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The Research on Net Takeoff Flight Path Calculation Method Based on Gross Flight Path Under Complicated Condition

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Abstract. In the operations at high elevation/complex terrain airport, to comply with the one engine inoperative take off flight path obstacle clearance requirement, the whole net takeoff flight path which often last over hundreds of kilometers need to be constructed, the key segment is the net third segment. At present, the manufacture's performance software, include Boeing and Airbus, can only export the net third segment data in standard second segment and straight out departure condition. for more complicated operation condition, such as extended second segment, turn and its mix departure, it has not net third segment data. In this paper, a new climb gradient acceleration rate method to calculate the net third segment is proposed, which is based on the gross flight path data calculated by manufacture's trajectory simulation performance software, and can handles the complicated operation conditions mentioned early. Take B737-700 for example, the different result are compared using manufacture's performance software, a simplified method and the new climb gradient acceleration rate method. The results show the new method has better precision than existing simplified method, and can show the regulation compliance in the one engine inoperative take off under complicated operation.

Keywords: Air transportation · Take off flight path · Performance software · EOSID · Takeoff analysis · Flight performance

1 Introduction

FAR 25/121 regulations [1] require, in one engine inoperation take off, when aircraft follows SID (standard instrument departure procedure), or EOSID (engine out standard instrument departure procedure), the net takeoff flight path should meet the 35/50ft obstacle clearance. In high altitude/complex terrain airport operation, the work to show this rule compliance is often the most workload and the most complicated part of the operational performance [2, 3].

In normal airports, it is enough for the net takeoff flight path to clear the obstacles in the first and second segments, and the typical flight distance is about 12–30 km. However, in high altitude/complex terrain airports located in western China, the takeoff flight distance need to consider obstacle clearance often extend to the order of 100 km

Proceedings of the 5th China Aeronautical Science and Technology Conference, LNEE 821, pp. 854–860, 2022.
https://doi.org/10.1007/978-981-16-7423-5_85

or even 200 km, and a large number of obstacles need to be cleared in the 3rd and 4th net takeoff flight path. Only after the determination of the 3rd net segment length, the 4th net takeoff flight path can be constructed.

At present, the manufacture performance software including Boeing and Airbus, such as BPS and TLO, only export the 3rd net segment length in standard 2nd segment and straight departure. Once deviate from this condition, there is no 3rd net segment data in the result. In the actual operation, it is often necessary to calculate the 3rd net segment length in extended 2nd segment, 3rd segment with MCT (Maximum Continuous Thrust), 3rd segment with turn flight, and the multiple combinations of these cases, in which the manufacturer's performance software cannot solve this problem. In current civil aviation practice, there exist several methods dealing this problem: some use the simplified algorithm below; some even use a fixed net /gross distance ratio multiplication, which are obvious incorrect. This is a must be solved problem in high altitude/complex terrain airport operation, especially in EOSID, RNP AR EOSID, and SID procedure design.

2 Regulation Requirement

Takeoff flight path (FAR 25.111) is a concept corresponding to One Engine Inoperation takeoff. Start from 35ft point above the runway, and is divided into 4 segments (FAR 25.121), as shown in Fig. 1:

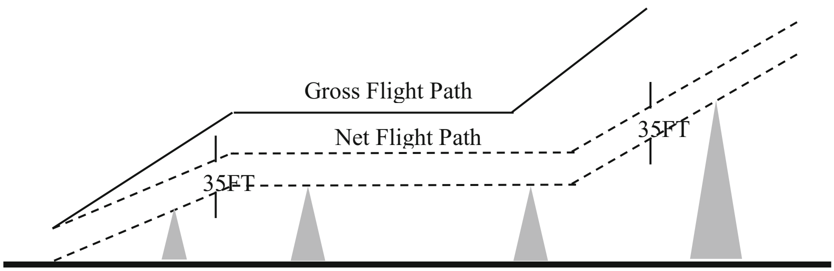

Fig. 1. Takeoff flight gross, net path 4 segment and obstacle clear requirement

In the 1st and 2nd segment, the engine thrust is in TOGA, climbs at a constant indicated speed V2. In the 3rd segment, the aircraft level off to accelerate to a clean configuration and VFTO speed. If the 3rd end within TOGA time limit (usual 5 or 10 min), it is called the standard 2nd segment; otherwise, it is called the extended 2nd segment. in latter case, the part or whole of 3rd segment is under MCT thrust, which is smaller than TOGA. The 4th segment is a constant indicated speed climb in clean configuration with MCT thrust.

The Gross take off flight path minus 0.8% (for twin-engine) gradient, we get the Net take off flight path. Regulations (FAR 121.189) require that the net take off flight path must clear all obstacle along this path by at least 35ft (straight departure) and 50ft (turn departure). Regulation (FAR 25.111) also requires that from 400ft above the take-off surface, the available climb gradient at each point of gross flight path shall not be less than 1.2% (for twin-engine). This available climb gradient can be converted into acceleration capability. Since the available climb gradient of the Net flight path is 0.8% lower than the Gross flight path, the length of the Net 3rd segment is longer than Gross 3rd seegment.

