be coordinated.

The rotating frame 28 constitutes an annular variable frequency valve structure that rotates around the engine centerline CL. In low-speed mode, the intermittent casing components 58 are positioned downstream of the forward support plate 30, preventing airflow from entering the intermittent casing components 58. The inlet 64 and outlet 66 are blocked by the forward support plate 30 and the rear support plate 32, closing the variable frequency valve (Figure 17) [13].

3. Design and Optimization of Control Systems

Zhen, M., Dong, X. Z., Zheng, J. C., Liu, X. Y., & Tan, C. Q. conducted a performance study of the Front Variable Area Bypass Injector (FVABI) under different operating conditions. The researchers designed and established a computational model focusing on the effects of area changes at the FVABI and the Mode Selection Valve (MSV) on the critical flow state. Based on a zero-dimensional engine performance model, they conducted a detailed analysis of variable geometry scheduling under typical subsonic cruise conditions. By validating the improved zero-dimensional bypass mixing computational model, the study demonstrated that the model has high efficacy in predicting the mixing characteristics of FVABI under different operating modes, with maximum errors of 2.3% and 6.2% for the total pressure recovery coefficient and the ejection ratio, respectively. This performance prediction method lays a solid foundation for the variable geometry design and performance optimization of VCE under typical mission configurations, showcasing its significant application potential in the advancement of aero-engine technology. Through detailed analysis and validation, this research not only provides theoretical support for the efficacy of FVABI but also offers important references for the design and optimization of future VCE systems [9].

Variable cycle engines (VCE) bring challenges with multiple control variables, complex control mechanisms, and high control difficulty. Qi Yiwen, Zhang Chi, & Chen Yuxi conducted a study on a model-based control plan design method for a dual-bypass VCE. Using the variable specific heat method, they established a nonlinear component-level mathematical model of the VCE and performed steady-state and dynamic performance simulation verifications under both single-bypass and dual-bypass working modes.

To address issues of poor iterative convergence and low computational real-time performance in the component-level model of the VCE, they proposed a modified Newton iteration method with dynamic damping coefficients. Simulation results showed that the improved iteration algorithm reduced computational time by more than 38% compared to the traditional Newton iteration algorithm, significantly enhancing the model's real-time computational performance.

Based on this, the researchers further explored control plans for the dual-bypass VCE in idle and above states. These included steady-state fuel flow control plans, nozzle area control plans, front/rear adjustable bypass ejector control plans, and over-limit protection control plans. This laid a solid foundation for further in-depth research on the forward design method of VCE control laws based on models.

Additionally, they designed a dual-loop closed-loop mode switching control law for the main fuel flow-engine pressure ratio and nozzle area-low-pressure speed. Simulation results showed that the designed dual-loop closed-loop control law ensured quick and smooth mode switching for the VCE, with thrust fluctuations controlled at around 1.5%. During single and dual-bypass mode switching, thrust fluctuation was only 0.12%, achieving constant thrust mode switching control.

In summary, the research made significant progress in improving the computational real-time performance and iterative convergence of the VCE model, successfully designing various control plans and closed-loop control laws, and verifying their effectiveness and stability under different working conditions. The study provides important theoretical and practical guidance for future VCE control system design, demonstrating its application potential in complex aero-propulsion systems. [14].

To study the characteristics and control laws of variable cycle engines (VCE), Long Qiangguang conducted research on a dual-bypass VCE, focusing on component-level modeling, system characteristics, control laws, and limit protection control. A component-level model of the dual-bypass VCE was established, and its characteristics were analyzed. The study considered the effects of the bleed air system and component geometric parameters on component characteristics. Through component-level model simulation, the rotational speed characteristics and typical variable geometry component characteristics of the VCE were obtained.

The research also investigated the control laws of the dual-bypass VCE, including steady-state control laws and acceleration/deceleration control plans. Control parameters and controlled parameters were selected, and the state control plan for the VCE was designed. The steady-state control laws were designed, and an acceleration control plan was developed based on the power extraction method. Numerical simulations verified the effectiveness of both the steady-state control laws and the acceleration/deceleration control plans.

