ICAS 2020 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

Modeling of Counter-Rotating Lift Fan/Main Engine Combined Propulsion System and Lift Fan Aerodynamic Design

Hailiang JIN, Xuan CHEN, Daobin QIU & Yueqian YIN

AECC Hunan Aviation Powerplant Research Institute, Hunan Key Laboratory of Turbomachinery on Small and Medium Aero-Engine, Zhuzhou, China, 412002

Abstract

This paper proposes an integrated analysis model based on the counter-rotating lift fan/main engine combined propulsion system. The whole power system is regarded as a “variable-cycle” turbofan engine, that is, a conventional double-ducted mixed-exhaust turbofan engine in cruise state and a three-ducted mixed-exhaust turbofan engine in a short/vertical take-off and landing (S/VTOL) state. The effects of the design parameters of the lift fan on the performance of the power system are investigated using this “variable cycle” three-ducted mixed exhaust turbofan engine analysis model. The optimized design parameters of the lift fan are obtained under power system's large-thrust, lightweight, and low-fuel-consumption design requirements. Based on these optimized design parameters, the design of high through flow counter-rotating lift fan without outlet stator blade was accomplished by using the technology of 3D computational fluid dynamic. At last, F135’s counter-rotating lift-fan was optimized using this method. The fan’s performance was established by the method of computational fluid dynamics. Compared with the result of F135, it shows that: The thrust per unit power and thrust per unit area were increased by 15% and by 16% respectively.

Keywords: counter-rotating, lift fan, main engine, integrated propulsion system, high throughflow, aerodynamic design

1. Introduction

S/VTOL fighters have greatly reduced the requirements for take-off and landing sites, which greatly expands the deployment range of fighters and improves the battlefield adaptability and survivability of fighters. In addition, S/VTOL carrier-based aircraft can significantly enhance the navy's amphibious combat capabilities and enhance operational flexibility. Therefore, the major aviation countries in the world have spent a lot of energy in the research of S/VTOL technology. In 1965, Peterson [1] first conducted a conceptual study on S/VTOL lift fans, which laid the foundation for the future research on lift fans. Afterwards, Przedpelgki et al. [2] [3] studied the design technology of lift fans for S/VTOL aircraft. In 1974, Hill [4] et al. carried out a conceptual design of a lift fan plus lift/cruise aircraft. In 1997, NASA [5] simulated the control and power system of a s S/VTOL aircraft and studied the angle adjustment law of the lift fan nozzle and the main engine nozzle. In 2000, Arnulfo [6] studied the lift fan of the S/VTOL power system, and proposed a low-pressure shaft mechanical drive, a low-pressure compressor outlet exhaust drive, a high-pressure turbine outlet exhaust drive, and a high-pressure compressor outlet exhaust. There are four types of air-driven lift fan schemes. The research shows that the scheme of low-pressure shaft mechanical drive and low-pressure compressor outlet exhaust drive is feasible. In 2003, Bevilaqua [7] discussed the further application of JSF's variable propulsion cycle. In 2008, P&W's F135-PW-400 engine was successfully used in the F35B fighter, marking that the lift fan of the S/VTOL power system has entered the engineering practical stage. Research shows that in the future, lift fans are moving towards higher flow capacity, lighter weight and a more simplified structure.

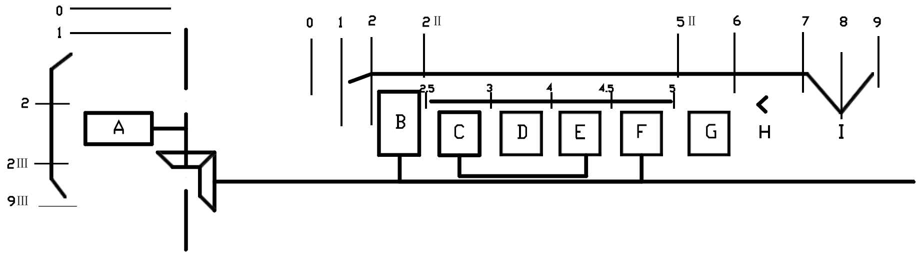
For the S/VTOL power system, on the one hand, to achieve the aircraft’s short-range/vertical take-off and landing, it should provide as much vertical thrust as possible; on the other hand, the lift fan is only used for short periods of time during take-off, landing and hovering.

