

# Research on Climbing Performance Calculation and Flight Test of Transport Aircraft

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**Abstract.** Climbing performance is one of the most critical indicators for evaluating aircraft flight performance and affecting flight safety. In the paper, the airworthiness regulations related to climbing performance in CCAR25 are researched and summarized in detail. An exhaustive method for calculating climb gradient during constant airspeed climb is developed. Meanwhile, the forward and reverse heading sawtooth climb method is designed to execute the climbing performance flight test. Finally, by comparing the calculation results of the climb gradient with the flight test results, it is proved that the aircraft meets the airworthiness requirements and the climb performance calculation model is reliable.

**Keywords:** Climbing Performance; Airworthiness Regulations; Climb Gradient; Flight Test

## 1. Introduction

Climbing performance refers to the ability of an aircraft to increase its altitude, determining its obstacle-crossing capacity during processes such as takeoff, go-around, and route climb. It is one of the most critical indicators for evaluating aircraft flight performance and affecting flight safety. For safety considerations, airworthiness provisions have set minimum climb gradient requirements for different stages<sup>[1]</sup>.

In the aircraft design process, climbing performance is mainly determined through theoretical calculations based on the lift-drag characteristics of the aircraft obtained through wind tunnel tests, numerical calculations, and other methods, combined with the available thrust of the engine. However, since the tests and numerical calculations used in the design process cannot fully reflect the actual lift-drag characteristics of the aircraft and engine operating characteristics, there will inevitably be differences between the theoretical calculation results and the actual climbing performance of the aircraft, requiring validation through flight tests.

This paper develops a climb gradient calculation algorithm and a method for the climbing performance flight test. Taking a large transport aircraft as an example, it compares and analyzes the theoretical calculations and flight test results of the climb gradient, thus verifying that the aircraft's climb gradient meets airworthiness provisions and that the climbing performance calculation model is reliable.

## 2. Airworthiness Regulations

CCAR25.117, 119, and 121<sup>[2]</sup> outline the requirements for configuration, speed, and climb gradient during takeoff climb, approach climb, and landing climb phases. Transport category aircraft must undergo flight tests to verify that the aircraft meets the regulatory requirements for climb gradient in each phase and to validate the aircraft's polar curve model and climbing performance calculation model. In combination with relevant content in the Advisory Circular (AC)<sup>[3]</sup>, the summary of the minimum climb gradient requirements for each climb phase is presented in Table 1, and the analysis summary of the configuration requirements for each climb phase is presented in Table 2.

Table 1. Minimum climb gradient requirements

Flight phase	Operating engine number(N-1)	All engine number(N)	Minimum climb gradient
1st takeoff segment	1/2/3	2/3/4	0.0/0.3/0.5

Flight phase	Operating engine number(N-1)	All engine number(N)	Minimum climb gradient
2nd takeoff segment	1/2/3	2/3/4	2.4/2.7/3.0
Final takeoff segment	1/2/3	2/3/4	1.2/1.5/1.7
Approach climb	1/2/3	2/3/4	2.1/2.4/2.7
Landing climb	1/2/3	2/3/4	3.2/3.2/3.2

Table 2. Configuration requirements of climb phases

Flight phase	Trust	Operating engine number	All engine number	Flap-Slat detent	L/G position	Airspeed	Weight
1st takeoff segment	TO	N-1	N	Takeoff	Down to up	$V_{LOF}$ to $V_2$	Weight when landing gear start to retract
2nd takeoff segment	TO	N-1	N	Takeoff	Up	$V_2$	Weight with landing gear fully retracted
Final takeoff segment	MCT	N-1	N	Takeoff	Up	$V_{FTO}$	Maximum takeoff weight limited by Gradient
Approach climb	GA	N-1	N	Approach	Up	Approach climb speed	Maximum landing weight limited by Gradient
Landing climb	8sGA	N	N	Landing	Down	$V_{REF}$	Maximum landing weight limited by Gradient

Note(i):N is the total number of aircraft engines;

Note(ii):TO is takeoff thrust, MCT is max continuous thrust, GA is go around thrust, 8sGA is 8 second go around;

Note(iii): $V_2$  is takeoff safety speed,  $V_{FTO}$  is final takeoff segment speed,  $V_{REF}$  is landing reference speed.

During the process of type certification, the flight test content can be set based on the above airworthiness regulations interpretation. Related flight tests can be conducted to obtain the aircraft's climb gradient. By comparing and analyzing the flight test results and the theoretical calculation model, it can be verified that the aircraft meets the requirements of the airworthiness clauses.

