Reduced Thrust Take-off Control Law Design for Large Commercial Aircraft

Haitao YIN[1, a], Yan LI[1, b]

[1]Xi'an Aerospace Propulsion Testing Technology Research Institute, Xi'an, 710025, China

[a]email: 285379354@qq.com, [b]email:756760638@qq.com

Keywords: Reduced Thrust Takeoff, Assumed Temperature, Derate Method

Abstract. As the actual take-off weight of the aircraft is less than the maximum take-off weight, the technology utilizing thrust less than maximum take-off thrust for take-off is called reduced thrust take-off. Reduced thrust take-off is in generally divided into Assumed Temperature and Derate Method. In this paper, the principle of reduced thrust take-off is analyzed, and the method combined Assumed Temperature and Derate Method is studied. At last, the vertical control law of reduced thrust take-off which combines. Assumed Temperature and Derate Method is designed and simulated for a large commercial aircraft. The results show, under the correct flight circumstances, reduced thrust take-off researched is very important to improve the economic benefits of the airline, which can reduce operating costs of the airline, improve engine life and reduce fuel consumption.

Introduction

During the flight of the large commercial aircraft, the take-off stage is one of the important stages in the whole flight. It not only affects flight safety directly, but has significant influence on the engine performance. It is an important issue faced by Civil Aviation to research further reducing the operating costs of airlines on the basis of meeting safety performance of take-off [1].

Civil Aviation large transport aircraft mostly uses the Reduced Thrust Take-off technology. Although there is a clear description of reduced thrust take-off in each flight manual, the technology is unable to carry out an in-depth research because of technology blockade and monopoly. Reference [1~2] analyze the temperature characteristic of high-bypass ratio turbofan aero-engine and take-off performance of large civil aviation, and the necessary condition of Assumed Temperature. Reference [3~4] research the influence of speed drop and turbine temperature on engine parameter. Engine CFM56-5B is studied in reference [5], and is further proved that reduced thrust can extend service life of the engine pressure turbine blade. Reference [6~7] cite B737 and B757 to prove that reduced thrust can reduce the temperature of engine turbine and the blade load. But these references only demonstrate qualitative to the technology of the Assumed Temperature, and study the influence of reduced thrust take-off on engine. It is lack of research to Derate Method, the influence of reduced thrust take-off on fuel consumption and quantitative data.

Therefore, The paper focuses on the study of the different method of reduced thrust take-off, and apply it on a certain civil aviation to prove the advantage of reduced thrust take-off on economic benefits.

Principle of Reduced Thrust Take-off

Reduced Thrust Take-off (known as flexible thrust take-off) is that aircraft use thrust less than normal engine thrust to take off on the premise to ensure the flight safety (meet to the requirements of the appropriate regulations).

Process of Reduced Thrust Take-off.

The take-off process of the aircraft is shown as Figure 1. In the process of take-off, ground acceleration stage is from loosing brake to lifting the front wheel. Take-off decision speed V_1 is reached at some point of that stage; take-off can not be interrupted when V_1 is reached. The speed when lifting the front wheel refers to as V_R. Pilots should keep the nose about 8° in this stage until aircraft leave the ground. Then aircraft needs to accelerate to take-off safety speed. After climbing, the aircraft usually keeps speed $(V_2 + 10kn)$ before it reaches enough height[7,8].

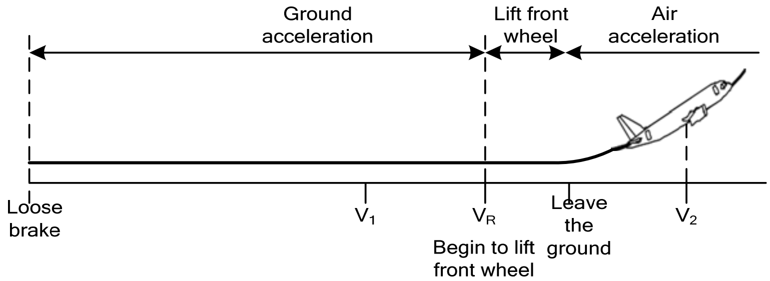

Fig. 1 Longitudinal sectional view of Take-off

In the case of the mess of the aircraft less than mess limited by airport length, V_1, V_2 and V_R will be reached in advance when full thrust take-off is used. So that Reduced Thrust Take-off can be used by excess runway when aircraft take-off. And it is possible to implement Reduced Thrust Take-off.

