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SYNTHESIZED ANALYSIS FROM DESIGN RANGE TO THE CONCETUAL DESIGN OF WIDEBODY AIRLINER

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Abstract

The Seat number and design range is the key parameter of a civilian airliner, and the direct reflection of market orientation. The current global wide-body airliner market is dominated by Boeing and Airbus companies. Both the two companies have settled the new generation of wide-body aircraft as a remote type, the controversy of the development of medium and short range wide-body aircraft has never stopped. As Airbus has launched the project of A330 regional, the advantages and profit of medium and short range wide-body aircraft become hotly debated. In view of this, this paper selected 300 seats level wide-body aircraft, from 6000 km to 15000 km design range, to analyze the combined impact from design range to the overall conceptual design, including wing parameters, aerodynamic performance, characteristic weights, fuel efficiency and the operating cost. Finally this paper aimed to conclude the benefit and losses due to range reduction, focused in technical prospective.

1 Issue of short-range wide-body airliner

Currently the global wide-body airliner market is monopolized by Boeing and Airbus Company. Wide-body airliner has a wide scope of design range, the representative new generation of wide-body airliner is 787 and A350XWB, both range has reached or more than 14000 km, now the mainstream products represented by A330 and 777, the design range of standard type is about 10000 ~ 11000 km, the design range of remote type is about 13000 ~ 14000 km. However, according to a research report released by the authoritative global air data information management company OAG, as shown in Table1, more than 95% of the global routes distance are less than 10000 km, In addition, the rapid development of current Asia-Pacific aviation market, makes the existing airports in this region tend to saturation, the future development of civil aviation industry is restricted by the limited airspace and airport congestion, the shortage of pilots and other factors has become more and more serious, more and more airlines use wide-body aircrafts to operate flight routes within 6000 km, in order to allow fewer flights carry more passengers.

Table 1 Route distance of global airliner [1]

Airliner Location	<9,000/km	<10,000/km	<12,000/km
China	87%	95%	99%
Asia Pacific	91%	95%	99%
Russia	95%	99%	100%
Europe	86%	96%	100%
Latin America	92%	97%	99%
Middle East	96%	97%	99%
North America	91%	93%	98%

2 Problem analysis and simplification

Range and seat number directly affect the wing design and engine choice, thereby have impact on the aerodynamic efficiency, operating empty weight, engine specific fuel consumption etc., and ultimately affect the block fuel consumption and the operating cost. According to the latest released market forecast report of 2015-2034 from Commercial Aircraft Corporation of China, the target market of wide-body aircraft seat number demand concentrated in 250-300 seats. The main purpose is to study the effect from design range to aircraft conceptual design, so a specific seat number is selected to simply the issue, then the size and shape of the fuselage is determined.

Another three assumptions were made to simplify the problem further. The first assumption is the most simple one, aircraft wing and engine remain unchanged with variation of design range; The second hypothesis is wing area and takeoff thrust to weight ratio remain unchanged remained unchanged with variation of range; The third hypothesis is wing and engine are optimized with variation of design range; Mach number and the wing shape of the plane keep constant. The first two assumptions are relatively simple, based on a certain type of 250 seats aircraft, the third assumption is most reasonable, based on a certain type of 300 seats aircraft concept.

3 Design range analysis

3.1 Design Weight analysis

The influence form design range to aircraft weight is mainly reflected in the maximum takeoff weight and operating empty weight, MTOW means maximum takeoff weight, OEW means operating empty weight. As shown in the figure 1, both MTOW and OEW decreased more or less linearly with the variation of range, but the takeoff weight decreased greatly, mainly due to the reduction of fuel.