### 3. Climb Gradient Calculation Method

Performing force analysis on the process of climbing at a constant indicated airspeed for aircraft to obtain dynamic equations. By solving the kinematic equations, the climb gradient of the aircraft is obtained. When the aircraft climbs at a constant indicated airspeed, assuming that sideslip and roll are not considered<sup>[4]</sup>, the kinematic equations in the track direction and perpendicular to the track direction are as follows:

$$\begin{cases} \frac{W}{g} \frac{dV}{dt} = T \cos(\alpha + \varphi_T) - D - W \sin \gamma \\ \frac{W}{g} V \frac{d\gamma}{dt} = L + T \sin(\alpha + \varphi_T) - W \cos \gamma \end{cases} \quad (1)$$

Where T is trust, L is lift, D is drag, W is aircraft weight,  $\alpha$  is attack angle,  $\varphi_T$  is thrust deflection angle,  $\gamma$  is track angle, V is true airspeed, g is gravitational acceleration.

Derive formula (1) as follows:  $\frac{dV}{dt} = \frac{dV}{dh} \frac{dh}{dt}$ ,  $\frac{dh}{dt} = V \sin \gamma$ , where h is height. Assuming that  $\alpha$  and  $\gamma$  is small and remains basically unchanged, we get formula (2), Where  $1 + \frac{V}{g} \frac{dV}{dh}$  is acceleration factor.

$$\begin{cases} \sin \gamma = \frac{T \cos(\alpha + \varphi_r) - D}{W(1 + \frac{VdV}{gdh})} \\ \cos \gamma = \frac{L + T \sin(\alpha + \varphi_r)}{W} \end{cases} \quad (2)$$

Under known the flight speed and altitude conditions, the lift and drag are related to the angle of attack. The constant indicated airspeed climb gradient of an aircraft can be obtained by solving formula (2) using the exhaustive method. Select the angle of attack according to a certain step size, calculate the lift and drag based on the angle of attack, and substitute them into formula (2) to calculate  $\sin \gamma$  and  $\cos \gamma$  separately. When the two satisfy the relationship in formula (3), the corresponding angle of attack is the desired one. After obtaining the angle of attack, the aircraft's climb gradient  $G_c$  can be solved according to formula (4).

$$\begin{cases} \sin^2 \gamma + \cos^2 \gamma = 1 \\ 0 \leq \sin \gamma \leq 1 \\ 0 \leq \cos \gamma \leq 1 \end{cases} \quad (3)$$

$$G_c = \tan \gamma \quad (4)$$

## 4. Climbing Performance Flight Test

### 4.1 Flight Test Method

The climbing performance flight test generally include two methods: level acceleration<sup>[5]</sup> and sawtooth climb. For the level acceleration method, multiple climbing performance parameters can be obtained at various speeds throughout a single acceleration process, making the test highly efficient. However, due to the rapid acceleration process, flight test data requires filtering and smoothing, slightly reducing data reliability. On the other hand, the sawtooth climb method requires a separate climbing flight test for each speed and altitude combination, resulting in a longer test duration. Nonetheless, this method simplifies data processing as flight test data does not need filtering or other treatments.

In this article, the adopted flight test method is the forward and reverse heading sawtooth climb, aiming to eliminate the influence of wind gradient on the climb gradient. During the climbing process, the aircraft climbs as perpendicularly as possible to the direction of the wind. The specific flight test steps are as follows:

- (i) The test is performed with the air conditioning system ON;
- (ii) Establish a constant speed steady straight climb state with given flap/slat configuration and engine state in Table 2, starting from 600~1000ft below the target test altitude. Maintain it until to 600~1000ft above the target test altitude. Make sure that the engine has a stable state during climbing;
- (iii) Repeat the test in opposite heading to eliminate the influence of the wind speed.

### 4.2 Flight Test Conditions

For transport category aircraft, in order to obtain flight test data recognized by the Civil Aviation Administration, airspeed calibration and flight thrust determination flight test are usually completed before climb flight test to obtain accurate aircraft speed and engine thrust.

Climbing flight test is required to be carried out in the forward limit of gravity center. Generally, a gravity center adjustment system will be installed on the aircraft for real-time adjustment.

It is recommended that climbing flight test be conducted in an airspace with stable airflow<sup>[6]</sup>, no turbulence, and no obvious wind gradient, in order to obtain better flight test data.