Restriction of Reduced Thrust Take-off.

Fig. 2 shows comparison of the same mess aircraft with full take-off and reduced thrust take-off. In Fig. 2, the greater thrust is, the larger climb gradient is. The aircraft cannot take off safely when the thrust cannot satisfy the minimum climb gradient. From the above analysis, we can draw the conclusion as follows. When the aircraft takes off at a certain condition, the thrust determines its climb gradient, and the climb gradient is limited to the actual take-off mess. Therefore, Reduced Thrust Take-off is limited to the actual take-off weight,

As angle of attack α and angle of incidence of engine φ_T are very small, we can get[8],

$$F - D - mg\sin\theta - m\frac{dV}{dt} = 0 \tag{1}$$

By the definition of the climb gradient (C.G), we gen formula of C.G,

$$C.G = \frac{r/c}{V} = \frac{\frac{F}{mg} - \frac{C_D}{C_L}}{1 + \frac{V}{g}\frac{dV}{dh}} \tag{2}$$

In formula (2), F is thrust of engine, D is air resistance, m is take-off mess, V is take-off speed, θ is pitch angle, C_L is lift coefficient, and C_D is drag coefficient. With given conditions of take-off, the greater the take-off mess is, the smaller the climb gradient is. Equation (2) shows that, when lift coefficient and drag coefficient are dug out and take-off speed is determined, we can determine the relationship of thrust and take-off weight,

From the above analysis, we can draw the conclusion as follows. In the case of known the maximum thrust of the engine, Reduced Thrust Take-off can be used to replace Full Thrust Take-off when the actual take-off weight is less than the maximum take-off weight.

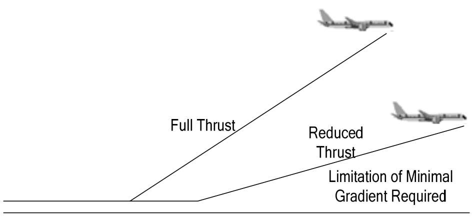

Fig. 2 Contrast of climbing ability

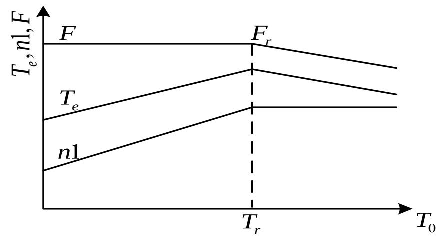

Fig.3 The temperature characteristic

Reduced Thrust Take-off Method

There are currently two kinds of Reduced Thrust Take-off method, Assumed Temperature and

Derate Method.

Assumed Temperature.

Assumed Temperature is the most common mode of the reduced thrust take-off currently. Assumed Temperature obtains take-off thrust less than full thrust of engine used one certain assumed temperature above actual temperature. We can look-up table to get the maximum assumed temperature based on the airport height, airport length, outside air temperature, wind direction and speed, and aircraft mess[1]. Fig. 3 is the typical temperature characteristic of high-bypass ratio turbofan engine at standard sea level[3].

In Fig. 3, T_r is the reference temperature, T_0 is air temperature, T_e is the engine air exhaust temperature, n_1 is the low-pressure rotor speed, F is the output thrust, and F_r is the reference takeoff thrust. When T_0 raises and $T_0 < T_r$, n_1 increases. Now takeoff thrust will keep F_r because of limitation of overpressure. When air temperature raises to T_r, T_e reaches to the limitation of takeoff. And T_e will no longer increase if air temperature continues to rise. n_1 will decrease with temperature increasing. And takeoff thrust F will reduce.

In light of this, when $T_0 < T_r$, turbine engine can remain takeoff thrust as F and vice versa. Therefore, T_r is the maximum air temperature which can remain takeoff thrust corresponding atmospheric pressure in the airport.

