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A Study on Combined Variable Geometries Regulation of Adaptive Cycle Engine during Throttling

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Abstract: The most remarkable variable cycle characteristic of the variable cycle engine (VCE) is that it keeps airflow almost constant during subsonic cruise throttling by modulating variable geometries, which can efficiently decrease spillage drag and increase installed thrust. One of the most critical challenges for the modulation lies in completely maintaining airflow, as well as avoiding specific fuel consumption (SFC) degradation during throttling. This has resulted in a need to investigate the modulation regulation of the adaptive cycle engine (ACE) which is a new concept for VCE and has greater potential for flexibly modulating airflow and pressure ratio. Thus, the aim of this paper is to study the variable geometries' modulation schedule of ACE in maintaining airflow during throttling. A configuration of an ACE concept and its modeling study are first put forward. Then, the control schedule is researched via the combination of sensibility analysis and basic working principle instead of optimizing them directly. Results show that when the net thrust decreases from 100% to about 55% during subsonic cruise and to 32% during the supersonic cruise, the demand airflow of the engine is kept almost constant, which greatly improves the installed performance during throttling.

Keywords: adaptive cycle engine; variable geometries modulation; maintain airflow during throttling; spillage

1. Introduction

Nowadays, the design of the next generation affordable aircrafts includes all-weather, long-range and multi-mission objectives, among others [1–5]. These objectives lead to new requirements for aircraft engine design. On one hand, the newly designed engine should have turbojet features such as higher specific thrust in order to qualify for thrust-stringent objectives such as non-augmented supersonic cruising and transonic climbing. On the other hand, it should also have the turbofan features of lower specific fuel consumption (SFC) to compete in fuel cost objectives such as long-range reconnaissance. Clearly, to achieve these conflicting goals in an engine, the variable cycle engine (VCE) is undoubtedly an ideal propulsion device [6–8].

VCE promises to provide high propulsive efficiency with a high bypass turbofan while retaining the ability to produce high specific thrust with a low bypass turbofan. With respect to VCE technology developments and guidance for future developments, a detailed general structure and working mode transformation have been investigated [9–12]. Then, performance simulation of VCE was performed to optimize parameters and to control variable geometries [13,14]. One of the greatest challenges during the design phase relates to how to optimize the various cycles and then to match them to the capabilities of the components [15]. Meanwhile, based on the public references so far, VCE can keep airflow constant during subsonic cruise throttling by modulating variable geometries, which can efficiently decrease spillage drag and increase installed thrust [7,16,17]. This is the most remarkable variable cycle characteristic of VCE.

However, there are still some issues that need to be resolved during throttling. For example, with the exception of studies that focus on the subsonic cruise [7,16,17], study on variable geometries combined modulation is overlooked. However, it is required to avoid spillage drag during supersonic cruise throttling. In these works, during subsonic cruise throttling, total airflow could not be maintained at 100% and it declined appropriately during throttling in reference [7], which led to spillage drag and decrease of installed thrust. Furthermore, when the airflow could be maintained completely, since variable geometries regulation is optimized directly instead of through theory analysis, it resulted in a negligible improvement in performance [16]. Although low pressure rotation speed (LPRS) remains constant based on theory analysis, SFC increases along with thrust, reducing to 87%, which results in SFC degradation when compared with conventional turbofans [17].

As a new concept for VCE, the adaptive cycle engine (ACE) consists of a typical double bypass VCE surrounded by a third bypass duct and a front fan with unchanged inlet guide vanes [18–20]. At present, the analysis of adaptive cycle engine is still in its preliminary stage. With the support of the Adaptive Engine Technology Development (AETD) plan, the adaptive cycle engine has made great progress. The core engine of ACE has been tested by the General Electric Aircraft Engine Group (GEAE) [19]. Zheng Jun-Chao analyzed the matching mechanism on an adaptive cycle engine [20].

In essence, the ACE is a triple bypass variable cycle engine as shown in Figure 1 in this paper. The fan system of ACE, which is divided into three sections, includes the front fan stage, a second fan stage with variable inlet guide vanes and a core driven fan stage (CDFS). Both the front fan and the second convertible fan are driven by low pressure turbine (LPT). Meanwhile, the CDFS and the high-pressure compressor (HPC) which both have variable inlet guide vane, are driven by the high-pressure turbine (HPT). The available variable geometries include variable stator vane $(VSV)_{Fan}$, VSV_{CDFS}, VSV_{HPC}, variable area nozzle $(VAN)_{HPT}$, VAN_{LPT}, variable area bypass injector (VABI; Pro-VABI means the front VABI, Rear-VABI means the rear VABI) and main nozzle throttle area (A_8) [9–12,18–20], as shown in Figure 2. Through the combined modulation of different variable geometries, this engine architecture makes it possible to avoid enormous inlet spillage drag under a significantly wide power range at constant airflow.

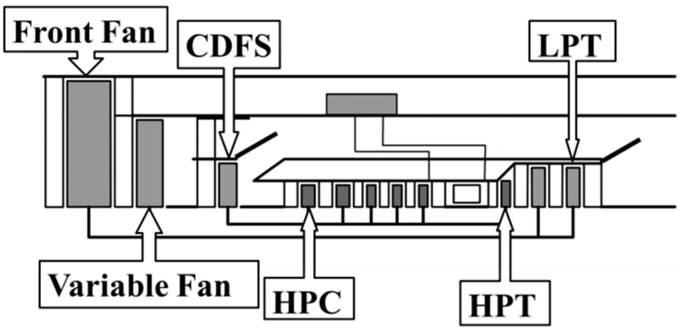

Figure 1. The configuration of an adaptive cycle engine. CDFS: core driven fan stage; HPC: high-pressure compressor; HPT: high-pressure turbine: LPT: low-pressure turbine.

Benefiting from the additional third bypass, ACE has a greater potential for flexibly modulating the airflow and pressure ratio. Therefore, it is necessary to study the control schedule of variable geometries based on a modeling study, which focuses on retaining airflow to avoid SFC degradation during subsonic and supersonic cruise. Due to the strong coupling relationship among the variable geometries, variable geometry adjustment can affect the matching of components directly. The strong coupling of variable geometries is what makes the modulation study extremely challenging. Nascimento and Pilidis postulated that one of the greatest challenges, during the design phase, is how to optimize the various cycles and then to match them to the capabilities of the components. The optimized method is based on thermodynamic relationships and component characteristics [15]. Therefore, in this paper, the variable geometry adjustment is researched via the principle analysis and quantitative research.

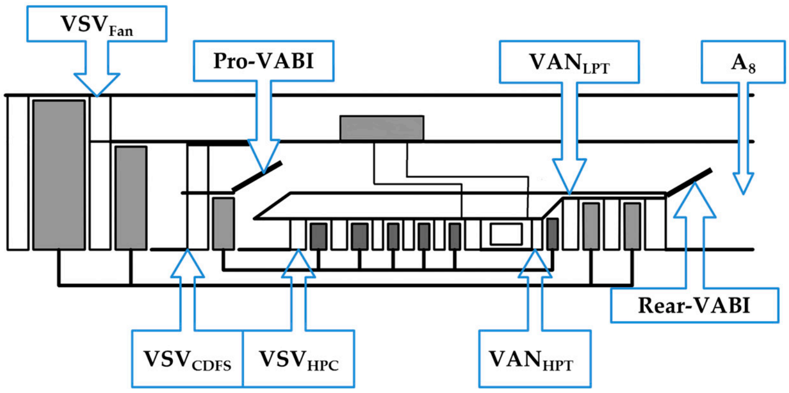

Figure 2. The variable geometries of an adaptive cycle engine (ACE).

In this article, the "Introduction" section gives a brief introduction on the need of ACE combined modulation of variable geometries. In the following section, ACE structural analysis and modeling are presented. The section "Study on the Method of Variable Geometries Modulation" discusses the control schedule of ACE variable geometries during throttling via the combination of sensibility analysis and basic working principle. Then, the next section demonstrates the control schedule of ACE variable geometries. The final section draws the conclusions.

