

Method for designing constant thrust power schedule

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Abstract: In order to make the power level angle (PLA) have the same bijection relationship with the thrust when the environment changes before operational limit exceedance, and ensure the pilot's ability of unrestricted throttle movement as well as the safety of the engine, a method used to design a constant thrust power schedule was proposed. The research was based on a simulink turbofan engine model and the results were organized as look-up tables in different structures with limitations. Simulation was done to confirm the validity and demonstrate the effectiveness of the schedule obtained with the approach. The constant thrust takeoff schedule, constant thrust idle schedule and constant thrust part power schedule with the present constant thrust control (CTC) method were proved to be valid. The results can be applied to this specific engine but the method can be applied to any areoengine and can be even extended to the unmanned plane.

Key words: power schedule; constant thrust; turbofan engine; operational limitations; control method

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Nomenclature

H/km	altitude	T_2/K	total temperature before the fan
$\Delta T/\text{K}$	the difference between the temperature at the sea level and 288.15 K	$T_{5\text{max}}/\text{K}$	temperature limitation after the turbine
$W_t/(\text{kg/s})$	fuel flow in the combustor	$N_{1\text{cor_idle}}/\%$	$N_{1\text{cor}}$ in idle condition
T_5/K	turbine exit temperature	$N_{1\text{cor_to}}/\%$	$N_{1\text{cor}}$ in takeoff condition
$N_{1\text{cor}}/\%$	corrected fan speed	$N_{1\text{cor_part}}/\%$	$N_{1\text{cor}}$ in part power condition
Ma	Mach number	$F_{\text{idle}}/\text{daN}$	thrust in idle condition
p_1/kPa	inlet total pressure	F_{to}/daN	thrust in takeoff condition
T_1/K	inlet total temperature	$F_{\text{part}}/\text{daN}$	thrust in part power condition
p_b/kPa	environment pressure	$F_{\text{normalized}}$	normalized thrust
T_b/K	environment temperature	$T_{5,\text{normalized}}$	normalized turbine exit temperature
$N_{1\text{cmd}}/\%$	rotation speed command of the fan	$\alpha/(\circ)$	power level angle

In the primary control loop of a gas turbine fuel control system, the reference command is calculated based on the throttle position set by the pilot which means the pilot's power request^[1]. That calculation is called power setting logic and it is divided into three basic logic paths: takeoff (TO) power schedule, idle power schedule and part power schedule.

The TO power schedule is most commonly expressed as a function of ambient temperature and the altitude^[2]. That function is always organized as a look-up table in modern fuel control system. The idle power schedule sets the reference value of the minimum steady-state power for an engine and the result also is a schedule organized as a look-up table. The part power

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schedule refers to the engine power that corresponds to any throttle position between the idle and the TO power is an interpolation between the idle power schedule and the TO power schedule with respect to the power level angle (PLA).

In general, the demand of thrust is same when a plane takes off or taxiings. However, the environment which influences engine's performance varies widely at different airports. For example, the lowest airport in China is the Turpan Airport whose altitude is -155 m and the highest airport is the Daocheng Yading Airport in Sichuan province whose altitude is more than 4 km. When the planes are stopped in these two airports, the inlet pressure of the former can be 1.77 times more than the latter. Moreover, the temperature varies in different seasons. In the history of China, the lowest temperature is 220.85 K. The highest temperature is 322.75 K and appears just in the airport in Turpan. As a result, constant thrust TO power schedule and constant thrust idle power schedule are needed.

However, the demand of TO thrust may change in some condition. One of the examples is the flex takeoff which means reducing some power during the process of takeoff. The flex takeoff has important meaning for the life of the turbine rotor blades. There are experiment results showing that if the TO thrust reduces 5% , the life of the turbine rotor blades will increase 25% and if the TO thrust reduces 10% , the life of the turbine rotor blades will increase 40% ^[3]. Therefore, constant thrust part power schedule used in conditions like flex takeoff is needed.

Constant thrust power schedule^[4] which is a combination of constant thrust TO power schedule, constant thrust idle power schedule and constant thrust part power schedule is present. Constant thrust power schedule means that the reference value of the primary control loop changes with the inlet condition to make sure the thrust is constant in particular condition in this paper. It is important because it gives the pilot the ability of unrestricted throttle movement

without considering the environment. In other words, the purpose of the power logic schedule is that the pilot can obtain the thrust he or she desired by moving the power level angle (PLA).