This study not only provided a detailed analysis of the component-level characteristics of the dual-bypass VCE but also systematically explored its control laws, offering theoretical support and practical guidance for the optimal design of VCEs. By establishing an accurate component-level model and conducting simulation verification, the paper demonstrated the performance of the VCE under different working conditions and the effectiveness of the control strategies, further advancing the development of VCE technology [15].

Turbine temperature is a key performance parameter of Variable Cycle Engines (VCE) as it reflects the engine's lifespan. To achieve the control objective of extending VCE life by maintaining constant engine thrust while satisfying various safety operational limits, the optimization of adjustable geometric components is used to lower the post-turbine temperature, known as the minimum turbine temperature mode. Miao Rongcheng conducted a study on the design of a multivariable optimization control system for the strongly coupled parameters among multiple adjustable components when switching from normal cruise mode to minimum turbine temperature mode in a VCE.

For the constrained optimization problem of minimizing turbine temperature in a VCE, the second norm of the thrust difference was included in the optimization evaluation function. Using the penalty function method to handle output constraints, the constrained optimization problem was transformed into an unconstrained minimization problem. Specifically, the Grey Wolf Optimizer (GWO) was employed, and the optimization effects were compared with the Sequential Quadratic Programming (SQP) algorithm of traditional nonlinear optimization problems, using different Mach number conditions under ground conditions and intermediate engine states (maximum non-afterburning state).

The results showed that while the SQP algorithm had a fast optimization convergence rate, it tended to fall into local convergence, reducing the post-turbine temperature by 2.19% and 1.54% for non-degraded and degraded VCE conditions, respectively. Conversely, the GWO algorithm exhibited better global search capability, reducing the post-turbine temperature by 6.16% and 7.08%, respectively.

Furthermore, addressing the strong nonlinearity and multi-parameter coupling issues of VCEs, a steady-state multivariable closed-loop controller based on the Active Disturbance Rejection Control (ADRC) strategy was designed. Firstly, based on the analysis of key component mechanisms and sensitivity analysis results of the VCE, four pairs of appropriate control and controlled variables were selected. Considering the difficulty in tuning multiple control parameters due to high dynamic and steady-state performance requirements during VCE switching control, a block-wise intelligent optimization method for controller parameters was proposed, setting different performance evaluation functions for different blocks.

In four typical working conditions, digital simulation verified that the controller could achieve the performance control effect, and hardware-in-the-loop simulation validated the real-time performance and effectiveness of the designed controller, showing certain engineering application value. To address the complexity issues caused by traditional control parameter scheduling methods within a wide envelope, an intelligent multivariable control method based on Genetic Algorithm (GA)-optimized BP Neural Network was proposed. This method used GA to optimize the initial weights and thresholds of the BP neural network, preventing the network from falling into local optima during training. The trained network was then used to design a VCE multivariable closed-loop controller. The control effect and generalization ability of the GA-BP neural network were verified using non-training condition a within the envelope and condition b outside the envelope, and the control effects of GA-BP were compared with the ADRC strategy.

The simulation results indicated that the method had good control effects on typical conditions set within the envelope and had a certain generalization ability without the need to partition the envelope. Through the establishment of accurate component-level models and simulation verification, researchers provided a detailed analysis of the characteristics and control laws of the dual-bypass VCE, systematically explored the effectiveness of optimization algorithms and control strategies, offering theoretical support and practical guidance for the optimal design of VCEs. This study demonstrated the performance and control strategy effectiveness of VCEs under different conditions, further advancing VCE technology development [16].