Derate Method.

The essence of Derate Method is regarding engine as a smaller power engine. The thrust of take-off must not exceed the maximum thrust of the virtual small power engine.

Fig. 4 is variation of engine thrust dependent on temperature which aircraft take off with full thrust and different levels of Derate Method. In general engine set two derating thrust level, TO1 and TO2. Each level has its restriction. As Derate Method determines the take-off performance, take-off performance chart corresponded to power must be used. Derate Method has no operating limitation. It can be used under any circumstances provided aircraft performance is allowed.

Different derate level usually corresponds to fixed reduced thrust, and specific data reduced by each airline may also be different (TO1 is 10% and TO2 is 20% in China Southern Airlines)[7]. And not all type can use Derate Method. Currently, all of types of Boeing can use Derate Method, and only can A319, A321, A330 and A340 use Derate Method in Airbus. There are six levels in A330 and A340. and thrust reduced is 4%, 8%, 12%, 16%, 20% and 24%.

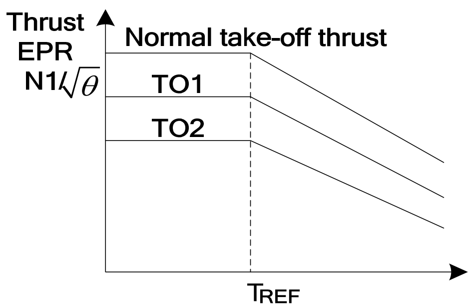

Fig. 4 The principle of Derate Method

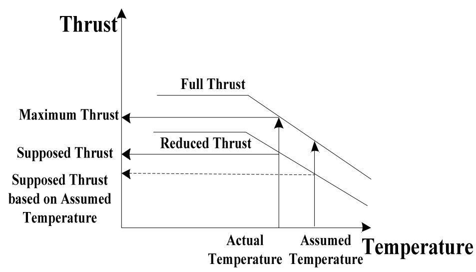

Fig. 5 Combining Reduced Thrust

Reduced Thrust Take-off Combining Assumed Temperature and Derate Method.

For Boeing aircraft, Derate Method and Assumed Temperature can be combined use. If actual takeoff mass is lighter than mass limited by Derate Method table TO1, and is larger than mass limited by table TO2, Assumed Temperature can be used meanwhile to further reduce thrust when level TO1 of Derate Method is used. The reason why combining TO2 and Assumed Temperature is not used is reduced thrust corresponding TO2 is larger generally. So it isn't necessary to further reduce thrust.

In Fig. 5, schematic diagram combining Assumed Temperature and Derate Method is given. Reduced thrust corresponding actual temperature is setting thrust. Meanwhile, we choose a certain assumed temperature higher actual temperature to use Assumed Temperature. Take-off thrust now is less than the take-off thrust with Derate Method.

Simulation Example

Structure and Processes of Simulation.

Vertical control law of Reduced Thrust Take-off is taken to design with a certain large passenger aircraft. The given aircraft is equipped with four turbofan engines. Thrust of single engine is 84.48 kN, and the maximum thrust of aircraft is 320.8 kN. Speed of lifting the front wheel is read as $V_R = 69.72 m/s$, and Take-off Safety Speed is $V_2 = 72.5 m/s$. Simulation process is shown as Fig. 6.

The aircraft takes off from loosing brake. First, press the joystick; when speed reaches to the speed of lifting the front wheel V_R, aircraft lifts the front wheel the pitch angular rate of 2.5° and prepares to take off; pitch angle maintains to 7.5° at last and continues to climb. The take-off stage ends when the altitude reaches to 35ft (10.7m).