3 Net 3rd Length Calculation

The length of the Net 3rd Segment depends on the Gross 3rd available climb gradient. The extended 2nd segment, turn flight in 3rd will all result in a decrease of Gross 3rd available climb gradient, and lead to the increase of Net 3rd segment.

3.1 Simplified Method

The algorithm needs to know the Gross 3rd length and the Gross gradient [7].

In this method, the Net 3rd segments is composed of L1 and L2 as shown in the figure below. The L1 length is the same as Gross 3rd segment, and the sinking amount is the gradient difference of 0.8%; L2 is determined by the Gross 3rd length and the Gross 4th gradient. The Net 3rd length is the sum of L1 and L2 (Fig. 2).

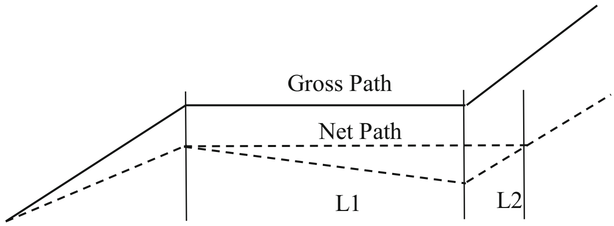

Fig. 2. The simplified method to calculate 3^{rd} net flight path.

According to the definition of net flight path, the 3rd segment length has nothing to do with the 4th Gross climb gradient. Therefore, this simplified algorithm has natural errors. This method has been used in many actual operation cases, but its accuracy has not been evaluated thoroughly.

3.2 Climb Gradient Acceleration Algorithm

This is the method based on definition and used in this paper (hereinafter referred to as the new algorithm). The motion equation of aircraft when in climbs is:

$$T - D - W \cdot \sin\gamma = W/g \cdot dv/dt \quad (1)$$

$$\sin\gamma = (T - D)/W - 1/g \cdot dv/dt \quad (2)$$

In the formula, T,W,v,γ are thrust, gravity, speed and climb angle respectively. When all thrust is used for climbing, that is, when dv/dt is zero, the maximum available climb angle can be determined by the following formula:

$$\sin\gamma\_available = (T - D)/W \tag{3}$$

If the climb angle with accelerates is called the residual climb angle, then the Eq. (2) becomes:

$$\sin\gamma\_residual = \sin\gamma\_available - 1/g \cdot dv/dt \tag{4}$$

For a small climb angle, $\sin\gamma = \tan\gamma = ROC/100$, the Eq. (3) becomes:

$$grad\_residual = grad\_available - 100 \cdot a/g \tag{5}$$

Therefore, in 3rd segment, the aircraft uses all its energy for climb (to maintain a constant true air speed), corresponding to an available climb gradient (must be greater than or equal to 1.2% for twin engine); this available climb gradient minus 0.8% (twin-engine) is the total remaining energy, that energy is used for the Net 3rd segment acceleration. In the end, we can get the Net 3rd length is:

$$L\_n = (a\_g \cdot L\_g/g)/(2 \cdot a\_g/g - grad\_net - grad\_bank) \tag{6}$$

This algorithm based on the definition of the net flight path. It can handle the 3rd segment using MCT thrust, turning flight in 3rd segment and all its combination. when Gross flight path is calculated from manufacturer's trajectory performance software, the whole Net flight path can be constructed.

4 Example – Standard 2nd Straight Departure

In this case, the manufacturer's performance software can calculate the 3rd Net length. Using this data as a benchmark to compare and verify the accuracy of the previous mentioned two algorithms.

4.1 Manufacturer's Performance Software

Ex1: B737–700/CFM-7B24 aircraft, structural weight 69399 kg, Flap 1, A/C Auto, A/I Off. airport elevation 411 m, runway 3200m, temperature 32 degrees Celsius, calm wind, standard sea level pressure, and no obstacles.

Calculated by Boeing software BPS: MTOW = 69399 kg, the std 2nd max level off height is 293 m, net level off height is 200 m, V2 = 148kt, VFTO = 215kt, OEI takeoff distance is 2440 m. The gross climb gradient in 2nd and 4th segments are 2.5/3.3 respectively. TOGA time limit is 5 min. The calculated takeoff flight path data is shown in Table 1.

Ex2: A320–214/CFM56-5B4 aircraft, structural weight 77000 kg, CONF1 + F, A/C Auto, A/I Off. airport elevation 2243 m, runway 3000 m, temperature 25 °C, calm wind, standard sea level pressure, 2 obstacles: the distance and height relative to DER are: 8800/252, 17900/392, unit meters.