2. Structural Analysis and Modeling of ACE

2.1. Operating Modes

Airflow from the front fan passes through the second variable fan and the outer bypass duct which is called the third bypass. A heat-exchanger is located in the third bypass which can cool the turbine cooling bleed and increase the HPT inlet temperature maximum limit effectively. Then, airflow from the variable fan passes through the CDFS and the outer bypass duct, which is called the front bypass. Clearly, airflow from the CDFS passes through the HPC and the outer bypass duct named the core bypass. The third bypass airflow is exhausted through the fixed third bypass nozzle, while other airflow will exhaust via the variable main nozzle.

As shown in Figure 2, VSV_{Fan} is used to modulate the airflow passed through the third bypass and the fan system pressure ratio. VSV_{CDFS} is designed to affect the airflow passed through front bypass and the fan system pressure ratio. VSV_{HPC} is connected with the airflow passed through the core and rotor speed difference. VAN_{LPT} is used to adjust LPT expansion ratio and HPT expansion ratio. Pro-VABI is designed to control the static pressure of the core bypass exit via modulation of the Pro-VABI area in order to avoid flow recirculation to the front bypass. Rear-VABI is used to modulate the airflow passed through bypass duct and mixing loss. A_8 is designed to adjust the LPT expansion ratio to control thrust in a wide range of the flight envelope. Through the combined modulation of various variable geometries, ACE has two different working mode alternatives to guarantee superior performance along a wide flight regime [18–20].

The third bypass and core bypass are open all the time. When the front bypass is open, it operates at triple bypass mode. In contrast, if the front bypass is closed, it operates in double bypass mode.

For subsonic cruise and part power operation, ACE operates at triple bypass mode reasonably well to provide higher bypass ratio. The entire inlet airflow is inducted by the front fan. The airflow is then divided between the variable fan and the third bypass. The third bypass flow is exhausted through the fixed third bypass nozzle. Meanwhile, the airflow from the variable fan is divided between the front bypass and CDFS inlet as the front bypass is open. Finally, the CDFS flow is divided between the core bypass and HPC inlet because of the open core bypass. The front bypass airflow is mixed with the core bypass airflow at Pro-VABI, requiring a static pressure balance. Then, the other static pressure balance is required at Rear-VABI between the mixed flows and the core flow which are then exhausted through the main nozzle. The gas paths of ACE at triple bypass mode are shown in Figure 3.

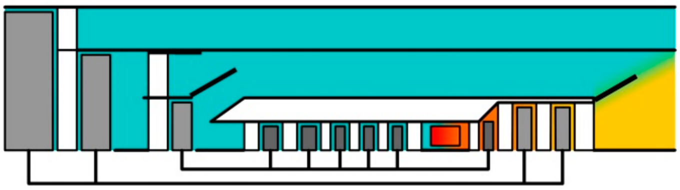

Figure 3. The gas paths diagram of ACE in triple bypass mode.

During max power and supersonic cruise operation, ACE operates in double bypass mode reasonably well to obtain a lower bypass ratio with almost all of the front fan flow being passed through the engine core. All the inlet airflow is inducted by the front fan. The airflow is then divided between the variable fan and the third bypass as the third bypass is open. The decreased third bypass flow compared with triple bypass mode is exhausted through the fixed third bypass nozzle because of the larger VSV_{Fan}. Meanwhile, all the air flow through the variable fan is inducted by the CDFS with the closed front bypass. Then, the airflow is split between the core bypass and HPC inlet because of the open core bypass. Finally, a static pressure balance is required at Rear-VABI between the decreased core bypass flow because of the larger VSV_{HPC} and the core flow which then are exhausted through the main nozzle. The gas paths of ACE in double bypass mode are shown in Figure 4.

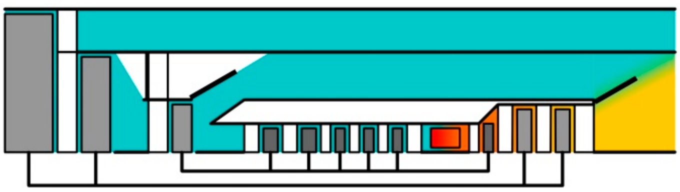

Figure 4. The gas paths diagram of ACE in double bypass mode.

2.2. ACE Modeling

The performance model of ACE is a zero-dimensional (0D) engine model controlled by multiple variables which provides a platform suitable for parametric cycle analysis, performance analysis and control schedule study at different ACE working modes. To calculate the engine thermodynamic and performance parameters, specific parameters such as engine cycle parameters and component parameters should be given in advance via the combination of theoretical analysis and balance equations.

To guarantee work of the ACE in triple bypass mode and double bypass mode, the related gas components are coupled together through the balance equations. The equations considered included the power-balance equations for each rotor, respectively, flow compatibility equations between the connected gas components and static pressure balance equations at the flow mixed zone.

More details about general 0D engine performance simulation can be found in the literature [21–23]. As the analysis of ACE is still in the conceptual stage of research, performance simulation of ACE is developed based on the modeling of a mixed flow turbofan engine. The modeling theory and method has been tested and verified accurately as shown in Figures 5 and 6. Consequently, the accuracy of the performance model of ACE can satisfy requirements about the study of concept design in this paper.

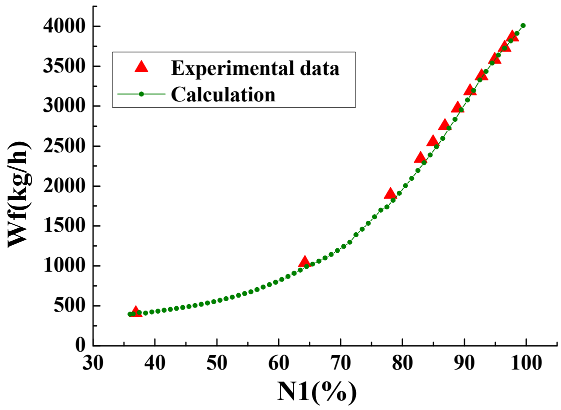

Figure 5. The demonstration of fuel consumption during throttling.Nl: low pressure rotor speed.

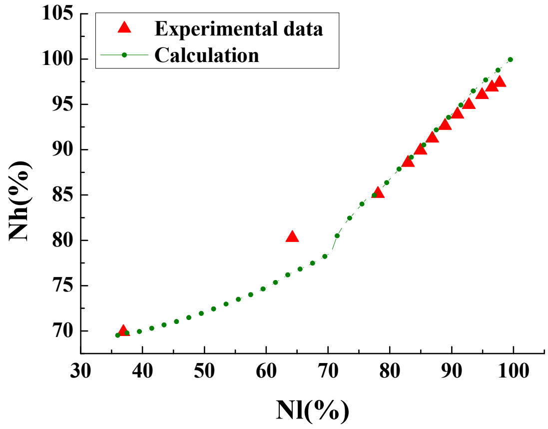

Figure 6. The demonstration of high pressure rotor speed (Nh) during throttling.

The working condition of ACE is set as 0 km, 0 Ma, which is the design point's working condition in triple bypass mode to calculate the engine key geometry parameters. Some important design parameters at design point are shown in Tables 1 and 2. The losses in the bypass ducts and the variable bypass are transformed into total pressure recoveries which are calculated during engine performance simulation. For most of the time, the aircraft gas turbine engine works at appropriate power which is less than the maximal thrust, to cut down SFC. Conventional turbojets or turbofans modulate thrust by reducing airflow along with declined LPRS. The main characteristic of ACE is maintaining engine airflow as power is reduced to decrease spillage drag, and increase installed thrust during throttling. Based on the optimized design parameters and an optimized control of variable geometry regulation, it is possible to study the route and method of combined variable geometry regulation during throttling.