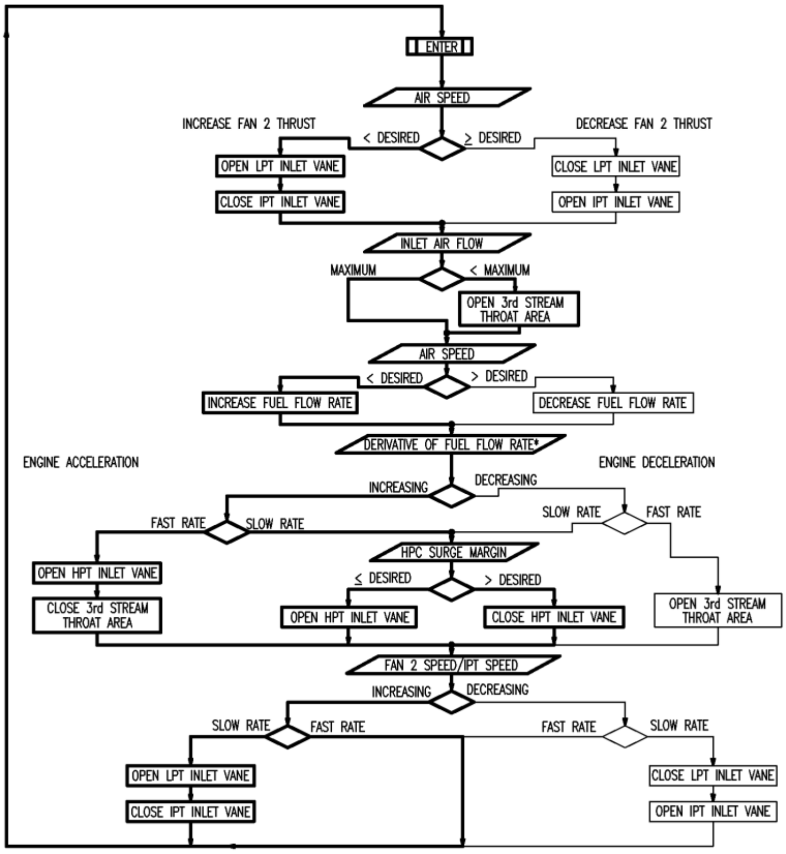

Figure 18. United Technologies Adjustable Turbine Patent Diagram [12]

PID controllers achieve feedback control by adjusting the proportional (P), integral (I), and derivative (D) parameters: P responds to the current error, providing a fast reaction; I accumulates the historical error, eliminating steady-state error; and D predicts error changes, improving system stability. They are suitable for simple, linear systems.

Deep Q Networks (DQN) combine Q-learning with deep neural networks for control in high-dimensional state and action spaces. Q-learning finds the optimal policy by learning the value function \(Q(s, a)\) for state-action pairs, while deep neural networks approximate the Q-value function, handling complex, high-dimensional environments. DQN is suitable for complex systems with strong adaptability and robustness (Figure 19-20).

Deep Deterministic Policy Gradient (DDPG) is a policy gradient-based reinforcement learning algorithm suitable for continuous action spaces. Its policy network directly outputs decision actions, making it suitable for continuous control; the value network evaluates the long-term returns of the policy, guiding policy updates; and experience replay and target networks improve training stability and efficiency. DDPG performs exceptionally well in complex, nonlinear control problems, achieving high-precision and fast-response control.

Zhao Fangjiao addressed the issue of the insufficient performance of a single PID controller for variable cycle aero engines under varying conditions by proposing thrust control methods based on Deep Q Networks and Deep Deterministic Policy Gradients. The study detailed the design of the two reinforcement learning controllers, including the selection of engine state input parameters and actuator action output parameters, the setting of reward functions based on control performance, the convergence conditions of the state-action networks, and the experience buffer mechanism based on engine characteristics.

Simulation results showed that these two reinforcement learning thrust controllers for variable cycle aero engines achieved good performance indicators under various external commands, verifying the stability and robustness of the intelligent control designs. They achieved stable, fast, and accurate thrust control for variable cycle aero engines under different operating points [17].