Calculated by Airbus software TLO: MTOW = 66700 kg, the std 2nd max level off height is 1237 m, net level off height is 936 m, V2 = 153kt, VFTO = 217kt, OEI takeoff distance is 2999 m. The gross climb gradients in 2nd and 4th segments are 3.93/1.76 respectively. TOGA time limit is 10 min. The calculated takeoff flight path data is shown in Table 1.

Table 1. Manufacture's Perf. software OEI takeoff flight path (as benchmark)

	1 + 2 seg len	3rd Gross Len	3rd Net Len
B737 Ex1	11726	10621	13632
A320 Ex2	37639	13669	17522

4.2 Simplified Method and Climb Gradient Acceleration Algorithm

Simplified algorithm and new algorithm, under the same calculation example conditions, the result of the Net 3rd segment is shown in Table 2.

It can be seen that, compared with the 4.1 benchmark data, the new algorithm has good results for both examples, and the deviation is less than 1%. The simplified algorithm shows a large deviation up to 43% in Ex2, makes the results unreliable in some case. The reason is: Compared with Boeing, Airbus models generally have a smaller climb gradient in 4th segment.

Table 2. Two algorithms vs. manufacturer's perf. software results: the 3rd seg. net length

	benchmark	Simplified	Dev %	New	Dev %
B737 Exam.1	13632	14021	+2.8%	13704	+0.5%
A320 Exam.2	17522	25065	+43%	17658	+0.8%

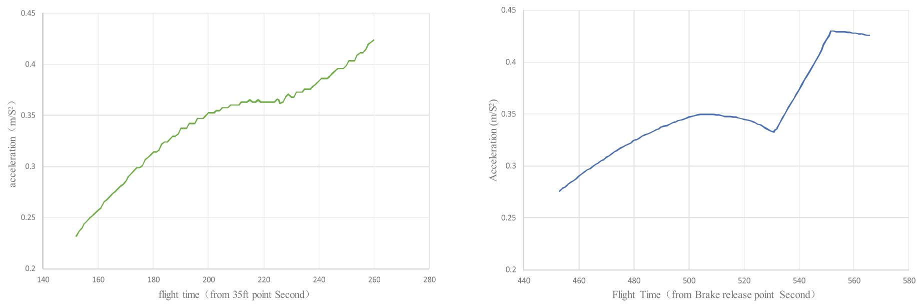

Fig. 3. The actual acceleration at each point of the 3rd gross seg. (Left B737, Right A320).

In Table 2, the new algorithm treats the third segment as a whole and calculates the average acceleration between its start and end points. However, the actual acceleration at each point of the gross 3rd segment is not the same and depend on aircraft model, as showed in Fig. 3.

Further calculation shows that the start-end 2 point average acceleration of the B737 is 0.016% lower than the each point average acceleration; the A320 is 0.059% lower. so Table 2 new algorithm result is a lit bit longer than actual 3rd net length. In fact, by comparing the acceleration used in new algorithm to the each point actual acceleration, the results accuracy of the new algorithm can be evaluated. This is very important in case of no benchmark like in next section.

5 Example – Extended 2nd Turn Departure

In this case, the manufacturer's performance software does not export 3rd net length data.

Base on the Gross flight path data derived from the manufacturer's trajectory performance software, the Net 3rd flight path data under complex condition is calculated. The gross 3rd segment used like this: accelerated under MCT, and is divided into 3 sections: a, straight flight + b, 15° bank angle 90° turn + c. straight flight. Using the new algorithm, each section uses each point actual average acceleration, considering the actual turn gradient loss, to calculate the 3rd net segment length.

B737-700 aircraft, 411 m elevation airport, extended 2nd max level off height is 474 m, turning gradient loss 0.32%, other conditions are the same as in Ex1. The 3 section data in 3rd segment and the calculated 3rd net length are shown in Table 3.

Table 3. new algorithms vs. manufacturer's perf. software results: the 3rd seg. net length.

3rd Gross Len	a. Straight		b. Turn		c. Straight		3rd Net Len
	len	Start/End IAS	Len	Start/End IAS	Len	Start/End IAS	
14368	5078	148/169	5979	169/195	3311	195/211	23968

The actual each point average acceleration used in each 3 section are: 0.1988, 0.2394, 0.3061. Because the gross available climb gradient 3rd segment is relatively small, the net 3rd length is much longer than normal, in this case, net is 1.668 times the gross length.

6 Conclusions

It can be seen that the simplified algorithm has natural defects and is not suitable for use in operational performance. The climbing gradient acceleration algorithm proposed in this paper has satisfactory accuracy, can handle any complex combination encountered in EOSID, RNP AR EOSID procedure design, and the accuracy of its results can be self-evaluated. It has special important value in those high altitude/complex terrain airport operation of china's south western and Tibet region.

Acknowledgements. This study was co-supported by: Key Laboratory of Flight Techniques and Flight Safety, CAAC, (No. FZ2020ZZ03), Civil Aviation Safety Foundation of CAAC (No. AS2016/11).

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