In Ref. [2], the author mentioned that because of the dependency of the inlet condition, the power setting reference value at each throttle position must be made as a function of the ambient pressure, the ambient temperature and the aircraft Mach number, but in most commonly condition, it is expressed as a function of the ambient temperature and the altitude. In Ref. [5], simulation was carried out to prove the correctness of this theory but how to get the schedule is not mentioned.

This paper researches on the way of getting the power setting schedule, which promises the performance as well as the safety of the engine^[6], based on the theory above and a Matlab/Simulink model of a turbofan engine whose validity has been proved before the research of this paper with the knowledge of the fan rotor speed at the design point and temperature limitation. The limitations like overspeed and any other operational limit exceedance are not included in this paper because they are the same as the temperature limitation and are very easy to be added with the method in this paper. It should be noted that any valid model can be used to substitute the model here without influencing the research process.

1 Model description

Nonlinear engine models are the basement of aeroengine simulation research^[7-9]. The platform for the following research is built with Matlab/Simulink with the turbofan engine nonlinear model above so that the research can be done graphically^[10-12]. The inputs and outputs of the model are shown in Fig. 1. The inputs are the environment condition H , ΔT , the control variable W_f and any other inputs, named as OtherInputs, make the model work but are not concerned in this paper. T_5 , Thrust and N_{1cor} are the output parameters needed to be recorded.

Other outputs not concerned in this paper, named as OtherOutputs, are also shown in Fig. 1. Therefore, the nonlinear model can be described as Eq. (1).

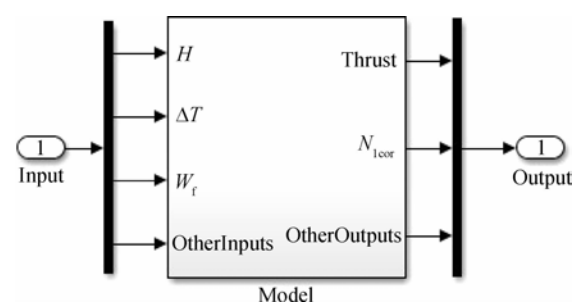


Fig. 1 Simulink model of the engine

[Thrust N_{1cor} OtherOutputs] =
f(H,ΔT,W_f,OtherInputs)

(1)

In common condition, H , ΔT and Ma will affect the inlet condition p_1 and T_1 together. The Eq. (3) to Eq. (8)^[13-15] show the detailed relationship of the parameters in Eq. (2).

[p₁, T₁] = g(H, ΔT, Ma)

(2)

The Eq. (3) to (6) are used to calculate the T_h and p_h at different altitudes.

When $H \leq 11 \text{ km}$,

T_h = 288 − 6.5 × H + ΔT

(3)

p_h = 101325 × (1 − H/44.3)^{5.255}

(4)

When $11 \text{ km} < H \leq 20 \text{ km}$,

T_h = 216.5 + ΔT

(5)

p_h = p₁₁ × e^[(11.0−H)/6.318]

(6)

Where $p_{11} = 2.26 \times 10^4 \text{ Pa}$ is the pressure of the atmosphere at 11 km above the sea level.

Then, the inlet total temperature T_1 and inlet total pressure p_1 can be calculated by Eqs. (7) and (8).

T₁ = T_h × (1 + $\frac{\kappa - 1}{2} Ma^2$)

(7)

p₁ = p_h × (1 + $\frac{\kappa - 1}{2} Ma^2$) ^{$\frac{\kappa}{\kappa - 1}$}

(8)

However, depending on the theory in Ref. [2], Ma is not considered as a variable in the research and is included in OtherInputs.

2 Schedule design procedure

The purpose of the design is to make sure that the PLA has bijection relationship with the

engine thrust when the environment changes. In order to include all conditions discussed in the introduction and without lose of generality, the range of ΔT is chosen as $-68 - 35 \text{ K}$ and the range of the altitude is selected as $-1 - 4 \text{ km}$ in the first step of the procedure in this paper. The increment of ΔT is 1 K and the increment of altitude is 1 km.