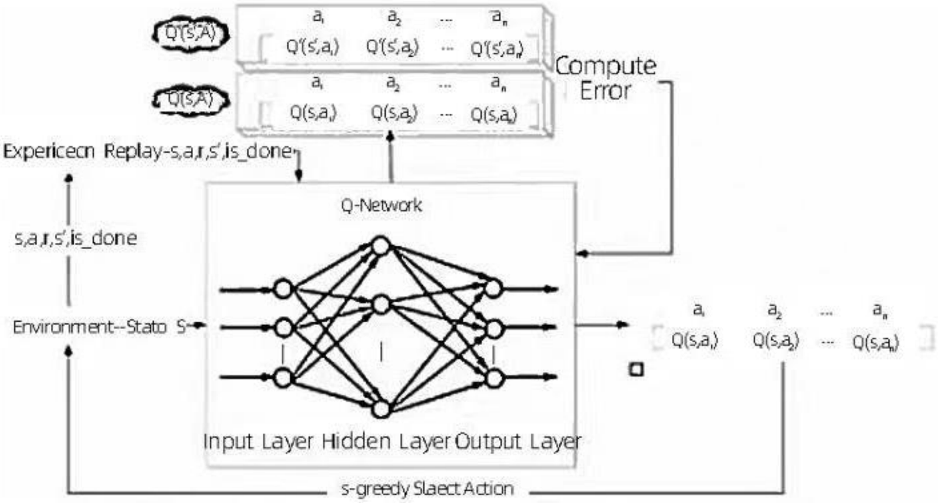

Figure 19. DQN Algorithm Flowchart 1

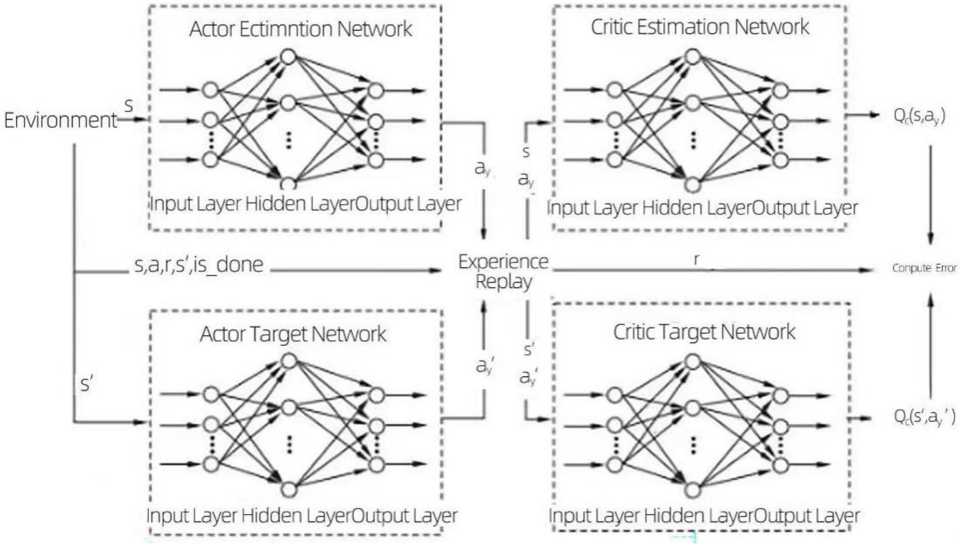

Figure 20. DQN Algorithm Flowchart 2

4. Reliability Study of Variable Cycle Engines

Variable cycle engines (VCEs) are characterized by variable active structures, multi-layer casings, and ultra-high rotor speeds, making the dynamics of the entire engine highly complex. Traditional structural dynamics analysis methods may not efficiently support the dynamic design of the entire engine. Therefore, it is essential to develop rapid analysis techniques for the overall structural dynamics of VCEs.