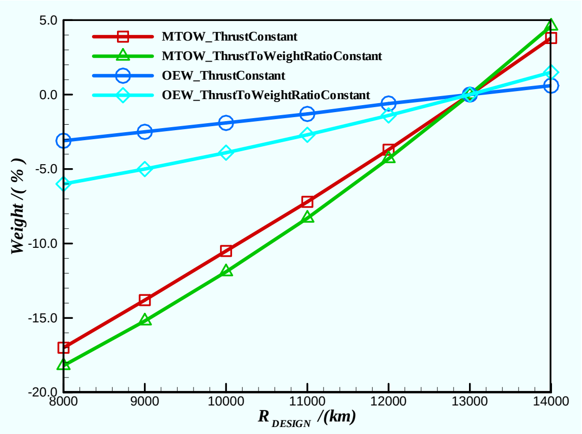

Fig. 1 Design weight variation with range

First of all, the wing area of different range is the same, the weight of the wing structure reduced with a shorter range. In takeoff thrust constant condition, the weight of the engine does not change, in condition of takeoff thrust to weight ratio invariant, the takeoff thrust with shorter range decreased, the weight of the engine also reduced with the thrust alleviation, so OEW reduced more than the engine constant condition.

3.2 Lift to drag analysis

The aircraft weights of the first two assumptions decrease with range reduction, while the reference wing area remains constant, the average lift coefficient of the cruise segment decreased. In addition, the average cruising altitude also has a direct impact on the average lift coefficient, which is determined by the initial cruising altitude and the distance of the cruising segment. Cruising altitude cannot be changed freely between 29000ft~41000ft according to the RVSM [2] standard, the initial cruising altitude is determined by the engine thrust. Therefore, the average lift coefficient of cruise varies with the change of the range and there is a sharp change. As shown in Figure 2, in engine unchanged conditions, cruising altitude keep constant with range equal or below 12000 km, cruising lift coefficient decreases linearly with the range reduction, cruising altitude reduced with range more than 12000 km, the cruise lift coefficient is offset to some extent; In thrust to weight ratio invariant conditions, the engine thrust with the range change apparently, cruising altitude unchanged with a range of more than 10000 km, the lift coefficient change linearly with range below 10000 km, the lift coefficient shift downward with the lack of engine thrust and the reduction cruising altitude.

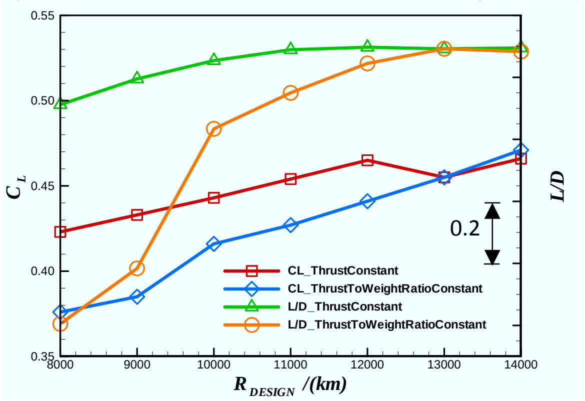

Fig. 2 Variation of cruise CL&L/D with range

According to the drag polar curve [3], the optimum cruising lift drag ratio corresponds to lift coefficient between 0.45~0.48. Engine unchanged, range higher than 11000 km, cruising lift to drag ratio maintain a high level, whereas decreased slightly with the range reduction. And constant thrust to weight ratio, lift to drag ratio decreases rapidly with shorter range, especially the range below 10000 km, the lift to drag ratio decreased very obviously, which will increase seriously the cruise fuel consumption.

3.3 Engine SFC analysis

In addition to lift to drag ratio, engine fuel consumption rate has a direct impact on the cruise fuel consumption. Generally speaking, the SFC is determined by the engine technology level and also influenced by thrust ratio in the same cruise condition. Thrust ratio means the ratio between the needed cruise thrust and the maximum cruise thrust. In condition of engine constant, this ratio decreases with range reduction. In condition of take off thrust to weight ratio constant, this ratio increases with range reduction. Generally speaking, the ratio between 80%~90% will have the minimum SFC; the other parts have a slightly higher SFC.