The design procedure is shown in Fig. 2. At each situation, the N_{1cor} makes the thrust constant, the $n_{1thrust}$ in Fig. 2, in TO condition is recorded as an element of the constant thrust TO schedule. The N_{1cor} makes the thrust constant in idle condition is recorded as an element of the constant thrust idle schedule. N_{1cor} makes the T_5 the same as T_{5max} , the n_{1t5} in Fig. 2, is recorded as an element of the T_5 limitation schedule.

The lower output values between the constant thrust TO schedule outputs and the T_5 limitation schedule outputs at the same situation consist of the TO schedule. The logic is shown in Fig. 3 and the result is shown as a map in the Fig. 4. The correctness of the schedule will be tested in the next section.

The logicto generate the idle schedule is shown in Fig. 5 and the result is shown in Fig. 6. The validation of the schedule is also going to be tested in the next section.

Part power schedule refers to the engine power that corresponds to any throttle position between the idle and the TO power. The simplest approach to calculating the part-power reference command value is to interpolate between the idle and the TO reference values with respect to PLA^[2]. It is expressed by Eq. (9). This approach is called constant thrust N_{1cor} control (CTNC).

N_{1cor_part} = N_{1cor_idle} +
 $\frac{(\alpha - \alpha_{idle}) \cdot (N_{1cor_to} - N_{1cor_idle})}{\alpha_{to} - \alpha_{idle}}$

(9)

Where α_{idle} means α in idle condition, α_{to} means α in TO condition and α_{part} means α in part power condition.

A realization of obtaining the part power schedule command of CTNC is shown in the Fig. 7.