While the rest of the state is regarded as the dead weight of the flight, so the lift fan should reduce the weight as much as possible. In addition, to ensure that the aircraft has a sufficient range in the normal cruising state, the power system should also take into account low fuel consumption. Therefore, it is necessary to select the design parameters of the lift fan reasonably to ensure that the entire power system has the largest thrust, the lightest weight, and the lowest fuel consumption rate. This article regards the entire power system as a "variable cycle" turbofan engine, that is, a conventional dual-duct mixed-exhaust turbofan engine in horizontal flight and a three-ducted separate and mixed exhaust turbofan in S/VTOL state. Under the entire "variable cycle" turbofan engine power system environment, analyze the effects of lift fans design parameters on the power system performance parameters. And optimize the design parameters of the lift fan, under the design constraints from the power system, like large thrust, light weight and low fuel consumption.

A large number of research work on counter-rotating fans have been carried out by researchers, and a large number of results have been obtained. In 1951, Young [8] proposed the concept of a counter-rotating fan and explained its basic principles. Sharma [9] began to conduct counter-rotating compressor experiments in 1985 and studied the effects of speed ratio and axial clearance. Since 2000, Kerrebrock et al. [10] have designed a high loading fan with a pressure ratio of 3.0, using the techniques like contour-rotating and boundary layer suction.

2. Establishing of the whole engine model

When the lift fan/turbofan engine combined power system is in the normal working mode, the lift fan drive shaft is not connected to the low-pressure shaft of the engine, and the lift fan does not work. The engine is not different from the traditional turbofan engine. When the aircraft takes off and landed vertically, the lift fan is connected to the low-pressure shaft. The engine balances the power distribution of the high- and low-pressure turbines by adjusting the nozzle throat, the bypass outlet, and the throat area of the low-pressure turbine guide vane. Therefore, the low-pressure shaft can provide additional power to drive lift fan, while the engine's main nozzle turns downwards, and the lift fan and the main engine simultaneously provide lift perpendicular to the ground. Figure 1 shows the schematic diagram of the combined power system of lift fan and turbofan engine.



(A: Lift fan; B: Fan; C: HPC; D: Combustor; E: HPT; F: LPT; G: Mixer; H: Afterburner; I: Nozzle)

Figure 1 – The schematic diagram for the combined power system.

When the combined power system of the lift fan and the turbofan engine is in the normal working mode, the lift fan does not work, and the mathematical models are the same as that of a conventional turbofan engine. If the lift fan is working, the balance equations of the combined power system need to be modified. The low-pressure turbine must drive the fan and the lift fan at the same time. Therefore, in the vertical take-off and landing state, the balance equations describing the combined power system are as follows:

(1) High pressure turbine power = high pressure compressor power.

(2) Low pressure turbine power = fan power + lift fan power.

(3) Conservation of low-pressure turbine and fan mass flow.

(4) Conservation of mass flow between high pressure turbine and high-pressure compressor.

(5) Static pressure balance between the inner and outer ducts of the mixer inlet.

(6) Conservation of mass flow between low pressure turbine and nozzle.

The working power of the lift fan in vertical mode must meet the power balance of the low-pressure shaft in the engine performance matching calculation, namely: lift fan power plus low-pressure compressor power equals low pressure turbine power. Ideally, if the above-mentioned power balance is satisfied, the low-pressure turbine speed will remain basically unchanged. When the lift fan is working, the working state of each component of the main engine will change accordingly. At this time, the working state of the main engine can be rebalanced by adjusting the variable geometry components. Fig.2 describes the procedures used to simulate the combined lift fan/main engine propulsion system.