Table 1. Design point parameters of ACE (1). W_a: total airflow.

Parameters	Wa (kg/s)	B_t	B_3	B_2	B_1
value	125	1.028	0.25	0.33	0.22

Table 2. Design point parameters of ACE (2). π_f: front fan compressor pressure ratio; π_v: variable fan compressor pressure ratio; π_{CDFS}: CDFS compressor pressure ratio; π_{HPC}: HPC compressor pressure ratio; δ: cooling air percentage.

Parameters	π_f	π_v	π_{CDFS}	π_{HPC}	δ
value	2	1.5	1.397	5	18.5%

The bypass ratio is defined as below: B_t: total bypass ratio; B_3: third bypass ratio; B_2: front bypass ratio; B_1: core bypass ratio; W_{af}: airflow of front fan; W_{av}: airflow of variable fan; W_{acdf}: airflow of CDFS; W_{ahpc}: airflow of HPC.

$$B_t = (W_{af} - W_{ahpc})/W_{ahpc}, \quad (1)$$

$$B_3 = (W_{af} - W_{av})/W_{av}, \quad (2)$$

$$B_2 = (W_{av} - W_{acdf})/W_{acdf}, \quad (3)$$

$$B_1 = (W_{acdf} - W_{ahpc})/W_{ahpc}, \quad (4)$$

3. Study on the Method of Variable Geometries Modulation

In a conventional invariable geometry engine, as the power is reduced, the airflow entering the engine is also reduced by decreasing LPRS, which results in spillage drag. Spillage drag is a phenomenon which results from an engine operating away from the inlet's maximum airflow, and traditionally maximum thrust point, with a given fixed engine inlet. The engine inlet is sized to capture the considerable air required by the engine maximum thrust design condition. If the size of engine inlet is invariable, this can result in significant spillage drag as the difference between current airflow requirement and maximum airflow increases [7,16,17].

According to the public references so far, VCE can keep airflow constant during subsonic cruise throttling by modulating variable geometries as power reduces, which can decrease spillage drag and increase installed thrust efficiently. This is the most remarkable variable-cycle-characteristic of VCE. Benefiting from the additional third bypass, ACE has greater potential to flexibly modulate airflow and pressure ratio. Therefore, it is necessary to study the control schedule of variable geometries' modulation based on the modeling study, which focuses on retaining airflow as thrust is reduced during the subsonic and supersonic cruise.

Due to the strong coupling among the variable geometries, variable geometry adjustment can affect the components which directly match. Therefore, the strong coupling of variable geometries is what makes the modulation study extremely challenging. Due to the unchanged inlet guide vanes of the front fan, the LPRS is kept constant to maintain airflow during subsonic and supersonic cruise throttling.

3.1. Variable Geometries Modulation during Supersonic Cruise

To assure remarkable performance, ACE operates in double bypass mode during supersonic cruise with a working condition is set as 11 km, 1.5 Ma. According to the quantitative research and components matching mechanisms, sensitivity analysis of six variable geometries (VSV_{Fan}, VSV_{CDFS}, VSV_{HPC}, Rear-VABI, VAN_{LPT} and A_8) modulation of the engine airflow and net thrust can be obtained. The VSV_{Fan} can change from 15 degrees (D) to −5 degrees. Meanwhile, the VSV_{CDFS} can vary from 45 degrees to 0 degrees. The VSV_{HPC} can change from −10 degrees to 10 degrees. Consequently, the sensitivity analysis based on VSV changing −5 degrees. When the engine operates at double bypass mode and LPRS is constant as stated above, the reduction of variable fan flow capacity by turning down VSV_{Fan} can decrease the thrust due to lower HPT inlet temperature (T_{t4}). This reduction drives more air flowing into third bypass, increasing B_3, while decreasing low pressure compression work. Then, an increased trend of LPRS occurs because of the excess of LPT output work for less low pressure compression work. Hence, for a constant LPRS, less fuel should be injected. Further, T_{t4} declines, leading to the reduced net thrust. Turning down VSV_{Fan} increases the outlet back pressure of the front fan. Then the front fan pressure ratio rises and the engine airflow decreases, as shown in Figures 7 and 8.

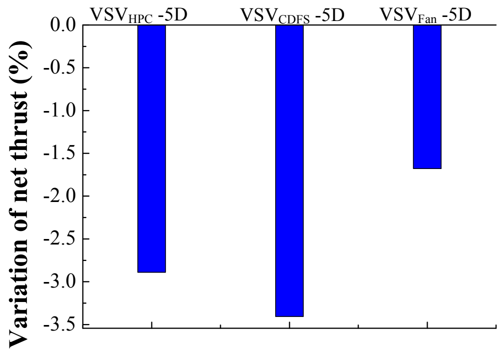

Figure 7. Sensibility analysis of VSV (variable stator vane) on thrust during the supersonic cruise.

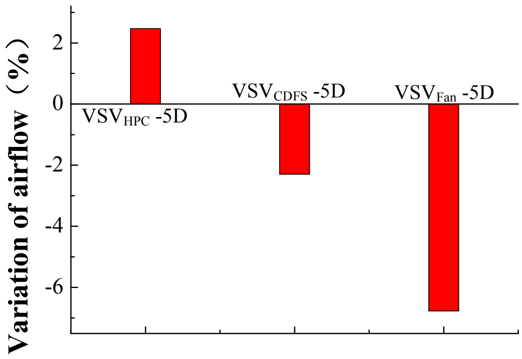

Figure 8. Sensibility analysis of VSV on airflow during the supersonic cruise.

The reduction of HPC flow capacity by turning down VSV_{HPC} can decrease the thrust due to lower T_{t4}. This reduction drives more air flow into the core bypass, increasing B_1 while decreasing engine core flow. Then, the required compression work of HPC is reduced and the distributing compression work of CDFS increases, which improves CDFS suction capacity and hence air flow. Thus, the outlet back pressure of variable fan decreases, which results in a reduction of the variable fan and front fan pressure ratio. Finally, the engine airflow increases, shown in Figures 7 and 8. Meanwhile, the amount of low pressure compression work decreases. Then, an increased trend of LPRS occurs because of the excess of LPT output work for less low pressure compression work. Hence, for a constant LPRS, less fuel is injected and T_{t4} is reduced. Finally, the specific thrust reduces, leading to the decrease of net thrust.

When the engine operates in double bypass mode and LPRS is maintained at a constant level, turning down VSV_{CDFS} decreases T_{t4} and net thrust. Directly, turning down VSV_{CDFS} decreases CDFS flow capacity. CDFS compression work drops when other parameters remain constant during the decrease of CDFS flow capacity. Then, this drop increases high pressure rotation speed (HPRS) and hence HPC suction capacity. As a result, there is greater engine core flow driving LPT. In this way, LPRS tends to rise as LPT output work improves. Hence for a constant LPRS, fuel flow has to decrease, resulting in the decrease of T_{t4}. Therefore, net thrust decreases for lower T_{t4}. According to the flow continuity relationship, the front fan flow capacity drops for the decrease of CDFS flow capacity. As for the front fan, its working point moves up slightly along the referred speed line. As shown in Figures 7 and 8, the corrected flow of front fan decreases as the engine airflow reduces.

When the engine operates at double bypass mode and LPRS is kept constant, turning down VAN_{LPT} can decrease T_{t4} and thrust. Directly, turning down VAN_{LPT} leads to the increase of LPT expansion ratio. This increase may improve LPT output work. Then, low pressure rotor work balance is broken and the LPRS tends to rise. Hence for a constant LPRS, less fuel should be injected, leading to a drop in T_{t4}. At the same time, turning down VAN_{LPT} leads to the decrease in the HPT expansion ratio. Therefore, high pressure rotor work balance is broken as a result of the decrease of HPT output work, which leads to HPRS reduction. This reduction drives more airflow into core bypass, increasing B_1. Thus, increased total bypass ratio and reduced T_{t4} cause the net thrust to decrease. Then, CDFS suction capacity decreases, while front fan outlet back pressure increases. Finally, the front fan pressure ratio rises and engine airflow decreases, which is shown in Figures 9 and 10.