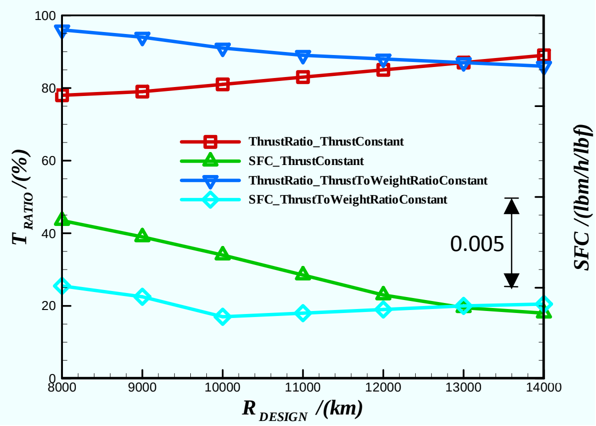

Fig. 3 Variation of cruise thrust point & *SFC* with range

As shown in Figure 3, SFC changes little in condition of thrust to weight ratio constant, SFC varies relatively large with the range in engine constant condition. However, the maximum deviation is less than 1%. Thus thrust ratio has certain effect of cruise SFC, but very slightly, the engine thrust have more influence on constraint performance, such as takeoff field length [4], second climb gradient, single engine ceiling and initial cruise altitude.

3.4 Block Fuel analysis

Along with the range reduction, OEW decreased, cruise lift to drag ratio decreased, cruise SFC increased, the three factors have a direct impact on the block fuel and their total effect is that block fuel decreases with the range reduction, but the reduced amplitude is limited. Make 13000 km as the benchmark, and 3500 nm is a typical route distance. Figure 4 shows block fuel varies with the changes of design range. In engine constant condition, block fuel reduced with shorter range to a lesser extent, block fuel consumption is decreased only about 1% from 13000 km to 11000 km; in thrust to weight ratio constant condition, block fuel decreased more obviously with range reduction, but when range below 10000 km, block fuel consumption is even increased. This is mainly due to the lower lift coefficient and lead to a decreased lift to drag ratio.

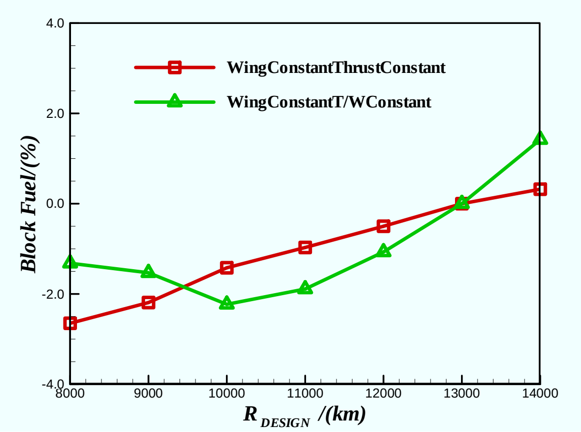

Fig. 4 Variation of typical route block fuel with range

4 Wing impact analysis

4.1 Wing area optimization

The cruise lift coefficient of the first two assumptions decreases with the range reduction, mainly due to the constant area of the wing. The more reasonable assumption is that the wing and the engine can change with the range, and the wing area is optimized for each design range. The law of the wing area variation with the range is the key to the study of the range. The selection of wing area is mainly determined by the balance between the aerodynamic and the weight, and considering other design constraints [5]. The lift of the aircraft is mainly generated by the wing, with the same fuselage, the larger the wing, the higher the proportion of the whole aircraft, the larger the lift drag ratio. At the same time, wing area is larger, heavier weight of wing structure, resulting in a heavier operating empty weight, making fuel consumption higher for specific payload and range. Therefore, there is a balance of wing area between aerodynamic and weight.

