Sensitivity Analysis of Aircraft Design Service Goal to Expected Operation Route

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Abstract. The design service goal of commercial aircraft is defined by flight cycles, flight hours and calendar years, which affects aircraft structure weight, maintenance interval and operation economy. The design service goal is closely related to expected operation route. Two methods are applied to calculate three lengths of anticipated flights, including short, medium and long flight. Criterion of utilization rate and minimum design service goal are used to calculate flight cycles and flight hours. Sensitivity analysis of aircraft design service goal in regard to expected operation route shows that flight cycles depend on short flight and flight hours depend on long flight. Shorter route distance leads to larger flight cycles and more significant change per unit of route distance. Longer route distance leads to larger flight hours and there exists an approximately linear relation.

1. Introduction
Commercial aircraft is a product which should be developed to comply with both customer and airworthiness requirements for the purpose of improving operation economy and operator profitability. Aircraft life limit is one of the most important characteristics of aircraft competitiveness and economy. To equally distribute acquisition cost during period of in-service, it is more desirable to have a longer aircraft lifespan for operators [1]. In design phase, design service goal is often used to indicate aircraft life.

Design service goal means a period of service during which primary structure is designed to be essentially free of detectable fatigue cracks, with a high degree of reliability and confidence [2]. It is usually defined as flight cycles, flight hours and calendar years. It is not directly tied to structural airworthiness but is a crucial requirement for aircraft fatigue design, as it affects structure weight and maintenance intervals. It is apparent that larger design service goal represents stronger and more durable structure. In this case the structure maintenance interval can be longer and consequently maintenance cost is lower. However, larger design service goal leads to heavier operating weight, which makes operation cost higher. Therefore, it is a kind of trade-off study to determine an appropriate design service goal.

Actually, design service goal is closely related to aircraft expected operation, especially the distribution of anticipated route distance. According to primary target market and corresponding statistical route data, expected operation of a new aircraft can be divided into short, medium and long flight, based on certain percentages. Fatigue design should comprehensively consider the difference of the above three kinds of flights.
Design service goal should be taken into consideration at the very beginning of a new aircraft development phase. Tang [3] proposed a method to determine minimum design service goal based on market study and anticipated market. Zhang [4] studied design service goal considering the tendency of aircraft retirement age and typical flight route. Wang [5] analyzed the route distribution in different markets, and concluded that it is more reasonable to focus on target market and exclude the route data in non-target market.

Considering the expected operation is very necessary to determine the design service goal, this paper aims to put forward the relation between aircraft design service goal and expected operation route. Sensitivity of flight cycles to short flight length, and flight hours to long flight length are analyzed.

2. Calculation of flight length

Flight length, which means the period of time from aircraft take-off to landing on the ground, should be clarified firstly when calculating the design service goal. Two methods are applied to divide the expected operation into short, medium and long flight. The first method is based on experience and the second is based on market data.

2.1. Experience based

Commercial flights are often categorized into short-, medium- or long-haul based on flight length. Short-haul represents short flight length and more frequent take-offs and landings, while long-haul represents long flight length and less frequent take-offs and landings. Medium-haul always represents flights in between.

Medium flight length should be determined by the market positioning of new aircraft. While short flight length is linearly related with medium flight length, and can be calculated by using the following empirical formula [4].

\[ h_{\text{short}} = 0.34 + \alpha \times h_{\text{medium}} \]  

(1)

In the formula, \( \alpha \) is equal to 0.46 for single-aisle narrow-body aircraft, and 0.4 ~ 0.6 for twin-aisle wide-body aircraft.

Long flight length depends on maximum flight duration. Considering the influences of wind, alternate diversion distance and reserve fuel, long flight length can be obtained by the following formula [4].

\[ h_{\text{long}} = 0.75 \times h_{\text{max}} \]  

(2)

Besides, \( h_{\text{max}} \) means the maximum flight duration.

The above formulas are universal experience to calculate the three typical flight lengths. However, for a new aircraft that mainly focused on specific markets, it is more appropriate to analyze the flight length based on the distribution of expected operation route.

2.2. Market data based

Generally, short, medium and long flight route are classified by a suitable combination of percentages of anticipated flights, within the aircraft design range. The combination of percentages should be matched with aircraft development purpose and its market forecast.

Take wide-body commercial aircraft as an example, figure 1 shows the distribution of global flight frequency and corresponding route distance in the year of 2017. The route distance in the figure is marked each 1000km as an interval. Actually, smaller interval is more helpful for analysis. The roughly domain for short, medium and long flights are also shown in the figure. It should be noted that the route distance in the figure is great-circle distance. Considering the factor of wind, actual route distance is about 5% ~ 10% larger than great-circle distance [4].