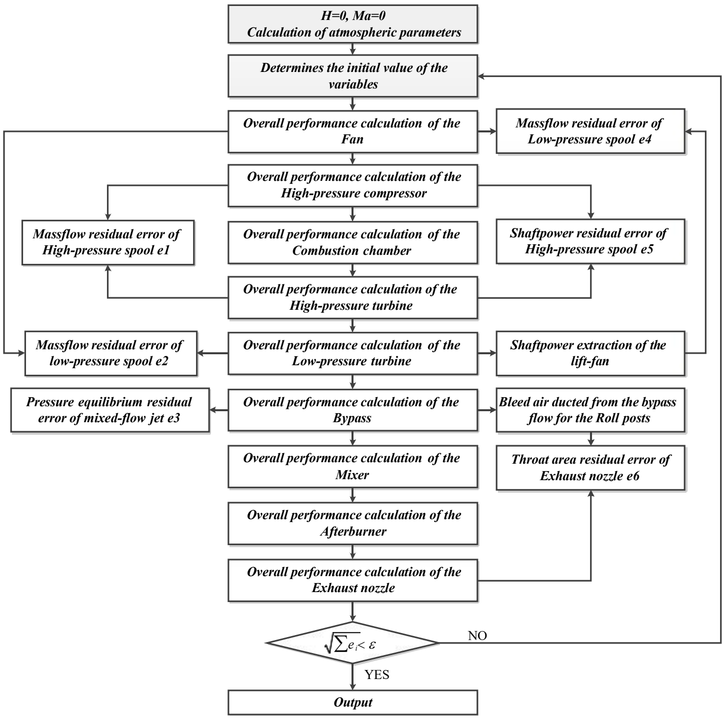


Figure 2 – Procedures used to simulate the combined lift fan/main engine propulsion system.

In order to ensure the maximum thrust generated by the entire power system at the top-level design stage of the engine, it is necessary to associate the parameters of whole engine concern, like lift fan thrust and power with the parameters of compressor design, for instance, pressure ratio, efficiency, and mass flow rate. A 1D model of the counter-rotating lift fan is also built, so that the thrust and power of the counter-rotating fan can be calculated through this model, with the specified load, rotation speed, and axial speed of the inlet and outlet, which builds a bridge for the integrated design of the whole engine and components.

3. Establishing of the 1D model for lift fan

Given the inlet axial speed, inlet outer diameter, inlet flow angle, inlet total temperature, and total pressure, the annular area of the inlet and outlet needs to be calculated to determine the radius of the inlet hub.

The total enthalpy can be obtained from the total temperature, the absolute velocity can be obtained from the axial velocity and the inlet flow angle, the static enthalpy can be obtained from the absolute velocity and the total enthalpy, and the static temperature can be obtained. According to the total temperature, total pressure and static temperature. The relationship between static pressure and static pressure can be calculated, and then the static density can be calculated, and then the inlet area can be calculated according to the flow conservation, and finally the inner diameter of the compressor can be calculated according to the geometry, and then the pitch diameter ratio and radius ratio can be calculated. According to the ratio of pitch diameter, the tangential velocity and relative velocity at the pitch diameter can be obtained. According to the relative velocity and the axial velocity of the rotor inlet, the relative flow angle of the rotor inlet can be obtained.

In the one-dimensional calculation, the outer diameter and axial velocity of the rotor outlet, the pressure ratio of the rotor, efficiency and load factor are specified, first to calculate the total enthalpy of the outlet according to the loading coefficient and blade speed. According to the circumferential velocity and axial velocity of the outlet, the absolute velocity of the outlet is obtained, and the static enthalpy of the outlet can be obtained from the total enthalpy and the absolute velocity, and the static temperature and pressure of the outlet can be obtained from the static enthalpy. And finally solve area of the rotor exit.

The initial efficiency is given artificially, and there may be large deviations. Therefore, the efficiency must be solved iteratively in the model to ensure the reliability of the efficiency. In this paper, the efficiency is mainly related to the diffusion factor and the Mach number. The diffusion factor is calculated through solidity, flow angle and velocities. And then calculate the pressure loss with diffusion factor, solidity and Mach numbers. Finally, the efficiency is solved in an iterative manner. After solving the parameters like mass flow rate, velocity, pressure and area, the power and thrust of the lift fan can finally be calculated.

4. Integrated design of lift fan and main engine

In the vertical state, the lift fan drive shaft is connected to the low-pressure shaft of the main engine, and power needs to be extracted from the low-pressure turbine to drive the lift fan. Compared with the normal cruise state, there must be a substantial increase in the output power of the low-pressure turbine under the vertical take-off and landing and hovering states, while the turbine aerodynamic efficiency will decrease.

Take the F135 engine as an example, its low-pressure turbine is designed as a 2-stage turbine to ensure high-power output, and the rotation direction is designed to be opposite to the high-pressure turbine to offset the gyroscopic torque on the two rotors. The variable operating characteristics of the low-pressure turbine are shown in Fig. 3. Compared with the cruise point in the horizontal flight mode, the rotation speed of the low-pressure turbine in the hovering point state in the vertical mode is basically the same, but an additional 22380kW of shaft power needs to be extracted. At the same time, the aerodynamic efficiency of the low-pressure turbine drops from 0.99 to about 0.96, about 3 percentage points.