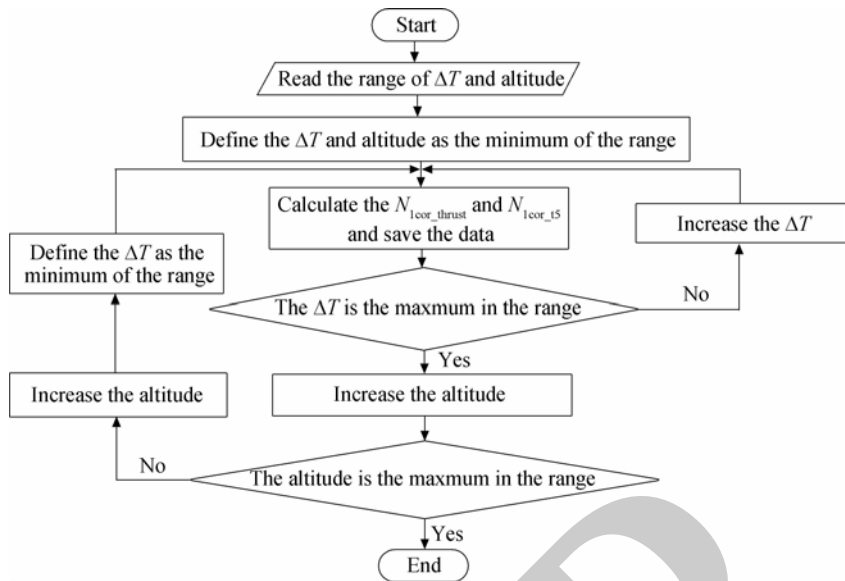


Fig. 2 Flowchart of the design procedure

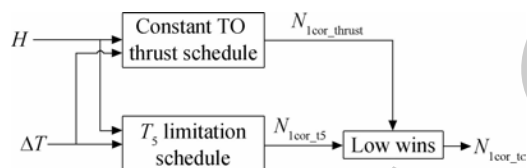


Fig. 3 Logic of TO schedule

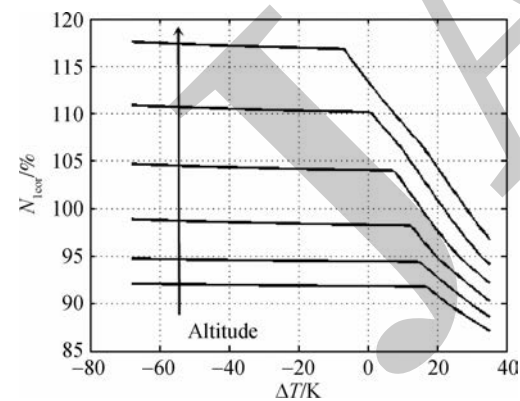


Fig. 4 Map of TO schedule

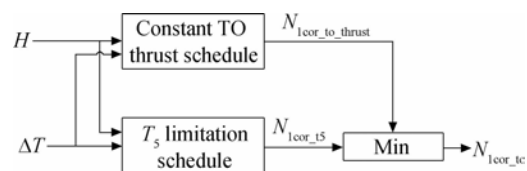


Fig. 5 Logic of idle schedule

Attention should be paid in this realization is that N_{1cor_to} and N_{1cor_idle} come from the constant thrust TO schedule and the constant thrust idle

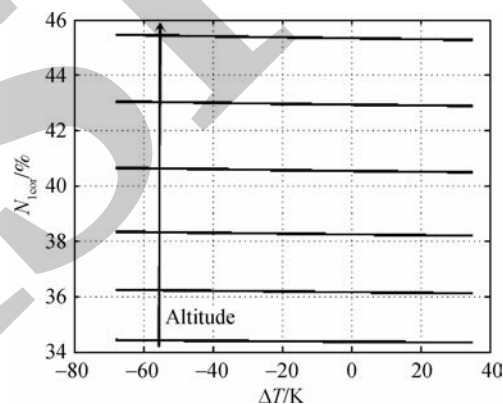


Fig. 6 Map of idle schedule

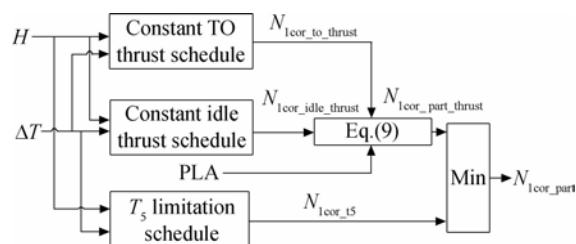


Fig. 7 Calculation procedure of CTNC

schedule instead of the TO schedule and the idle schedule because limitation is the same in all conditions. Therefore, it should not be related to the PLA. A part from the T_5 limitation in this paper, it should be noticed that any limitation should not be related to the α .

In order to improve the linearity between the PLA and the engine thrust, another approach

described as Eq. (10) is presented. This approach, relatively, is named as the constant thrust control (CTC) in this paper.

$$F_{part} = F_{idle} + \frac{(\alpha - \alpha_{idle}) \cdot (F_{to} - F_{idle})}{\alpha_{to} - \alpha_{idle}} \quad (10)$$

Where α_{idle} means α in idle condition, α_{to} means α in takeoff condition and α_{part} means α in part power condition.

The process of how to obtain the part power schedule command of CTC is shown in the Fig. 8.

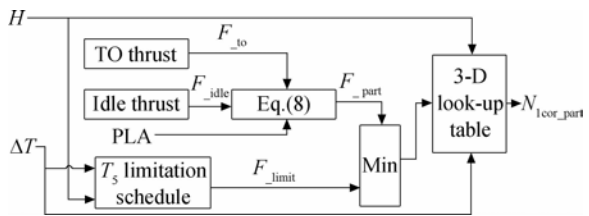


Fig. 8 Calculation procedure of CTC

It is illustrated in Fig. 8 that CTC is more complex than CTNC because there is a 3-D look-up table which can be described with Eq. (11). It turns the thrust into N_{1cor} as well as takes environment condition into consideration.

$$N_{1cor} = f(H, \Delta T, F) \quad (11)$$

Although the 3-D look-up table should in-

clude the relationship between the thrust and N_{1cor} at every H and every ΔT to make sure in any environment condition the N_{1cor} ensuring the desired thrust can be obtained with the help of the 3-D look-up table in Fig. 8, the number of the data in the table will be very large if the sampling points are as dense as what we have done above. It is not allowed if it is contained in the controller.