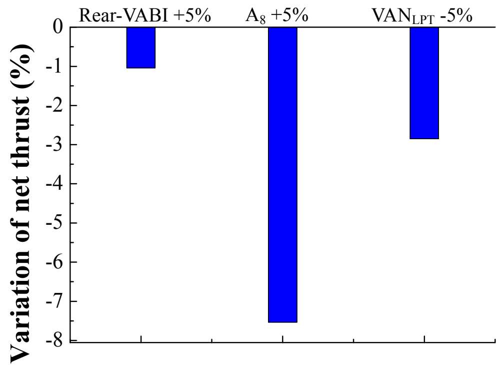

Figure 9. Sensibility analysis of area on thrust during the supersonic cruise.

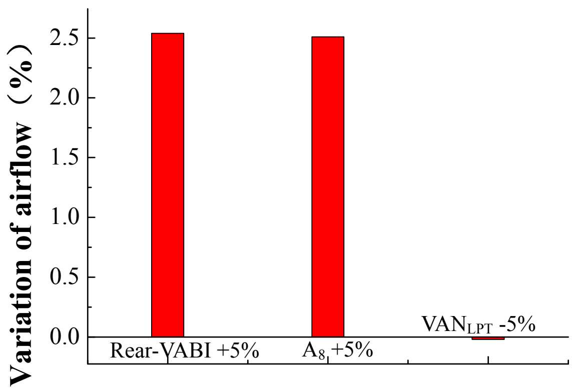

Figure 10. Sensibility analysis of area on airflow during the supersonic cruise.

As a result of the constant LPRS, turning up Rear-VABI can decrease the thrust due to lower T_{t4}. Directly, turning up Rear-VABI drives more airflow into core bypass increases B_1, while increasing CDFS flow capacity. Then, variable fan and front fan outlet back pressure decreases, which reduces low pressure compression work. Therefore, an increase trend of LPRS occurs because of the excess of LPT output work for less low pressure compression work. Hence for a constant LPRS, less fuel should be injected. Furthermore, declined T_{t4} leads to the reduced net thrust. As for the front fan, the working point moves down slightly along the referred speed line. As shown in Figures 9 and 10, the corrected flow of the front fan increases, while the engine airflow rises.

When the engine operates at double bypass mode and LPRS is maintained constant, turning up A_8 decreases T_{t4} and reduces thrust. Directly, turning up A_8 drives more air flowing into core bypass increases B_1, while increasing CDFS flow capacity. Then, the variable fan and front fan outlet back pressure decreases, which reduces low pressure compression work. Meanwhile, turning up A_8 leads to the increase of LPT expansion ratio. As a result, LPT output work increases leading to a break in low pressure rotor work balance. An increased trend of LPRS occurs owning to this break. Hence, for a constant LPRS, less fuel should be injected. Finally, T_{t4} declines, which results in the reduction of net thrust. As for the front fan, the working point moves down slightly along the referred speed line. As shown in Figures 9 and 10, the corrected flow of the front fan increases, while the engine airflow rises.

Based on the sensitivity analysis mentioned above, the variable geometry adjustment is researched combining the basic engine working principle analysis during the supersonic cruise in this section.

According to the basic engine working principle, the essence of maintaining airflow during throttling decreases the specific thrust by modulating variable geometries along with increased total bypass ratio, lower exit total pressure and temperature of LPT and bypass duct. Turning down VSV_{Fan}, VSV_{CDFS} and VSV_{HPC} can drive a larger percentage of the airflow through the bypass streams, increasing total bypass ratio. As the total bypass ratio increases, air flow through the engine core is reduced. Then, LPT output work decreases. This is caused by declined working airflow. The decreased LPT output work will lead to a break in the low pressure rotor work balance. As a result, turning up A_8 can enlarge the LPT expansion ratio to maintain a low pressure rotor work balance. Due to the constraint of a reasonable value of turbine expansion ratio, turning down VAN_{LPT} appropriately can let LPT work efficiently and obtain suitable T_{t4}. As a result of the decline of HPT expansion ratio caused by VAN_{LPT} reduction, T_{t4} will be higher to satisfy the high pressure rotor work balance. Meanwhile, turning down VSV_{Fan}, VSV_{CDFS} and VSV_{HPC} will reduce the compressor pressure ratio. Therefore, due to the increased LPT expansion ratio and decreased compressor pressure ratio, exit total pressure and temperature of LPT and bypass duct will reduce logically. Finally, exit total pressure and temperature of the main nozzle will decline, resulting in the reduced specific thrust. Based on the valuable guidance and advice as stated above, the variable geometries' modulation is viable for retaining airflow during throttling, which is shown in Figures 11 and 12.

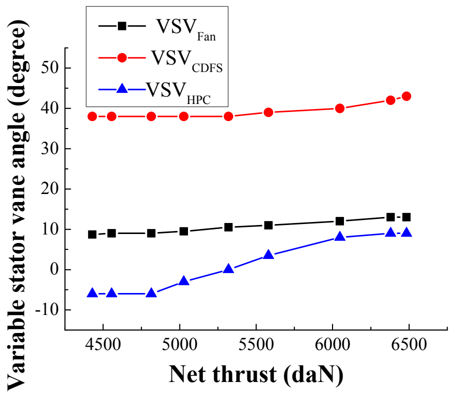

Figure 11. Adjustment of VSV during supersonic throttling.

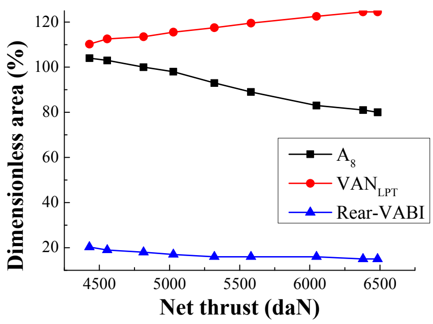

Figure 12. Adjustment of area during supersonic throttling.

3.2. Study on the Variable Geometries Modulation during Subsonic Cruise

Since the essence of maintaining airflow during throttling is decreasing the specific thrust, it is viable to keep the engine airflow almost constant with reduced thrust via transforming from double bypass mode with low bypass ratio to triple bypass mode with high bypass ratio during subsonic cruise. When high specific thrust is required in flight mission, ACE operates at double bypass mode and decreases its thrust during throttling by modulating variable geometries. When the cruise required thrust is further reduced, ACE transforms from double bypass mode to triple bypass mode. Then, ACE can keep airflow constant during subsonic cruise furthered throttling by modulating variable geometries. Therefore, thrust can decrease continuously during mode transformation but airflow is able to be maintained at a constant level during subsonic cruise throttling.

When ACE operates at double bypass mode during subsonic throttling, variable geometries regulation is similar to the adjustment during supersonic throttling instead of the Rear-VABI. Due to the lower engine inlet total temperature, the inlet total temperature of HPC becomes lower during the subsonic cruise. During throttling, HPRS rises along with turning down VSV_{CDFS}. Therefore, the corrected speed of HPC will be out of the reasonable value during subsonic throttling at double bypass mode. Based on the engine working principle, turning down Rear-VABI can increase the total temperature of HPC, which solves the above-mentioned problem. However, the adjustment of Rear-VABI is restricted and has been minimized. Consequently, the Rear-VABI remains unchanged, in contrast with the adjustment during supersonic throttling.