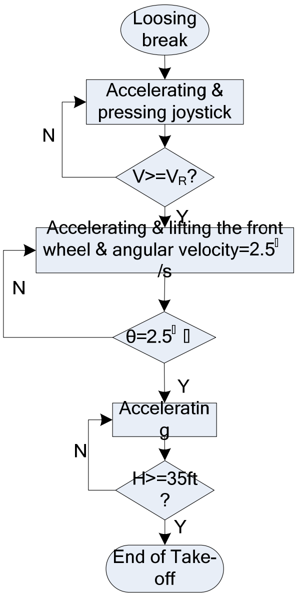

Fig. 6 Simulation process of take-off

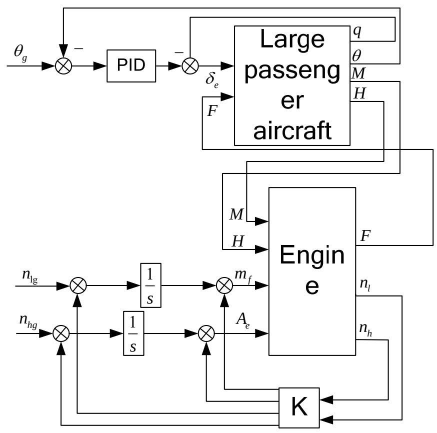

Fig. 7 Control Structure of Take-off

According to flight manual, we can get the change of the engine thrust caused by airport height and temperature as table 1.

Tab. 1 Relationship between N1 and height and temperature of the airport

Assumed Temperature	Airport Height（1000ft）				
	2	3	4	5	6
60	89.0	89.1	89.1	89.1	89.0
55	90.7	91.1	91.0	91.0	90.8
50	92.3	93.1	92.9	92.9	92.5
45	92.7	93.9	94.8	94.8	94.2
40	93.0	94.3	95.3	95.3	95.3
35	93.4	94.8	95.9	95.9	95.8
30	93.6	95.0	96.5	96.4	96.4
25	93.7	94.5	96.5	96.5	96.7
20		94.4			
The Minimum Assumed Temperature	26	24	29	27	25

Now we make simulation combining Assumed Temperature and Derate Method. Assuming that the actual temperature is $20^{\circ}C$, airport height is 3000ft, and its length is 1500m. Under these conditions, optional maximum assumed temperature is $57^{\circ}C$ from interpolation with table 1, and N1 corresponding to this temperature is 90.2762%. Derate Method is set as two levels. TO1 is set as 10%, and TO2 is set as 20%. And thrust is reduced further with Assumed Temperature based on

TO1, actual thrust should be the maximum thrust of 80.2762%. The structure of longitudinal take-off combining of flight and thrust is shown as Fig. 7, which aircraft model is controlled with PID and engine model is controlled with Optimal Servo.

Simulation Results.

The model is simulated by MATLAB. Responses of speed, altitude, distance rolling and fuel quantity of the full thrust and Reduced Thrust Take-off is show as Fig. 8 to Fig. 11.