Chen Yun conducted a study focusing on the parametric modeling techniques for the casing system and rotor system of VCEs, considering the influence of bolt connection stiffness. A rotor-support-casing dynamic model of the entire VCE was established, enabling rapid estimation and analysis of the engine's structural dynamics. The modal analysis results of the entire engine indicated that the error in modal frequencies for each mode was less than 10%, and the MAC values for matched modes were all above 0.8, demonstrating the model's accuracy and reliability.

Additionally, by establishing a virtual high-pressure rotor model, it was concluded that a simplified hexahedral model could replace the detailed model. This approach increased the calculation efficiency of critical speeds for the low-pressure and high-pressure rotors by 92.0% and 93.0%, respectively, and the calculation efficiency for dual-rotor critical speeds by 88.9%, with errors within acceptable ranges. Using a detailed casing model with solid thin-layer connections and a virtual thin-layer connected shell model for the casing, exemplified with the intake casing and compressor casing, the MAC values for matched modes were all above 0.8, indicating that the model maintained good computational efficiency while ensuring accuracy.

Ultimately, the researchers developed a rapid estimation software for the overall dynamics of VCEs. This software supports parametric modeling of the casing and rotor systems, completes thin-layer connection modeling, and calculates the equivalent elastic modulus of thin layers. It enables quick calculation of rotor critical speeds while maintaining a certain level of accuracy. This study provides effective tools and methods for the dynamic design of VCEs, improving design efficiency and ensuring the accuracy of analysis results to a certain extent. It offers significant technical support for the optimized design and application of VCEs in the future [18].

With the advancement of modern aero-engine design, manufacturing, testing, and control technologies, the concept of the adaptive Variable Cycle Engine (VCE) has emerged, focusing on multi-functionality, high performance, long life, and high reliability. Theoretical and technical progress has been steadily achieved. According to the technological requirements of VCEs, XXX analyzed their characteristics, technical advantages, and potential applications, and discussed the development and issues in reliability and technical risks both domestically and internationally. The analysis primarily focused on the structural strength control system and the reliability and technical risks in testing.

By precisely controlling the operating parameters of the engine, VCEs can provide the required thrust under various flight conditions while reducing turbine temperature and extending engine life. Domestic research on improving VCE reliability focuses on enhancing stability and durability under complex flight conditions. Key technical risks in testing and practical applications include material fatigue, component wear, and the impact of high-temperature, high-pressure working environments on the engine. Internationally, significant progress has been made in adaptive control and intelligent monitoring technologies. By leveraging big data and artificial intelligence, the performance and reliability of VCEs have been further enhanced. Extensive wind tunnel experiments and flight tests have validated the performance and reliability of VCEs under various flight conditions. However, challenges remain in addressing high-temperature materials and the complex aero-thermal environment.

Regarding the reliability and technical risks in structural strength control systems and testing, finite element analysis and optimized design ensure the structural strength of key engine components under high-temperature and high-pressure conditions. The use of new high-temperature alloys and composite materials improves the durability and fatigue resistance of components. During testing, the comprehensive performance and reliability of VCEs are assessed by simulating different flight conditions, with sensors and data acquisition systems monitoring the engine status in real time to detect and address potential issues promptly. Failure tree analysis and failure mode analysis are employed to identify potential failure sources for design improvements.

The analysis of the characteristics, technical advantages, potential applications, and reliability and technical risks of VCEs provides an important theoretical foundation and practical guidance for the research and development of VCEs. Further development requires breakthroughs in materials science, control technologies, and testing methods to enhance the overall performance and reliability of VCEs, meeting the high demands of modern aero engines [19].