Regarding such working characteristics, the low-pressure turbine is required to have a strong ability to work in variable conditions, and this function must be achieved by adjusting some variable components. However, there is no document that clearly states that the inlet area of the mixer for bypass duct and the throat area of low-pressure turbine guide vane are adjustable.

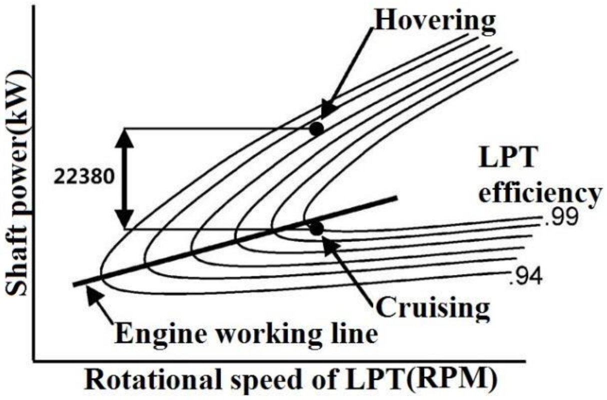


Figure 3 – Performance map for the low-pressure turbine of F135-PW-600.

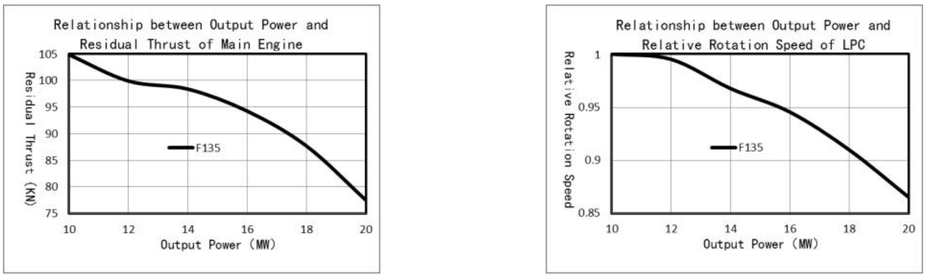
From the previous analysis, there are several ways to increase the output power of the low-pressure turbine:

(1) Increase the fuel flow to increase the inlet temperature of the low-pressure turbine. Generally speaking, due to material limitations, the inlet temperature of the low-pressure turbine is already the maximum design temperature and cannot continue to be increased.

(2) Increase internal flow. Due to the limitation of the speed of the high-pressure rotor, it can be seen from the characteristics of the high-pressure compressor that the effect of individually adjusting the area of the low-pressure turbine guide to increase the internal flow of the engine at the maximum state will be very limited.

(3) Increase the pressure drop of low-pressure turbine.

These methods can be used altogether to increase the output power of low-pressure turbine. Figure 4 shows the relationship between the residual thrust of the main engine and the relative speed of low-pressure rotor when large amount of power is extracted from the low-pressure shaft. It can be seen that as the extracted power of the low-pressure shaft increases, the remaining thrust and relative speed of the main engine are reduced.



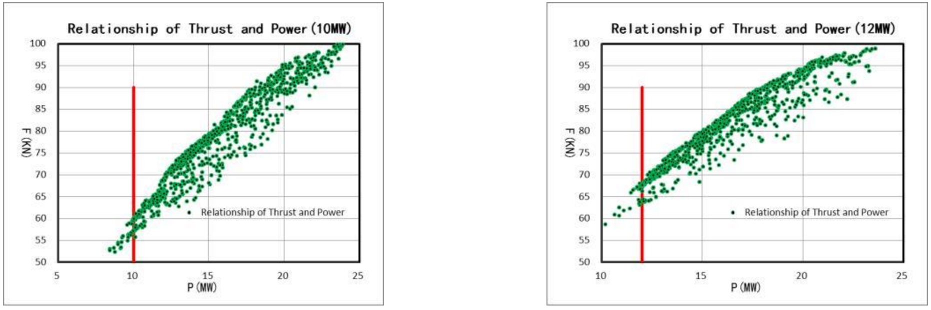
(a) Residual thrust of main engine (b) Relative rotation speed

Figure 4 – The variation of main engine residual thrust and relative rotation speed as the extracted power changes.