According to the distribution of global flight frequency and aircraft market positioning, expected operation areas and corresponding statistical data are screened out to calculate the distances of short, medium and long flight.
Figure 1. Distribution of flight frequency and distance in the year of 2017 (wide-body aircraft)

\[ L_{\text{short}} = \frac{\sum_{i=N_1}^{N} (D_i \times F_i)}{\sum_{i=N_1}^{N} (F_i)} \]

\[ L_{\text{medium}} = \frac{\sum_{i=N_2}^{N} (D_i \times F_i)}{\sum_{i=N_2}^{N} (F_i)} \]

\[ L_{\text{long}} = \frac{\sum_{i=N_3}^{N} (D_i \times F_i)}{\sum_{i=N_3}^{N} (F_i)} \]

\[ N_1 + N_2 + N_3 = 1 \]

Among them, \( N_1, N_2 \) and \( N_3 \) imply percentage of short, medium and long flight route, respectively. \( N \) represents total frequency of whole flights. \( D_i \) and \( F_i \) mean the distance and frequency of the \( i \)-th flight route. Different combination of \( N_1, N_2 \) and \( N_3 \) results in different combination of short, medium and long route distance. The optimal combination of the above three percentages should be nicely matched with aircraft expected operation.

Time for ground taxiing is not included in flight length, which mainly depends on cruise speed, route distance, and climb & descent strategy. Under a fixed cruise speed and flight profile, the relation between flight length and route distance is shown in figure 2 and there exists a good linear relation [3]. On the basis of figure 2, short, medium and long flight length can be obtained according to above three route distances.

Figure 2. Relation between flight length and route distance

Figure 3. Relation between flight length and utilization rate

3. Calculation of Design Service Goal

3.1. Criterion of Utilization Rate

Utilization rate per day means average flight hours in a single day. It directly ties to flight length, as shorter flight length leads to more take-offs and landings each day, and then more time for engine start,
pre-flight inspection, aircraft turn around service and ground taxiing. In this case, utilization rate is lower. Based on historical statistics, relation between utilization rate and flight length is shown in figure 3 [4]. However, as more and more point-to-point long-haul routes are planned, also as the continuous improvement of airline operation efficiency, utilization rate tends to increase gradually. For a new aircraft, expected utilization rate could be a bit higher than data in figure 3.

The relation in the figure 3 can be expressed as:

\[ h = 0.0025H^3 + 0.051H^2 - 0.5068H + 1.3377 \]  

(7)

According to utilization rate and flight length, flight cycles and flight hours in a certain calendar year can be calculated by the following formulas.

\[ \text{FlightCycles} = \frac{H}{h} \times 365 \times Y \]  

(8)

\[ \text{FlightHours} = \text{FlightCycles} \times h \]  

(9)

Besides, \( Y \) means calendar year. The current generation of civil transport aircrafts is designed for at least 20 to 25 years [4].

3.2. Criterion of Minimum Design Service Goal

The relation between flight length and minimum design service goal had been already proposed, as shown in figure 4 [3-4]. It should be noted that the curve in the figure is only used to determine flight cycles within 20 calendar years. Actually, this design service goal is often exceeded by many operators of commercial aircrafts, so criterion of minimum design service goal is conservative.

![Figure 4. Minimum design service goal](image)

The fitting equation for the solid segment in figure 4 is:

\[ \log(\text{FlightCycles}) = 4.7 - 0.74 \log h \]  

(10)

It can be concluded that, the design service goal obtained from criterion of minimum design service goal are almost the same with result from criterion of utilization rate (when \( Y \) is equal to twenty calendar years).

4. Sensitivity Analysis to Expected Operation Route

Flight cycles mainly depend on short-haul flight while flight hours depend on long-haul flight. Their relations are shown in figure 5 and figure 6.

Shorter route distance leads to larger flight cycles and more significant change per unit of route distance. As the increase of route distance, flight cycles appear to be very little change. Flight cycles
have great influence on aircraft primary structure, propulsion system and landing gear, so it is quite critical to determine the typical short flight route.

Flight hours affect the life limitation of onboard systems like fly control actuators, hydraulic components, cabin air-conditioner system and so on. It is apparent that longer route distance leads to larger flight hours, and the calculation result shows an approximately linear relation.

![Figure 5. Relation between flight cycles and route distance](image)

![Figure 6. Relation between flight hours and route distance](image)

5. Conclusions
Two methods are applied to calculate three typical lengths of anticipated flight, including short, medium and long flight. The first method is based on experience and the second is based on market data. Criterion of utilization rate and minimum design service goal are used to calculate flight cycles and flight hours. Sensitivity analysis of design service goal in regard to expected operation shows that flight cycles depend on short flight and flight hours depend on long flight. Shorter route distance leads to larger flight cycles and more significant change per unit of route distance. Longer route distance leads to larger flight hours and there exists an approximately linear relation.

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