However, the effect of the ΔT is much smaller than the other two factors and it will be proved later. Therefore, the sampling points of ΔT chosen in this research are $-68, -40, -20, 0, 20$ K and 40 K. Then, the calculation procedure for the 3-D look-up table is shown in Fig. 9 and the data of the look-up table is plotted and shown in the Fig. 10.

In Fig. 10, we can see that the surfaces of the N_{1cor} data at different ΔT are almost coincident. An amplified part of the surfaces is shown in the top left corner of Fig. 10 where the ΔT decreases from top to bottom.

When the α is the α_{idle} , the N_{1cor_part} equals the N_{1cor_idle} . When the α is the α_{To} , the N_{1cor_part} equals the N_{1cor_to} . Therefore, the logic shown in

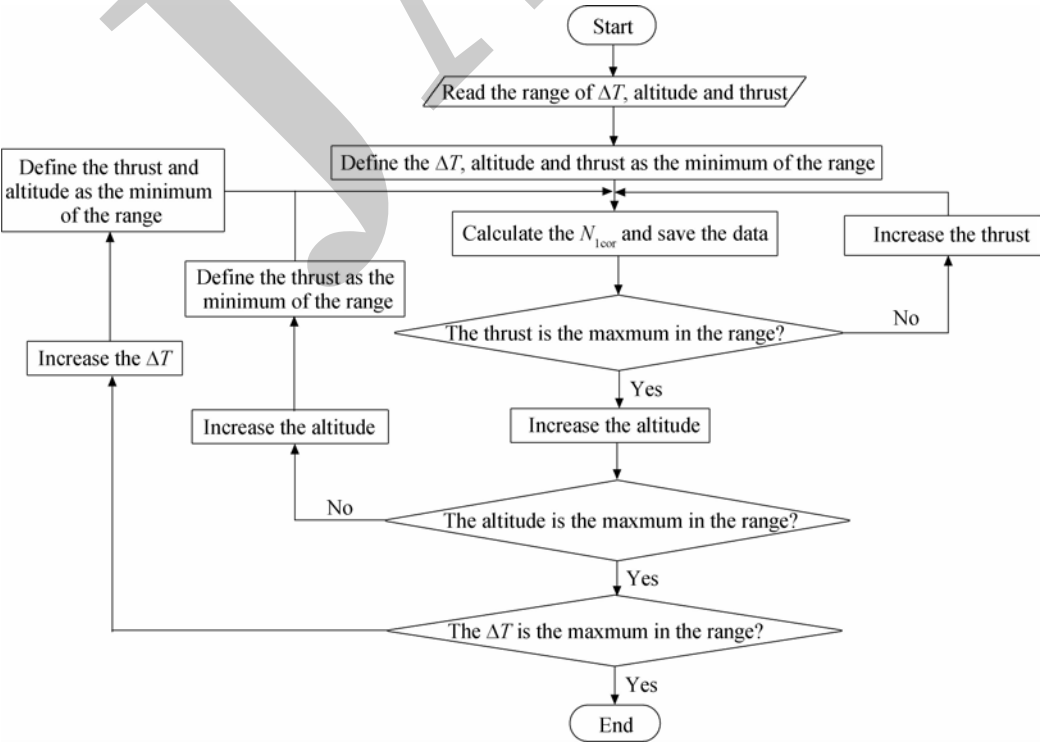


Fig. 9 Calculation procedure for the 3-D look-up table

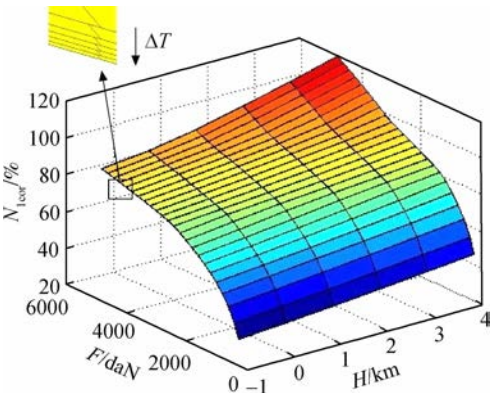


Fig. 10 3-D look-up table for N_{1cor} calculation

Fig. 7 and Fig. 8 is suitable for describing the whole power setting schedule with the CTNC and CTC.