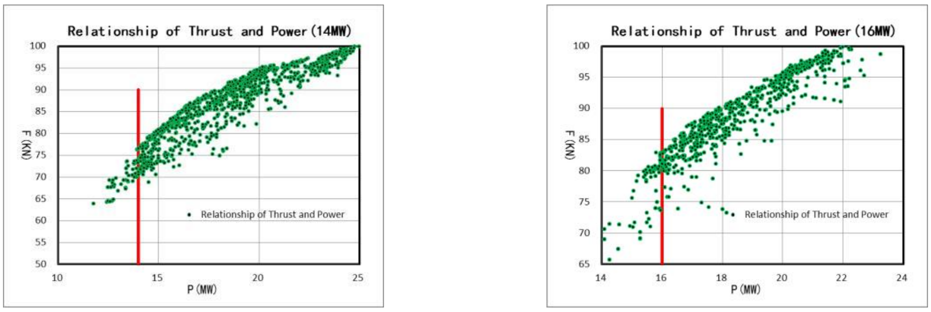
In order to ensure the maximum thrust generated by the entire power system at the top-level design stage of the engine, it is necessary to associate the parameters of overall concern, like lift fan thrust and power with the parameters of compressor design, for instance, pressure ratio, efficiency, flow. In this paper, the thrust and power of the counter-rotating fan can be calculated with the given loading, rotational speed, and axial speed of the inlet and outlet through models, which builds a bridge for the integrated design of the whole engine and components.

Using the one-dimensional model of the counter-rotating fan combined with the genetic algorithm, taking the F135 main engine as an example, the total thrust of the combined power system of its lift fan and turbofan engine was optimized. The detailed process of optimization is as follows: First, ensure that the input power and rotation speed of the lift fan meet the relationship between the output power of the main engine and the relative speed of the low pressure rotor; then, optimize the thrust of the lift fan at each output power and speed, the outer diameter of the lift fan is limited to less than 1.3m when optimizing; finally, the total thrust of the lift fan and the turbofan engine at this output power is solved.

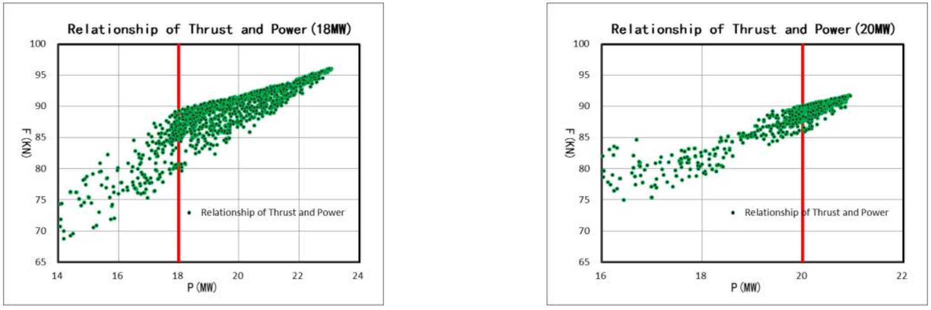
In the actual solution, the power of the lift fan is the output value, and it is difficult to limit its value by input when the loading, mass flow, and axial speed are released. Therefore, in the calculation, the power and thrust are both set as the target value of the genetic algorithm for searching. The maximum thrust that can be generated at this power is finally selected as the optimal value. Fig. 5 shows the thrust optimization diagram of the lift fan when the low-pressure turbine extracted power is 10, 12, 14, 16, 18, and 20MW respectively. The abscissa is the power of the lift fan, and the ordinate is the thrust. The different points represent lift fans with different design parameters.



(a) 10MW output power (b) 12MW output power



(c) 14MW output power (d) 16MW output power



(e) 18MW output power (f) 20MW output power

Figure 5 – The thrust optimization map of the lift fan with low pressure output power.

The genetic algorithm is used to optimize the 6 power points. The relationship between the lift fan power and the optimal thrust of the lift fan is obtained and shown in Fig 6. It can be seen from this figure that as the increases of the input power for the lift fan, the maximum thrust that can be generated from the lift fan also increases. Figure 7 shows the relationship between the lift fan power and the total thrust. It can be found that as increases of the input power for the lift fan, the maximum thrust that can be generated by the lift fan/turbofan engine combined power system increases first and then decrease. The maximum peak thrust occurs when the output power range is 16 to 18 MW. Table 1 shows the specific parameter values for optimal calculation under different powers. It is known from the Table 1 that the maximum thrust occurs when the fan outer diameter is 1.27m and the total thrust is 175.37kN, the output power is 18MW at this point. F135’s lift fan outer diameter is 1.27m, and its total thrust is 176.6kN when the output power is 18.9MW. The calculated parameters from the lift fan/main engine model are similar to those adopted by F135 (See Table 2).