5. Conclusion and Outlook

This paper delves into the design and optimization of Variable Cycle Engines (VCEs), aiming to achieve high efficiency across the entire flight envelope through advanced technologies such as bypass ratio adjustment, multi-parameter control, and the introduction of auxiliary turbines. The study indicates that VCEs can maintain optimal performance in both low-speed and high-speed flight by flexibly adjusting the bypass ratio, significantly enhancing fuel economy and flight performance. Public literature primarily focuses on three aspects:

5.1. Optimization of Thermodynamic Cycles

By adjusting the bypass ratio, VCEs can flexibly alter airflow distribution during different flight phases, achieving optimal thermodynamic cycles. In low-speed flight, a high bypass ratio mode is adopted to improve fuel efficiency and thrust; in high-speed flight, the bypass ratio is reduced to decrease air resistance and enhance high-altitude, high-speed flight efficiency. Future research should continue to explore how to optimize thermodynamic cycles under various flight conditions to further improve the overall performance of VCEs.

5.2. Design and Optimization of Control Systems

Multi-parameter control is key to achieving bypass ratio adjustment and performance optimization. By precisely controlling the flow area of the fan, intermediate-pressure turbine, high-pressure turbine, and low-pressure turbine, VCEs can operate efficiently under various flight conditions. However, the complexity of the control system increases the difficulty of design and debugging. Future research should focus on developing more refined control algorithms and more efficient system integration solutions to improve the control system’s response speed and reliability. For example, advanced sensor technology and intelligent algorithms can enable real-time monitoring and dynamic adjustment of each component, thereby optimizing engine performance.

5.3. Reliability Study of Variable Cycle Modes

Although the complexity and weight of VCEs have increased, the performance gains are significant. The introduction of three-stream designs and adaptive turbine technology allows VCEs to flexibly adjust airflow during different flight phases, achieving optimal performance. However, issues such as increased frontal area, dead weight, and control system complexity require further research and optimization. Future engineering work should focus on the following areas:

1) Materials and Manufacturing Technology: Use lightweight, high-strength new materials and advanced manufacturing processes to reduce engine weight and system complexity.

2) Robust Control Algorithms: Develop more robust control algorithms that can adaptively adjust under various flight conditions, enhancing system stability and reliability.

3) System Integration Optimization: Optimize system integration schemes to reduce the dead weight and complexity of the control system, improving the overall system efficiency.

Future research and engineering work should continue to focus on adjustable turbine design and bypass ratio adjustment to further enhance the performance and reliability of VCEs. Particularly, in-depth studies are needed on how to optimize control logic and system response speed without significantly increasing system complexity and weight, ensuring that VCEs perform excellently and exhibit high adaptability and robustness under various flight conditions. Through these efforts, VCEs will play a crucial role in the future aviation sector, driving the further development of aero-engine technology. This will not only help improve aircraft fuel efficiency and flight performance but also positively impact the reduction of aviation emissions and the enhancement of aviation safety.

In summary, the design and optimization of VCEs have not only improved the performance and adaptability of aero-engines but also provided important technical reserves for the future development of aviation technology. As research deepens and technology advances, VCEs are expected to play an increasingly important role in future aviation applications, promoting leaps in aviation technology development.

References

[1] MARCO A. B. DO NASCIMENTO, PERICLES PILIDIS, 1991, The Selective Bleed Variable Cycle Engine, ASME, International Gas Turbine and Aeroengine Congress and Exposition Orlando, FL June.

[2] MARCO A. B. DO NASCIMENTO, PERICLES PILIDIS, 1992, An Optimization-Matching Procedure for Variable Cycle Jet Engines, ASME, International Gas Turbine and Aeroengine Congress and Exposition Cologne, Germany June 1-4.

[3] U.T.J. Gronstedt, Pericles Pilidis, 2000, CONTROL OPTIMIZATION OF THE TRANSIENT PERFORMANCE OF THE SELECTIVE BLEED VARIABLE CYCLE ENGINE DURING MODE TRANSITION, ASME, International Gas Turbine & Aeroengine Congress & Exhibition, Munich, Germany, May 08-11, 2000.

[4] Martin Dodds, Pericles Pilidis, 1999, THE INFLUENCE OF A VARIABLE CAPACITY TURBINE IN THE PERFORMANCE OF A VARIABLE CYCLE ENGINE, ASME, International Gas Turbine & Aeroengine Congress & Exhibition Indianapolis, Indian, June 7-June 10.