This section mainly introduces the regulation of variable geometries during subsonic cruise throttling at triple bypass mode whose working condition is set as 11 km, 0.8 Ma. According to the quantitative research and components matching mechanisms, sensitivity analysis of six variable geometries (VSV_{Fan}, VSV_{CDFS}, VSV_{HPC}, Rear-VABI, VAN_{LPT} and A_8) modulation on the engine airflow and net thrust can be obtained. When the engine operates at triple bypass mode and LPRS is constant, as stated earlier, the reduction of variable fan flow capacity by turning down VSV_{Fan} can decrease the thrust due to lower T_{t4}. At the same time, turning down VSV_{CDFS} decreases T_{t4} and net thrust. The effect of turning down VSV_{Fan} and VSV_{CDFS} on airflow and net thrust is similar to the effect at double bypass mode. According to the histogram in Figures 13 and 14, although turning down VSV_{Fan} can cause a significant reduction of net thrust, VSV_{Fan} also has a great influence upon airflow. Therefore, the modulation of VSV_{Fan} should be controlled appropriately to maintain airflow as thrust reduces during the subsonic cruise.

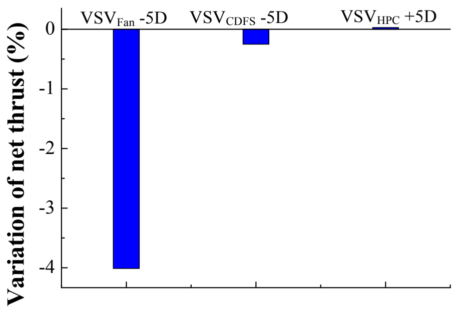

Figure 13. Sensibility analysis of VSV on thrust during the subsonic cruise.

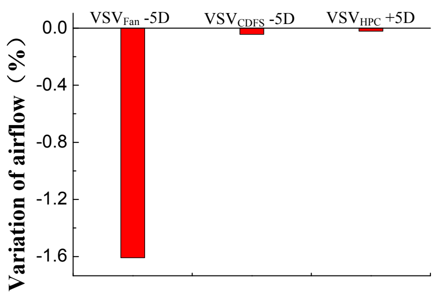

Figure 14. Sensibility analysis of VSV on airflow during the subsonic cruise.

When the LPRS is kept constant, the rise of HPC flow capacity by turning up VSV_{HPC} will increase the thrust due to higher T_{t4}. This increase induces more air flow into engine core, decreasing B1, while increasing the flow through the engine core. Then, the required compression work of HPC rises and the distributing compression work of CDFS reduces, which declines CDFS suction capacity and hence air flow. Thus, the outlet back pressure of the variable fan increases, which results in the rise of the variable fan pressure ratio, and the engine airflow decreases. Meanwhile, the low pressure compression work increases. Then, a decrease trend of LPRS occurs because of the reduced LPT output work and higher low pressure compression work. Hence, for a constant LPRS, more fuel should be injected, while T_{t4} rises. Finally, the specific thrust increases, leading to the net thrust rising, which is shown in Figures 13 and 14. Although it is beneficial to turn down VSV_{HPC} for constant airflow during throttling, VSV_{HPC} will remain unchanged due to the minimum regulation constraint.

At triple bypass mode, turning up VAN_{LPT} will increase thrust due to lower bypass ratio. Directly turning up VAN_{LPT} leads to the rise of HPT expansion ratio. This increase may improve HPT output work. Then, the high pressure rotor work balance is broken and as a result the HPRS tends to rise. Therefore, CDFS suction capacity increases, while the variable fan outlet back pressure decreases. Finally, low pressure compression work reduces. Further, an increased trend of LPRS occurs because of the excess of LPT output work and less low pressure compression work. Hence, for a constant LPRS, less fuel should be injected, which leads to T_{t4} declining. Finally, due to the combined effects of lower bypass ratio and higher T_{t4}, net thrust rises. Because of the changeless pressure ratio of the front fan, airflow is almost the same as shown in Figures 15 and 16. Since airflow is insensitive to VAN_{LPT}, it is beneficial to turn down VAN_{LPT} for constant airflow during throttling.

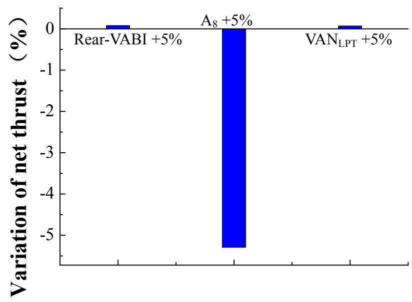

Figure 15. Sensibility analysis of area on thrust during the subsonic cruise.

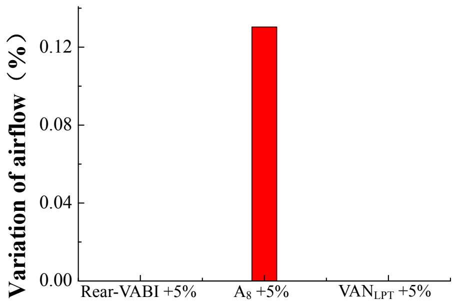

Figure 16. Sensibility analysis of area on airflow during the subsonic cruise.

When the engine operates at triple bypass mode and LPRS is maintained at a constant level, turning up A_8 decreases T_{t4} and therefore reduces thrust. The effect of turning up A_8 on airflow and net thrust is similar to the effect at the double bypass mode. According to the histogram in Figures 15 and 16, turning up A_8 can reduce net thrust and increase airflow effectively. Consequently, under the premise of satisfying the constraints, it is worth turning up A_8 during throttling.

When the engine operates at triple bypass mode and LPRS is constant, as stated earlier, turning up Rear-VABI will increase the thrust due to higher T_{t4}. Directly, turning up Rear-VABI drives more air flowing into core bypass and increases B_1, while reducing engine core airflow. Meanwhile, turning up Rear-VABI leads to the decline of LPT expansion ratio. Therefore, a decreased trend of LPRS occurs because of the lower LPT output work. Hence, for a constant LPRS, more fuel should be injected. Further, as shown in Figure 15, higher T_{t4} leads to an increased net thrust. Because of the changeless pressure ratio of the front fan, airflow is almost the same, which is shown in Figure 16. Since airflow is insensitive to Rear-VABI, it is beneficial to turn down Rear-VABI for constant airflow.

Based on the sensitivity analysis mentioned above, the variable geometry adjustment is researched, combining the basic engine working principle analysis during the subsonic cruise in this section.

According to the basic engine working principle, the essence of maintaining airflow during throttling is to decrease the specific thrust by modulating variable geometries along with increased total bypass ratio, lower exit total pressure and lower temperature of LPT. Turning down VSV_{Fan} and VSV_{CDFS} can induce a larger percentage of the total airflow through the bypass streams with increased total bypass ratio. As the total bypass ratio increases, flow through the engine core is reduced. Then, LPT output work decreases. This is caused by declined working airflow. The decreased LPT output work will lead to a break in the low pressure rotor work balance. As a result, turning up A_8 can enlarge the LPT expansion ratio to maintain a low pressure rotor work balance. Due to the constraint of the reasonable value of the turbine expansion ratio, turning down VAN_{LPT} appropriately can let LPT work efficiently and obtain suitable T_{t4}. As a result of the decline of HPT expansion ratio caused by VAN_{LPT} reduction, T_{t4} will be higher to satisfy high pressure rotor work balance. Meanwhile, turning down VSV_{Fan} and VSV_{CDFS} will reduce the compressor pressure ratio. Therefore, as a result of the enlarged LPT expansion ratio and decreased compressor pressure ratio, the exit total pressure and temperature of LPT and bypass duct will reduce logically. Finally, the exit total pressure and temperature of the main nozzle will decline, resulting in the reduced specific thrust. Based on the valuable guidance and advice as stated earlier, the variable geometries' modulation schedule is obtained regarding retaining airflow during throttling, which is shown in Figures 17 and 18.