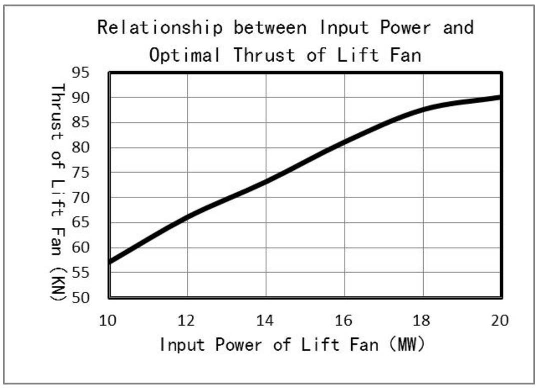


Figure 6 – Relationship between input power and optimal thrust of lift fan.

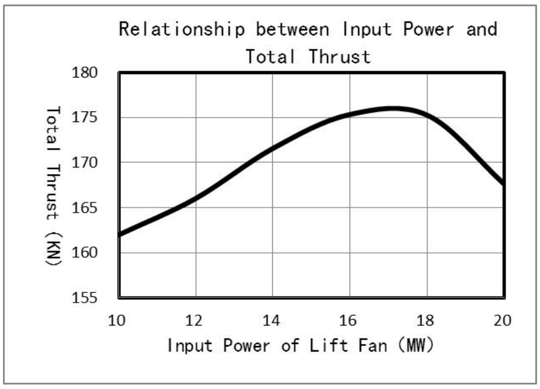


Figure 7 – Relationship between input power and total thrust of the combined power system.

Table 1 - Specific parameter values for optimal calculation under different powers

Relative Nominal Speed	0.865	0.910	0.946	0.968	0.996	1.001
Power of the lift fan (Mw)	20.00	18.00	16.00	14.00	12.00	10.00
Thrust of the lift fan (kN)	90.10	87.70	81.10	73.20	66.10	57.14
Outer diameter of the lift fan (m)	1.27	1.27	1.20	1.12	1.11	1.04
Total thrust (kN)	167.59	175.37	175.34	171.58	166.00	161.98

Table2 - Comparison of optimization results with F135 engine parameters

	Searching results	F135 results
Power of the lift fan (Mw)	18	18.9
Outer diameter of the lift fan (m)	1.27	1.27
Total thrust (kN)	175.37	176.6

5. Counter-rotating lift fan aerodynamic design

An input power of 17MW is selected for the lift fan according to the optimization results of the model. The other design parameters are also obtained from optimization results. The design parameters of the lift fan are compared with the lift fan of F135 engine which power the F35B aircraft. The performance parameters of the lift fan in this paper are slightly improved compared with the F135 lift fan, as shown in Table 3.

Table 3 - Design parameters comparisons of the new design lift fan and the F135 lift fan

	F135 lift fan	The new designed lift fan
Output power (MW)	18.97	17
Thrust of lift fan (kN)	81.2	≥81
Thrust per unit power(kN/MW)	4.28	≥4.7
Thrust per unit area(kN/m^2)	71.38	≥75
Corrected mass flow(kg/s)	204	204
Total pressure ratio	2.4	2.15
Adiabatic efficiency	0.883	0.883
Stall margin	-	≮22%
Outlet flow angle (deg)	-	≤10°
Inlet Mach number	-	≮0.6

The aerodynamic design of the counter-rotating lift fan was conducted using the 1D, S2, and blading tools according to the design parameters in Table 3. The blading results of the lift fan are shown in Fig. 8. Each row of blades has an elliptical leading edge, with a minimum radius of curvature of 0.6mm.