[5] Sun Mingxia, Liang Chunhua, Suo Dejun, Liu Dianchun, 2021, Analysis of the Progress of the U.S. Sixth-Generation Fighter Engine, Aero Engine, Vol. 47, No. 3.

[6] Clark, R. A., Shi, M., Gladin, J., & Mavris, D. (2022). Design and analysis of an aircraft thermal management system linked to a low bypass ratio turbofan engine. Journal of Engineering for Gas Turbines and Power, 144 (1), 011019.

[7] Wen Qi, Pei Xinyan, Tian Hongyu, & Hou Lingyun. (2023). Study on the Impact of Air-Oil Heat Exchangers on the Overall Performance of Variable Cycle Aero Engines. Propulsion Technology, 44 (2), 32-41.

[8] Eiler, Donald C.,2011, Variable cycle boost propulsor, EUROPEAN PATENT SPECIFICATION, EP 1302640B1.

[9] Zhen, M., Dong, X. Z., Zheng, J. C., Liu, X. Y., & Tan, C. Q. (2023). Performance prediction method for forward variable area bypass injector of variable cycle engine based on numerical simulation. Journal of Engineering for Gas Turbines and Power, 145 (6), 061002.

[10] Jagdish S. Sokhey, Anthony F. Pierluissi, 2014, Gas Turbine Engine System and Supersonic Exhaust Nozzle, US 20140238043A1.

[11] Felix Izquierdo, Timocy J. McAlice (United Technologies Corporation), 2014, Nozzle Section for a Gus Turbine Engine, US 20140165575A1.

[12] Daniel Bernard Kupartis, 2016, GAS TURBINE WITH TWO SPOOL FAN AND VRAIABLE VANE TURBINE, US 20160186667A1.

[13] Gary D. Roberge (United Technologies Corporation), 2011, REAR PROPULSOR FOR A VARIABLE CYCLE GA TURBINE ENGINE, US8082727B2.

[14] Qi Yiwen, Zhang Chi, & Chen Yuxi. (2022). Thrust Control of Variable Cycle Engines Based on Reinforcement Learning Methods. Journal of Shenyang Aerospace University, 39 (3), 40-49.

[15] Long Qianguang. (2021). Research on Control Plans for Dual Bypass Variable Cycle Engines (Master's thesis, Nanjing University of Aeronautics and Astronautics). https://link.cnki.net/doi/10.27239/d.cnki.gnhhu.2021.001517 doi:10.27239/d.cnki.gnhhu.2021.001517.

[16] Miao Rongcheng. (2021). Research on Control Laws for Dual Bypass Variable Cycle Engines (Master's thesis, Nanjing University of Aeronautics and Astronautics). https://link.cnki.net/doi/10.27239/d.cnki.gnhhu.2021.001026 doi:10.27239/d.cnki.gnhhu.2021.001026.

[17] Zhao Fangjiao. (2022). Design of a Multivariable Optimization Control System for Variable Cycle Engines (Master's thesis, Dalian University of Technology). https://link.cnki.net/doi/10.26991/d.cnki.gdllu.2022.000465 doi:10.26991/d.cnki.gdllu.2022.000465.

[18] Chen Yun. (2021). Research on Rapid Analysis Technology for the Overall Structural Dynamics of Variable Cycle Engines (Master's thesis, Nanjing University of Aeronautics and Astronautics). https://link.cnki.net/doi/10.27239/d.cnki.gnhhu.2021.000600 doi:10.27239/d.cnki.gnhhu.2021.000600.

[19] Zhang Zhilan. (2013). A Brief Analysis of the Reliability and Technical Risks of Variable Cycle Aero Engines. In Proceedings of the 13th Sub-venue of the 15th Annual Meeting of the China Association for Science and Technology: Seminar on Design, Manufacturing, and Application Technology of Aero Engines (pp. 586-591). AVIC Shenyang Engine Design and Research Institute.