### 4.3 Flight Test Risk Assessment

The main risks of climbing performance flight test are stall, single engine failure, and double engine failure. The main risk mitigation measures are as follows:

- (i) Conduct simulator drills before the test;
- (ii) Complete the evaluation of the minimum control speed before the test, and complete prerequisite flight tests such as stall speed flight test and engine starting flight test;
- (iii) Be familiar with the surrounding obstacles in the airspace, and try to choose an airspace with lower obstacles for testing;
- (iv) Carry out the test step by step, first conduct high-altitude, high-speed climbing tests, and then conduct low-altitude, low-speed climbing tests;
- (v) During the test, gently control the aircraft throttle lever and rudder input;
- (vi) During the test, pay attention to airflow turbulence;
- (vii) During the test, the ground monitoring focuses on the angle of attack and engine-related parameters;
- (viii) APU is in working condition during the test;
- (ix) Before the critical engine is shut down, put the ignition start switch of the other engine in the "CONT" position.

## 5. Flight Test Data Analysis

### 5.1 Flight Test Data Analysis Method

Climbing performance flight test data analysis aims to obtain the climb gradient through flight test data. It involves calculating the climb rate based on the time history curve of altitude and then determining the climb gradient based on true airspeed and climb rate. The specific steps are as follows:

- (i) Analyze and select flight test data from the stable climbing segment, ensuring that the calibrated airspeed fluctuation is within  $\pm 3\text{kn}$ , the allowable deviation for both forward and reverse headings is  $\pm 5^\circ$ , the engine thrust is stable at the target thrust level, the fuel flow rate of the shut-down engine is zero, and the average heights of the selected segments for both forward and reverse headings remain consistent;
- (ii) Use formula (5) to calculate climb rate through altitude, where  $\Delta H$  is altitude,  $\Delta t$  is time,  $V_y$  is climb rate.

$$V_y = \frac{\Delta H}{\Delta t} \quad (5)$$

- (iii) Use formula (6) to calculate climb gradient through climb rate and true airspeed, where VT is true airspeed.

$$G_c = \frac{|V_y|}{\sqrt{V_T^2 - V_y^2}} * 100\% \quad (6)$$

- (iv) Take the average of the climb gradients in both forward and reverse headings.

### 5.2 Flight Test Result Analysis

Taking a certain large aircraft as an example, the comparison between the theoretically calculated climb gradient and the flight test results is shown in the Figure 1.

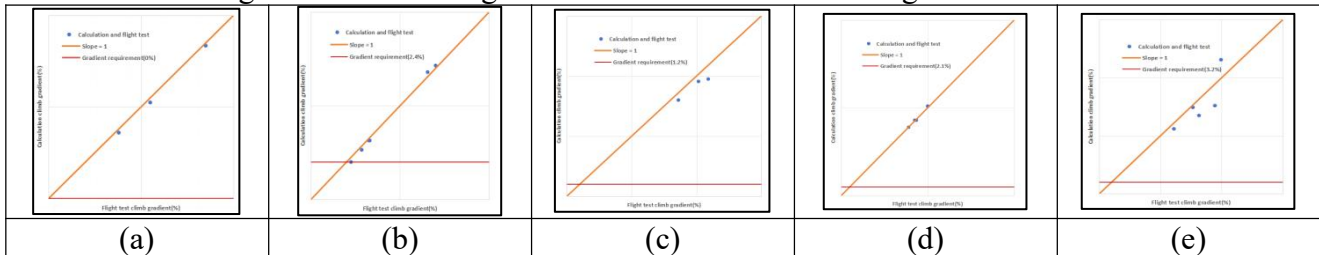


Fig. 1 Climb gradient: (a) 1st takeoff segment, (b) 2nd takeoff segment, (c) final takeoff segment (d) approach climb, (e) landing climb.

From the calculation and flight test results of climb gradient in the figure, it can be concluded that: the aircraft climb gradient meets the requirements of airworthiness regulations; the calculation results of climb gradient are basically consistent with the flight test results, and the climbing performance calculation model can be used for climbing performance calculations.

## 6. Summary

The paper analyzes the dynamic process of aircraft climb through force analysis, and designs a exhaustive method for climb gradient calculation during constant airspeed climb. Meanwhile, the paper studies the airworthiness regulations related to climbing performance in CCAR25, and designs and summarizes the forward and reverse heading sawtooth climb flight test method, flight test conditions, flight test risk assessments, and flight test data analysis method for the climbing performance of transport aircraft. Finally, by comparing the calculation results of the climb gradient with the flight test results, it is proved that the aircraft meets the airworthiness requirements and the climb performance calculation model is reliable.

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