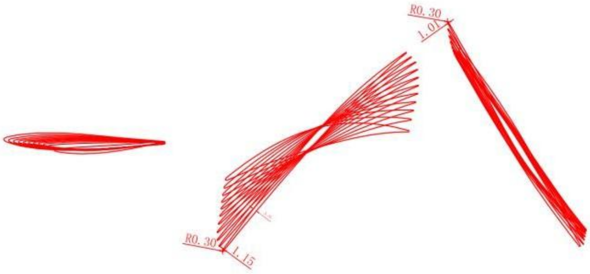


Figure 8 – Blading results of the high throughflow counter-rotating lift fan without outlet stator vane. The performance characteristics and flow field of the lift fan are obtained from CFD results using CFX. The blade model of the lift fan is shown in Fig. 9. The computational results of pressure ratio characteristics and efficiency characteristics of the new designed lift fan are shown in Fig. 10 and Fig. 11 respectively. The pressure ratio is 2.15, mass flow rate is 208.7kg/s, the efficiency is 0.8872, and the stall margin is 24.03% at near design point, which satisfy the design goals.

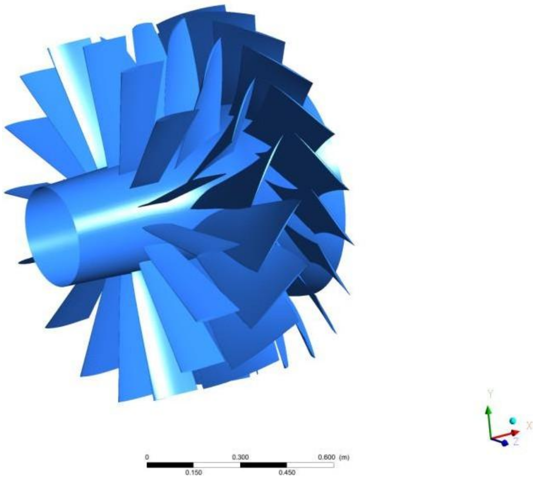


Figure 9 – Blade models of the new designed counter-rotating lift fan.

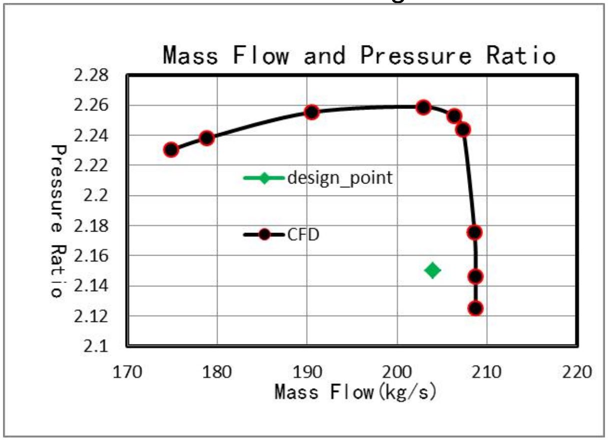


Figure 10 – Pressure ratio characteristics of the lift fan.

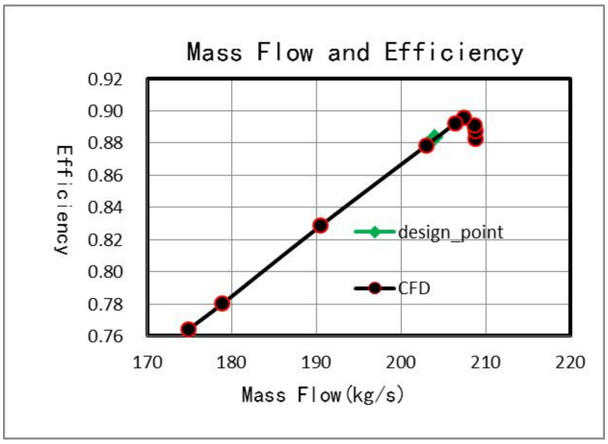
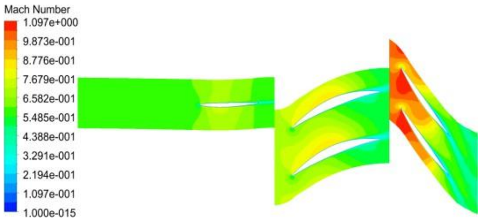
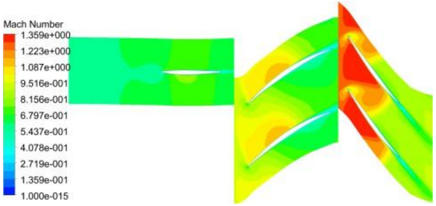


Figure 11 – Efficiency characteristics of the lift fan.