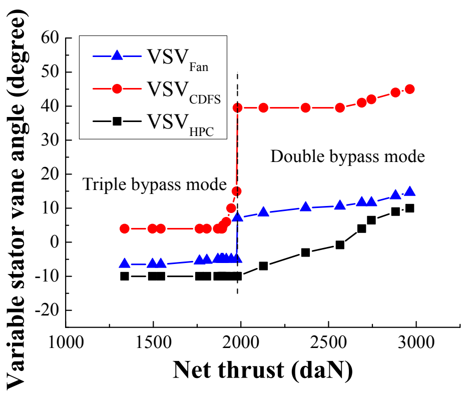

Figure 17. Adjustment of VSV during subsonic throttling.

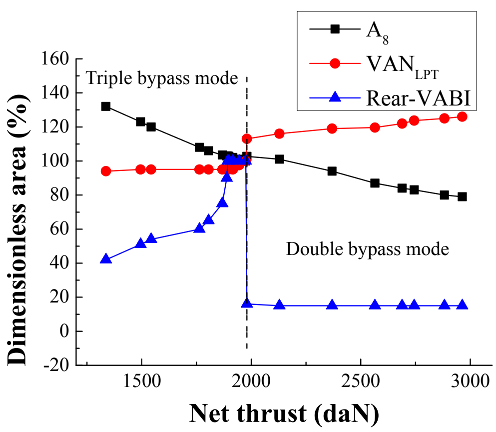

Figure 18. Adjustment of area during subsonic throttling.

4. The Demonstration of Variable Geometries Modulation Schedule

Based on the variable geometries' modulation schedule mentioned above, the cycle parameters and performance can be obtained during throttling. To prove that the modulation method described above is a reasonable method, it is worth analyzing the parameters along with thrust reduction during the supersonic and subsonic cruise.

4.1. The Demonstration at Supersonic Cruise

During supersonic throttling, HPRS (N_h) first increases and then decreases as T_{t4} decreases. This is shown in Figure 19. At the beginning of throttling, T_{t4} declines along with the increased total bypass ratio and enlarged A8. Meanwhile, HPRS rises because of the excess of HPT output work for lower high pressure compression work, which results from VSV_{CDFS} and VSV_{HPC} declining. Further, at the end of throttling, T_{t4} decreases sequentially as a result of increased LPT expansion ratio and reduced low pressure compression work, which is caused by declined VSV_{Fan}. At the same time, HPT output work reduces. This is caused by decreased T_{t4} and declined HPT expansion ratio for turning down VAN_{LPT}. Then, due to the lower HPT output work for high pressure compression work with constant VSV_{CDFS}, HPRS reduces.

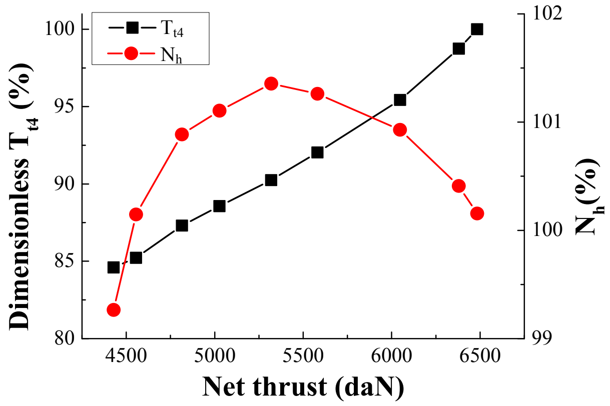

Figure 19. Variation of HPRS and T_{t4} during supersonic throttling.

As illustrated in Figure 20, turning down VSV_{HPC} drives more air flow into the core bypass. This increases B1, while decreasing HPC flow capacity. The reduction of variable fan flow capacity by turning down VSV_{Fan} can increase the total bypass ratio. This reduction induces more air into the third bypass, resulting in increased B_3. Due to the combined effects of B_1 and B_3, total bypass ratio rises.

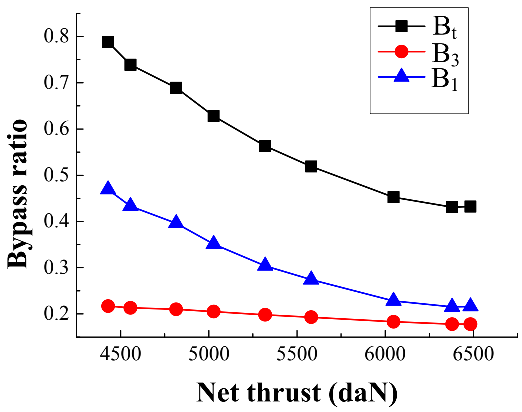

Figure 20. Variation of bypass ratio during supersonic throttling.

According to Figure 21, the main nozzle exit total pressure (P_{t9}) and total temperature (T_{t9}) reduce significantly, which can decrease the specific thrust. As shown in Figure 22, the main nozzle thrust decreases obviously, while the third bypass nozzle thrust changes inconspicuously.

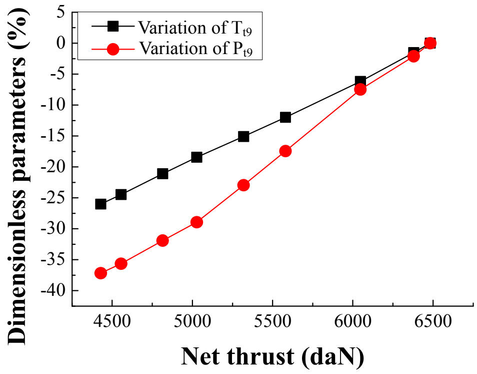

Figure 21. Variation parameters of main nozzle exit during supersonic throttling.

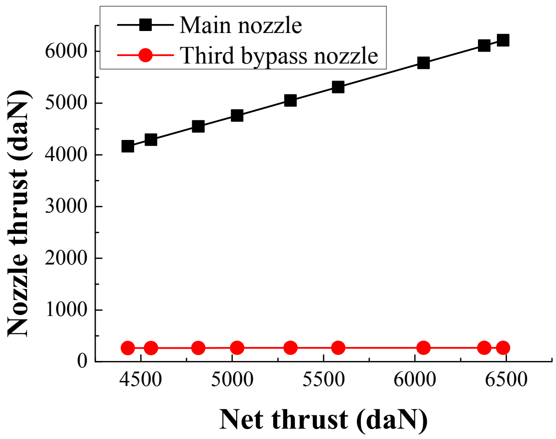

Figure 22. Nozzle thrust during supersonic throttling.

Based on the analysis of cycle parameters and performance parameters as stated earlier, the most remarkable variable-cycle-characteristic of ACE is constant airflow during throttling, which is different from the conventional invariable turbofan. As total bypass ratio and total pressure ratio of ACE is higher than conventional invariable turbofan, thermal efficiency and propulsion efficiency of ACE is higher. Consequently, it is necessary to compare the performance during throttling to further prove the variable-cycle-characteristic.

During supersonic cruise throttling, as shown in Figure 23, the performance parameters of ACE are compared with the performance of conventional Advanced Turbofan (ATF) whose net thrust decreases via reducing LPRS.

Relative results show that the overall airflow and LPRS of ACE remains constant with improved SFC even though net thrust decreases by about 32% during the supersonic cruise, while the airflow of conventional ATF reduces by 18% as shown in Figure 23. Meanwhile, as T_{t4} declines, the SFC of ACE decreases by 11% which is 6% lower than the value for ATFs. Conclusively, through the combined modulation of different variable geometries, ACE makes it possible to avoid severe inlet spillage drag and improve the installed performance efficiently under a considerable wide power range with constant airflow.