3 Validation

An experimental program was carried out to validate the three power setting schedules. It is a traditional negative feedback system whose structure is shown in the Fig. 11. The feedback signal is the N_1 calculated by the model which represents the actual rotation speed of the fan. The system simulation platform is built with Simulink to find out if the schedule can always make the thrust constant before reaching the temperature limitation and whether the over temperature will happen or not.

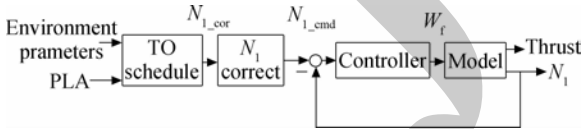


Fig. 11 Structure of the feedback system

Without loss of generality, the α is set to be 60 degree representing takeoff. Also, we assume 20 degree representing idle.

The simulation results of TO and idle are shown in the Fig. 12 to Fig. 15. In the results of TO condition, the thrust is hold constant when inlet condition changes till the T_5 limitation is reached. Then, the thrust decreases and the T_5 remains unchanged. In the results of idle condition, the thrust is hold constant during the whole simulation because the T_{5max} will not be

exceeded in idle condition when T_5 increases with the ΔT . It is exactly the same as designed. They reflect that the schedule is valid.

When it comes to the part power schedule, both of the CTNC and CTC should be tested. Be-

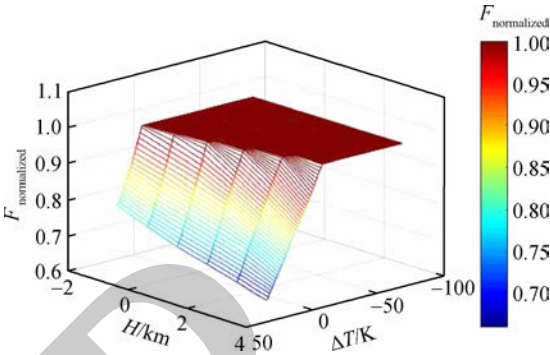


Fig. 12 Thrust during the simulation of TO

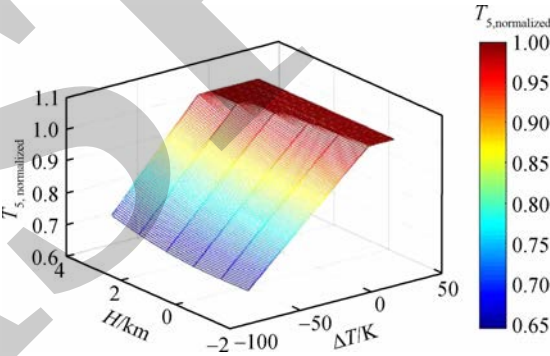


Fig. 13 T_5 during the simulation of TO

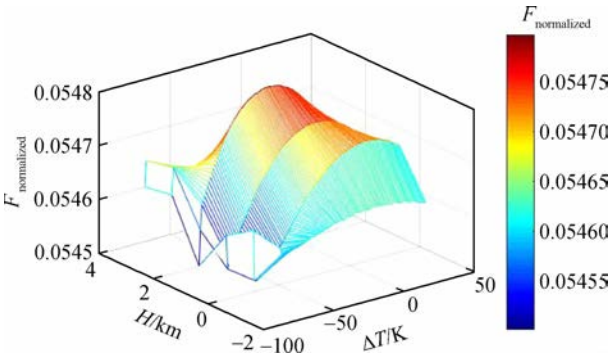


Fig. 14 Thrust during the simulation of idle

sides, although the part power schedule should be tested in all α between α_{idle} and α_{to} , for simplicity, only the simulation results of part power schedule when α is 50 degree are shown in the Fig. 16 to Fig. 19.

It should be noted that the vertical ordinates of Fig. 12 to Fig. 20 are normalized parameters which is normalized with Eqs. (12) and (13).