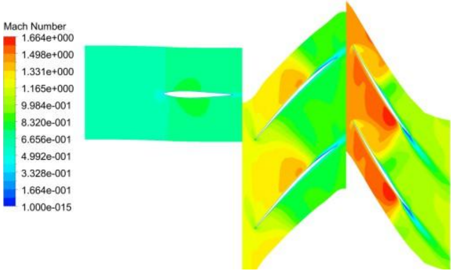
Figure 12 shows the relative Mach number contours for the hub, mid-span, and tip sections of the counter-rotating fan. It can be seen from the figure that the flow condition is good, and there is basically no separation in each section.



(a) hub



(b) mid-span



(b) tip

Figure 12 – Mach number contours at hub, mid-span and tip sections of the lift fan.

Table 4 compares the thrust and power of this lift fan with that of F135. The calculated thrust and power ratio of the F135's counter-rotating fan are 81.3kN and 18.98MW respectively. The same method is used to calculate the thrust and power of the fan described in this paper, and the thrust is 82.04. kN, the power is 16.59MW, the thrust per unit power is 4.94 (kN/MW), and the thrust per unit area is 82.68 (kN/m^2), all of which exceed the design requirements.

Table 4 - Comparison of performance between two lift fans

	Thrust (kN)	Input power (MW)	Thrust per unit power (kN/MW)	Thrust per unit area (kN/m^2)
F135 lift fan	81.3	18.98	4.28	71.53
The new designed lift fan	82.04	16.59	4.94	82.68

6. Conclusion

This paper has developed a method that regards the lift fan plus main engine power system as a "variable cycle" turbofan engine and realizes the optimization of lift fan parameters under the entire power system environment. The following conclusions can be drawn:

(1) A one-dimensional design model of the counter-rotating compressor is established, through which the thrust and power of the counter-rotating fan can be calculated, provided that the load, rotation speed, and axial velocity of the inlet and outlet are specified, making it possible to design the lift fan and main engine in an integrated manner.

(2) The multi-objective genetic algorithm, together with the one-dimensional model of the counter-rotating lift fan and the calculation model of the lift fan-turbofan engine combined power system, is used to optimize the lift fan and turbofan engine combined power system in the engine's top-level design stage.

(3) Taking the F135 main engine as an example, the method developed in this paper is used to optimize the parameters of its lift fan. The resulting parameters are closer to those selected by F135, with similar extracted power, which verifies the feasibility of the method proposed in this paper.

(4) Based on the optimization design parameters, the 1D, S2, and 3D design of the counter-rotating fan was conducted and analyzed through CFD methods. The CFD calculation showed that: the thrust of this newly designed counter-rotating lift fan is basically the same as that of F135's lift fan. However, the unit power thrust and unit area thrust of the newly design lift fan increased by 15% and 16% respectively, compared with F135's lift fan.

7. Acknowledgement

This paper is supported by the Aviation Science Foundation (2015ZB08006).

8. Copyright Statement

References

[1] Peterson J M. Lift Fan VSTOL Concept for further applications. Journal of Aircraft. Vol. 2: Issue.2: Pages. 94-99, 1965.
[2] Przedpelgki Z J. Lift Fan for advanced V/STOL Aircraft. AIAA 1965-708, 1965.
[3] Przedpelgki Z J. Lift Fan Technology Studies. Cincinnati, US: General Electric Company, 1967.
[4] Hill P C, Wasters M H. Conceptual Design of a Lift Fan plus Lift/Cruise Fighter Aircraft. AIAA 1974-969,1974.
[5] Franklin J A. Revised Simulation Model of the Control System, Displays, and Propulsion System for an ASTOVL Lift Fan Aircraft. NASA Technical Memorandum 112208, 1997.
[6] Arnulfo. Assessment of Remote Lift Fan Jet Engines. Proceedings of ASME TURBOEXPO, 2000-GT-151, MunichGermany, 2000.
[7] Bevilaqua P M. Future Application of the JSF Variable Propulsion Cycle. AIAA 2003-2614, 2003.
[8] Yonug R H. Contra-rotating Axial Fans. J. Instn. Heat. Vent. Eng. 18: 187, 1951.
[9] Shama P B, Jain Y P, Jha N K, et al. Stalling Behavior of a Counter-rotating Stage. 7th International Symposium on Air Breathing engines, ISABE paper 85-7087, 1985.
[10] Kerrebrock J L, Epstein A H, Merchant A A, et. al. Design and Test of an Aspirated Counter-rotating Fan. Journal of Turbomachinery, 130 (2): 198-206, 2008.