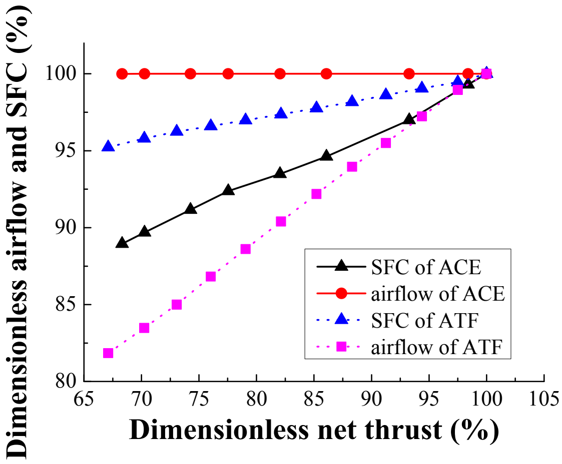

Figure 23. The performance comparison during supersonic cruise.

4.2. The Demonstration at Subsonic Cruise

The parameters variation tendency at double bypass mode during subsonic cruise is similar to the above-mentioned variation tendency during the supersonic cruise. Therefore, this section mainly analyzes the variation tendency of cycle parameters and performance parameters at triple bypass mode during subsonic throttling.

During subsonic throttling at the triple bypass mode, HPRS first increases and then decreases as T_{t4} decreases, which is shown in Figure 24. At the beginning of throttling, T_{t4} declines slowly. Turning up A_8 leads to the increase of LPT expansion ratio. Therefore, the increased LPT expansion ratio and rapid upward total bypass ratio lead to the unobvious increase of LPT output work, which results in a break in low pressure rotor work balance. Further, an increasing trend of LPRS occurs because of the excess of LPT work. Due to the constant LPRS, less fuel should be injected, which leads to T_{t4} reducing slowly. Meanwhile, high pressure compression work declines, resulting from the lower VSV_{CDFS}. Therefore, HPRS rises because of the excess of HPT output work for lower high pressure compression work. Further, at the end of throttling, T_{t4} declines significantly. Low pressure rotor compression work reduces, resulting from a decline in VSV_{Fan}. Meanwhile, increased LPT expansion ratio and smooth upward total bypass ratio lead to the increase of LPT output work. As a result, the increased LPT output work will lead to a break in the low pressure rotor work balance because of the excess of LPT output work for less low pressure compression work. An increased trend of LPRS occurs owning to this break. Hence, for a constant LPRS, less fuel should be injected. Finally, T_{t4} declines significantly. Therefore, the high pressure rotor work balance is broken as the HPT output work resulting from rapid upward T_{t4} decrease, which leads to HPRS reduction.

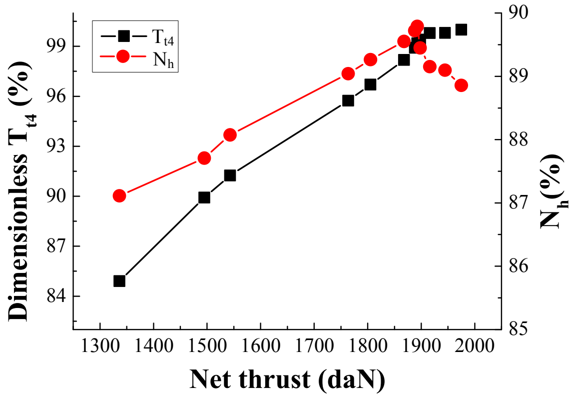

Figure 24. Variation of HPRS and T_{t4} during subsonic throttling.

As illustrated in Figure 25, total bypass ratio rises during throttling. At the beginning of throttling, the decline of CDFS flow capacity by turning down VSV_{CDFS} will increase B_2. Then, for a constant VSV_{CDFS}, the decrease of CDFS suction capacity caused by downward HPRS can increase B_2 continuously. Meanwhile, B_1 first increased and then decreased as HPRS varied, as mentioned above. As VSV_{Fan} changes a little, B_2 changes inconspicuously. Consequently, due to the combined effects of B_1, B_2 and B_3, the total bypass ratio rises.

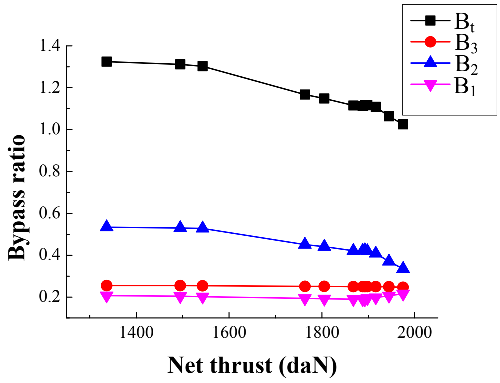

Figure 25. Variation of bypass ratio during subsonic throttling.

According to Figure 26, the main nozzle exit total pressure and total temperature reduce significantly. Therefore, reduced total pressure and total temperature and increased total bypass ratio can decrease specific thrust through the above-mentioned theory analysis. As shown in Figure 27, main nozzle thrust obviously decreases, while the third bypass nozzle thrust changes inconspicuously.

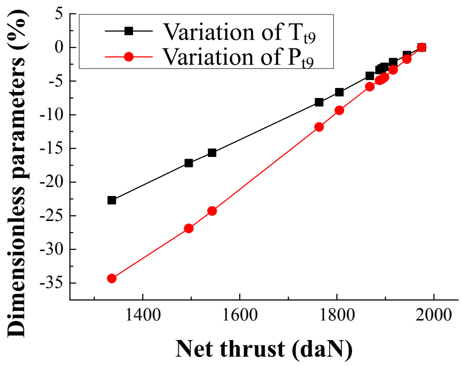

Figure 26. Variation parameters of main nozzle exit during subsonic throttling.

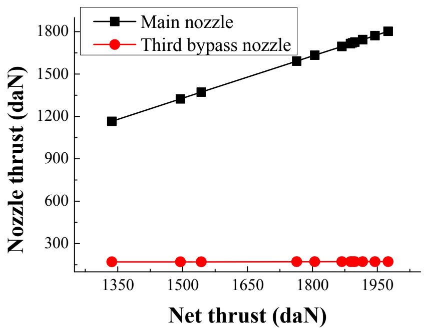

Figure 27. Nozzle thrust during subsonic throttling.

Based on the analysis of cycle parameters and performance parameters as stated earlier, the most remarkable variable-cycle-characteristic of ACE is to keep airflow constant during throttling, which is different from the conventional invariable turbofan. As total bypass ratio and total pressure ratio of ACE are higher than the conventional invariable turbofan, thermal efficiency and propulsion efficiency of ACE is higher. Consequently, it is necessary to compare the performance during throttling to further prove the variable-cycle-characteristic.

During subsonic cruise throttling, as shown in Figure 28, the performance parameters of ACE are compared with the performance of conventional ATF whose net thrust decreases via reducing LPRS.

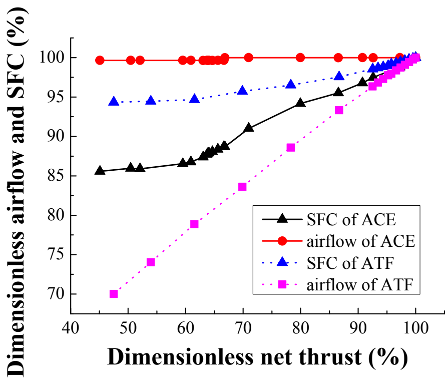

Figure 28. The performance comparison during subsonic cruise.

As thrust reduces by 50% during subsonic cruise, and if the LPRS of ACE remains constant, ACE matches the engine airflow demand to the inlet airflow by transforming from double bypass mode to triple bypass mode. Moreover, it avoids specific fuel consumption degradation, as mentioned in the references, while the airflow of conventional ATF reduces by 30%, as illustrated in Figure 28. Meanwhile, as T_{t4} declines, the SFC of ACE decreases by 14.4% which is 8.4% lower than that seen for ATFs. Resulting from the optimal control of variable geometries' modulation, a continual decrease in thrust during mode transformation, constant airflow and obviously improved SFC are realized during subsonic cruise throttling. Conclusively, through the combined modulation of different variable geometries, ACE makes it possible to avoid severe inlet spillage drag and improve the installed performance efficiently under a considerably wide power range with constant airflow.