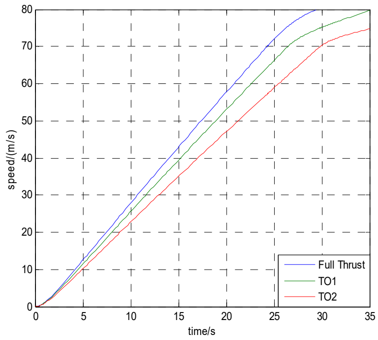

Fig. 8 Speed response

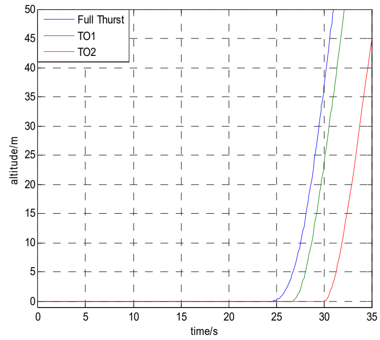

Fig. 9 Altitude response

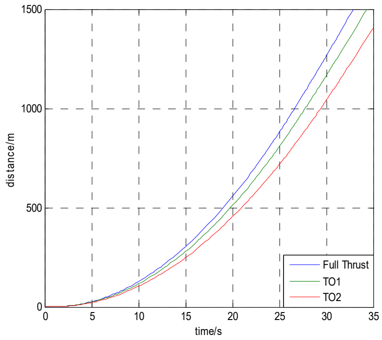

Fig. 10 Distance response

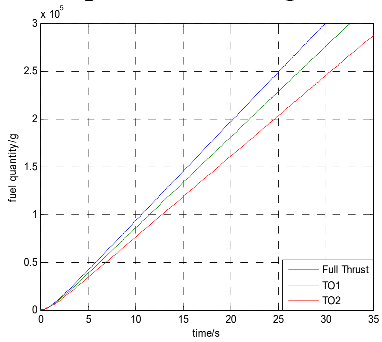

Fig. 11 Fuel quantity response

When the aircraft takes off to 35ft (10.7 meters) from the ground, the aircraft state of full thrust take-off and reduced thrust take-off combining Assumed Temperature and Derate Method is shown as Tab. 2.

Tab. 2 State contrast of full thrust take-off and reduced thrust take-off

Take-off Mode / Parameter	Full thrust take-off	Reduced thrust take-off
Time/s	27.65	31.86
Speed/m/s	77.6	72.6
Distance of landing/m	877	1048
Fuel quantity/kg	276	261

Compared Reduced Thrust combined with Assumed Temperature and Derate Method with full thrust, take-off time is prolonged 15.23%, and distance is increased 19.50%, and fuel is reduced 5.43%, take-off speed is $V = 72.6 > V_2$. Simulation results show that, as length of airport allowing, using Reduced Thrust Take-off can ensure the security of take-off, and reduce fuel consumption greatly, and has a significant role in improving economic efficiency.

In this paper, the simulation proves that Derate Method can reduce fuel consumption and transportation costs. Derate Method can also reduce in-flight shutdown rate and unscheduled engine removal rate, and improve safety standard of airlines. Thus it is necessary to study and spread Reduced Thrust Take-off.

Conclusion

In this paper, the simulation proves that Reduced Thrust Take-off can reduce fuel consumption and transportation costs at the same time to ensure safety at the expense of increasing distance of landing. It is obvious that the operating cost of airlines is reduced by Reduced Thrust Take-off. At the same time, Reduced Thrust Take-off can reduce inflight shutdown rate and unscheduled engine removal rate. And it is conducive to improving the safety and reliability of large aircraft. Therefore, it is necessary to implement Reduced Thrust Take-off on the basis of satisfying take-off safety performance and airworthiness regulation.

References

[1] Tingyu Zhao. Necessity Analysis of Reduced-Thrust Taking-off of Turbofan Engines [J]. Tianjin: Journal of Civil Aviation University of China, 2005, 23(3). 6~8.

[2] Yan Chenghong. Reduced Thrust Takeoff[A]. Canada: ICAS 2002 CONGRESS. 2002.

[3] Xinmin Wang, Haitao Yin, Yi Zheng, Rong Xie. Research of Reduced Thrust Take-off of Large Passenger aircraft Based on Assumed Temperature. Computer Simulation[J], 2013(30), 8:36~40,45.

[4] Chmiela B, Sozanska M, Cwajna J. Identification and evaluation of freckles in directionally solidified casting made of PWA 1426 nickel-based superalloy[J]. USA: Archives of Metallurgy and Materials. 2012, 57(2). 559~564.

[5] Xinmin Wang, Haitao Yin, Yi Zheng, Rong Xie. Reduced Thrust Take-off of Large Passenger Aircraft Based on Derate Method. Lecture Notes in Electrical Engineering[J]. 2013, 2: 9-16.

[6] Ao, Liangzhong. Thrust lever angle signal processing of an aircraft engine[J]. Proceedings - 2012 International Conference on Computer Science and Electronics Engineering, ICCSEE 2012. 2012, 613~616.

[7] Xiaoming Liu, Tingyu Zhao, Xiaohang Wen, Etc. Reduced-Thrust Takeoff Technique Applied to Passenger Airplanes [J]. Xi’an: Flight Dynamics, 2009, 27(3). 83~85.

[8] Zhihuai Chen, Runping Gu, Junjie Liu. Aircraft Performance Engineering [M]. Beijing: Ordnance Industry Press. 2006. 49~55.