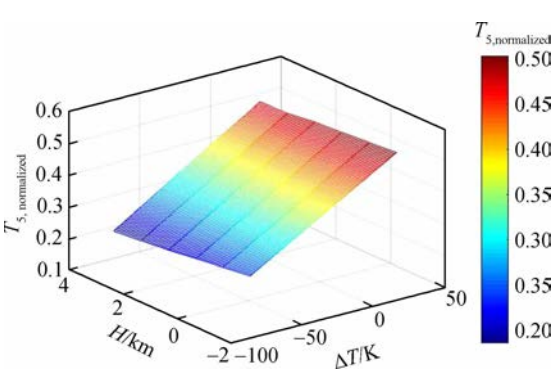


Fig. 15 T_5 during the simulation of idle

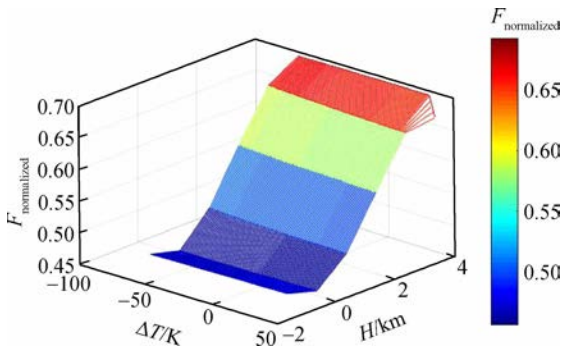


Fig. 18 Thrust during the simulation of part power (CTNC)

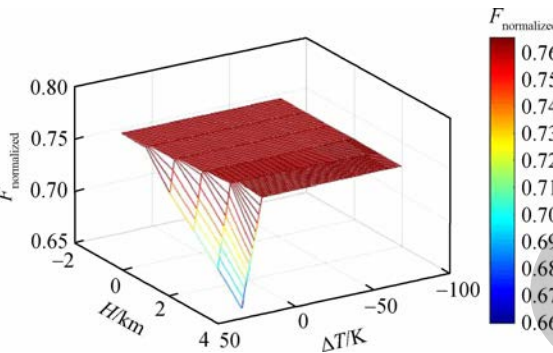


Fig. 16 Thrust during the simulation of part power (CTC)

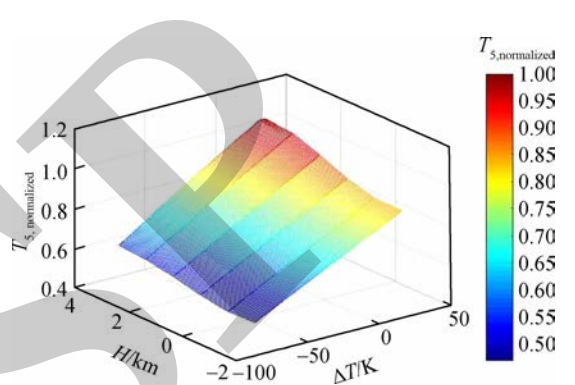


Fig. 19 T_5 during the simulation of part power (CTNC)

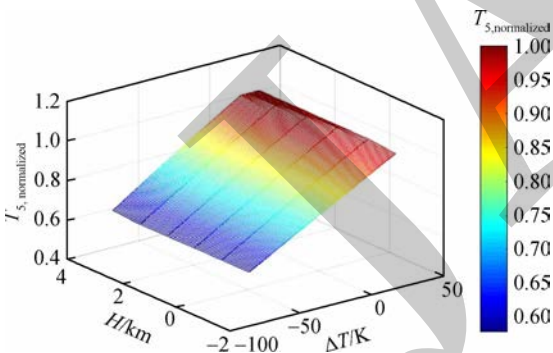


Fig. 17 T_5 during the simulation of part power (CTC)

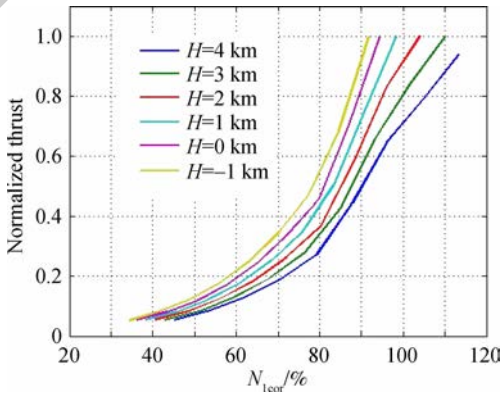


Fig. 20 Relationship between thrust and N_{1cor} in different altitudes

$$F_{normalized} = \frac{F}{F_{to}} \quad (12)$$

$$T_{5,normalized} = \frac{T_5}{T_{5max}} \quad (13)$$

The result of the CTC is the same as designed while the result of CTNC is very different from expectation. It is unable to make the thrust unchanged when the inlet condition changes because the relationships between the N_{1cor} and the thrust are different when the environment changes as shown in Fig. 20. Same N_{1cor} does not en-