For further research, the installation modeling will be established based on the previous references to analyze the advantages of ACE on spillage [24]. The calculation process of installation modeling is shown in Figure 29.

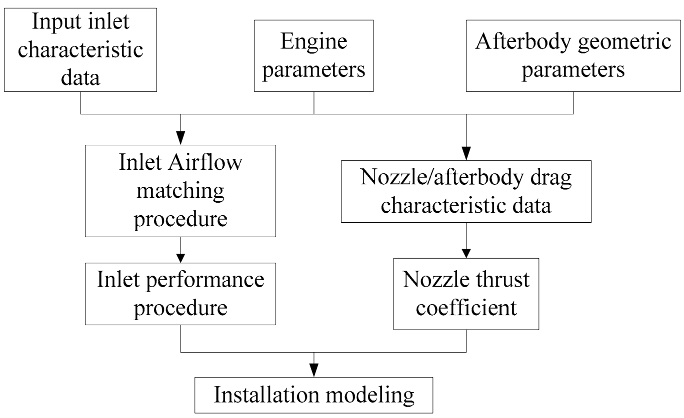

Figure 29. The calculation process of installation modeling.

5. Conclusions

Although the strong coupling of variable geometries is what makes the study of modulation extremely challenging, the control schedule of variable geometries' modulation of ACE to maintain airflow during throttling is reasonably researched in this paper by combining sensibility analysis and basic working principles.

Keeping LPRS of ACE constant, the essence of maintaining airflow during throttling is to decrease the specific thrust by modulating variable geometries along with increased total bypass ratio, lower exit total pressure and temperature of nozzle.

Relative results show that the overall airflow of ACE remains constant with improved SFC even though net thrust decreases by about 32% during supersonic cruise, while the airflow of conventional ATF reduces by 18%. Meanwhile, when the engine thrust reduces from 100% to 50% during subsonic cruise, the ACE engine maintains a constant engine airflow with improved SFC, while the airflow of conventional ATF reduces by 30%.

If LPRS and airflow of the ACE remain constant, the total bypass ratio and total pressure ratio are higher than for conventional invariable turbofan during throttling, which results in higher thermal efficiency and propulsion efficiency of ACE. Therefore, the variable geometries modulation mentioned above is a feasible solution to improve aero engine performance.

Based on the more variable geometries, not only does ACE obtain improved performance during throttling, but it can guarantee superior performance under a significantly wide power range. Consequently, it is a most promising propulsion candidate for next-generation affordable aircraft.

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Author Contributions: Ya Lyu completed the ACE performance model and analyzed the variable geometries modulation. Hailong Tang and Min Chen provided important support on data analysis and writing paper.

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References

1. Ballal, D.R.; Zelina, J. Progress in Aeroengine Technology (1939–2003). *J. Aircr.* **2004**, *41*, 43–50. [CrossRef]
2. Ulizar, I.; Pilidis, P. Predicted performance characteristics of a variable cycle turbofan. *Aeronaut. J.* **1997**, *101*, 263–268.
3. Liang, C. Future Aircraft Turbofan Engine Technologies. *Aeroengine* **2005**, *31*, 54–58. (In Chinese)
4. Li, B.; Zhao, C. Consider on Variable Cycle Engine and Adaptive Cycle Engine Technology Development. *Aeronaut. Manuf. Technol.* **2014**, *20*, 76–79. (In Chinese)
5. Kurzke, J. *The Mission Defines the Cycle: Turbojet, Turbofan and Variable Cycle Engines for High Speed Propulsion*; RTO Educational Notes, EN-AVT-185 Lecture; NATO: Brussels, Belgium, 2010.
6. Westmoreland, J.S.; Howlett, R.A.; Lohmann, R.P. Progress with variable cycle engines. *Supersonic Cruise Res.* **1979**, *79*, 371.
7. Johnson, J.E. Variable cycle engines—The next step in propulsion evolution. In Proceedings of the 12th Propulsion Conference AIAA/SAE, Palo Alto, CA, USA, 26–28 July 1976.
8. Willis, E.A.; Welliver, A.D. Variable-Cycle engines for supersonic cruising aircraft. In Proceedings of the 12th Propulsion Conference AIAA/SAE, Palo Alto, CA, USA, 26–28 July 1976.
9. Johnson, J.E. Variable Cycle Engine Developments at General Electric-1955–1995. *Progress Astronaut. Aeronaut.* **1996**, *165*, 105–158.
10. General Electric Co. *Aerodynamic/Acoustic Performance of YJ101/Double Bypass VCE with Coannular Plug Nozzle*; NASA-CR-159869; General Electric Co.: Cincinnati, OH, USA, 1981.
11. Brazier, M.E.; Paulson, R.E. Variable Cycle Engine Concept. In Proceedings of the 11th International Symposium on Air Breathing Engines, Tokyo, Japan, 20–24 September 1993.

12. Liu, H.; Wang, R. Investigation of General Structure and Mode Transition Mechanism of Variable Cycle Engine. *Aeroengine* **2008**, *34*, 1–5. (In Chinese)
13. Vyvey, P.; Bosschaerts, W. Study of an Airbreathing Variable Cycle Engine. In Proceedings of the 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, San Diego, CA, USA, 31 July–3 August 2011.
14. Zhou, H.; Wang, Z.; Zhang, X.; Cao, M. Optimization of Variable Cycle Engines by Using an Improved Differential Evolution. In Proceedings of the 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, USA, 28–30 July 2014.
15. Nascimento, M.A.R.; Pilidis, P. An Optimisation-Matching Procedure for Variable Cycle Jet Engines. In Proceedings of the ASME 1992 International Gas Turbine and Aeroengine Congress and Exposition, Cologne, Germany, 1–4 June 1992; American Society of Mechanical Engineers: New York, NY, USA, 1992; p. V002T02A029.
16. Wu, T.; Luo, G.; Zeng, J. Optimization of Variable Geometry Modulation for Variable Cycle Engine Based on Differential Evolution. In Proceedings of the Fifteenth Session Propulsion System Aerodynamics and Thermodynamics Conference Collected Papers, Hangzhou, China, 18–20 september 2015. (In Chinese)
17. Simmons, R.J. Design and Control of a Variable Geometry Turbofan with an Independently Modulated Third Stream. Ph.D. Thesis, The Ohio State University, Columbus, OH, USA, 2009.
18. Li, B.; Chen, M.; Zhu, Z. Steady Performance Investigation at Various Modes of an Adaptive Cycle Aero-engine. *J. Propuls. Technol.* **2013**, *8*, 002. (In Chinese)
19. Li, W.; Niu, W. GE adaptive cycle engine test more than expected. *Aerodyn. Missile J.* **2013**, *12*, 75. (In Chinese)
20. Zheng, J.; Chen, M. Matching Mechanism Analysis on an Adaptive Cycle Engine. In Proceedings of the Fifteenth Session Propulsion System Aerodynamics and Thermodynamics Conference Collected Papers, Hangzhou, China, 18–20 September 2015. (In Chinese)
21. Chen, M.; Tang, H.L.; Zhu, Z.L. Goal programming study on the mode transition of turbine based combined cycle engine. *Chin. J. Aeronaut.* **2009**, *22*, 486–492.
22. Hailong, T.; Jin, Z. A study of object-oriented approach for aeroengine performance simulation. *J. Aerosp. Power* **1999**, *4*, 018.
23. Chen, M.; Tang, H.; Zhang, K.; Hui, O.; Wang, Y. Turbine-based combined cycle propulsion system integration concept design. *Proc. Inst. Mech. Eng. G J. Aerosp. Eng.* **2012**. [CrossRef]
24. Pang, K. Refinement Study on the Model of Double Bypass Variable Cycle Engine Performance. Master's Thesis, Beihang University, Beijing, China, 2014. (In Chinese)