sure same thrust at different altitude. And the 3-D look-up table in the structure of CTC takes this fact into consideration and modify the N_{1cor} with inlet condition to ensure the constant thrust. It should be noted that the influence of the ΔT is relatively small and will not be discussed here.

4 Discussion

First of all, although the $N_{1\text{cor}}$ has direct relationship with the thrust^[5], the robustness of the CTNC is unacceptable as shown in Fig. 18.

Another attention should be paid on the difference between the relationship of the $N_{1\text{cor}}$ and α and the relationship of the thrust and α in the CTNC and CTC.

For simplicity, only the result of the situation at the standard sea level is shown in this part.

A series of steady state command $N_{1\text{cor}}$ of these two control ways is recorded in each α and is shown in the Fig. 21.

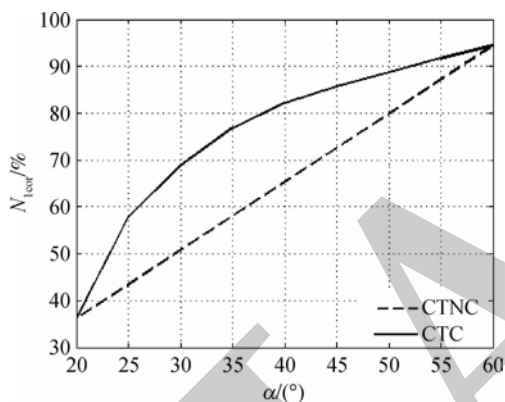


Fig. 21 Different $N_{1\text{cor}}$ command of two approaches

As what is illustrated in Fig. 21, the command $N_{1\text{cor}}$ of these two control ways is very different when the α changes. The $N_{1\text{cor}}$ command of CTNC increases linearly when the α changes. Meanwhile, when the CTC works, it is nonlinear and the increasing trend decreases when the α signal increases.

The thrust of this simulation is shown in the Fig. 22.

As present in the Fig. 22, the relationship between the α and the thrust of the CTC is much more linear. Moreover, CTC has an advantage that the TO segment is less sensitive to the α for ease of manual throttle adjustment by the crew or the operator^[2]. This characteristic is important because it means it will be more convenient for the pilot to control the plane. In the other

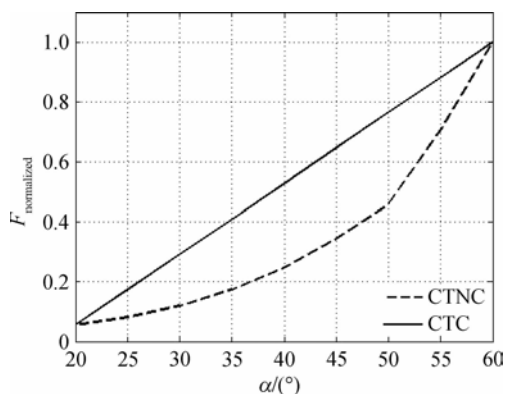


Fig. 22 Thrust of two approaches when α changes

hand, the thrust of the CTNC is much more sensitive near the TO segment. It means the pilot should be more careful when he or she tries to reduce the TO thrust and more experience is demanded.

5 Conclusion

The procedure to develop a constant thrust power setting schedule was proposed in this paper. Method taking operational limitations into account was introduced and T_5 limitation was given as an example.

Validation of the TO schedule and idle schedule was proved through simulation, and the result of the experiment proved the schedule had the ability to make the thrust unchanged as the environment changes.

Besides the simplest CTNC, a more complex but accurate way to get the part power schedule named as CTC was present.

A simulation was done to check the validation of part power schedules generated with the CTNC and CTC. The CTC proves to be a better choice in the constant thrust research power setting schedule in this paper.

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