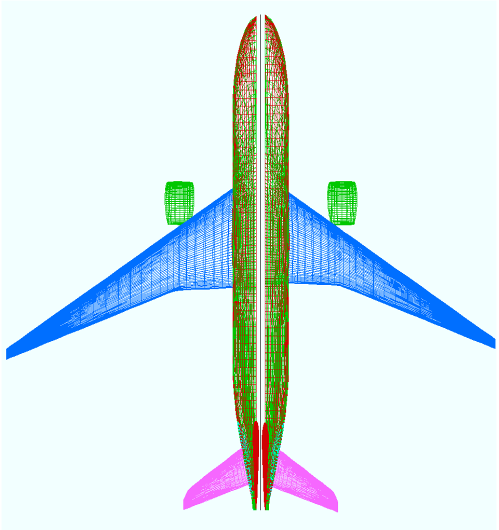

Fig. 5 Mesh model in aerodynamic model

The full aircraft lift to drag ratio is calculated by the aerodynamic model [6], the mesh model used is shown in Figure 5, left and right parts of the mesh model correspond to the wing of the larger and smaller wing, fuselage, tail, nacelle remained unchanged. The relative position of the wing and fuselage according to the average aerodynamic chord midpoint alignment, and consider the trimming of HTP, nacelle position relative to the wing remained unchanged.

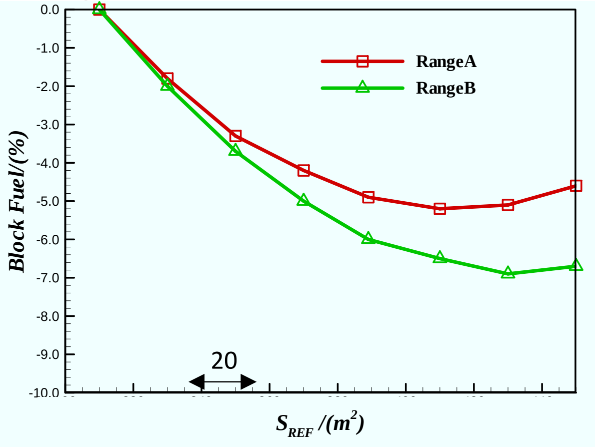

Fig. 6 Variation of block fuel with wing reference area

Block fuel reflects the combined influence of wing area to weight and aerodynamic. Under specific design range, the block fuel variation with wing area is calculated and shown in figure 6. Range A curve stands for a short range aircraft, Range B curve stands for a far range aircraft, both fuel consumption curves with wing area showed a spoon type change, the bottom of the region reflects weight and aerodynamic to achieve the optimum balance. At the left side of the bottom, the main impact is the aerodynamic, the right side of the bottom shows the main factor is weight. Far range aircraft have a right offset of bottom area, means that the optimum wing area will increase with bigger range.

Consider other performance and fuel consumption constraints [7], the optimum wing area is given for each design range, and the correspondent lift to drag ratio is calculated. Figure 7 shows the Wing reference area and lift to drag ratio variation with range.

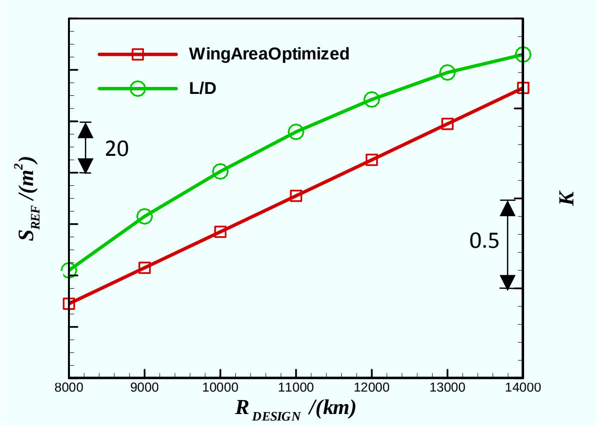

Fig. 7 wing reference area & L/D variation with range

4.2 Block Fuel analysis

According to the optimized wing area changes with range, the block fuel variation with range are compared under the three assumptions, Figure 8 shows that block fuel of aircraft with wing area optimized reduced most obviously, especially for range below 10000 km. wing area optimization make the block fuel consumption reduction trend continue. Overall, the block fuel decrease due to the range reduction is limited, compared with its loss of competence due to a shorten range. The total benefit could be very expensive.

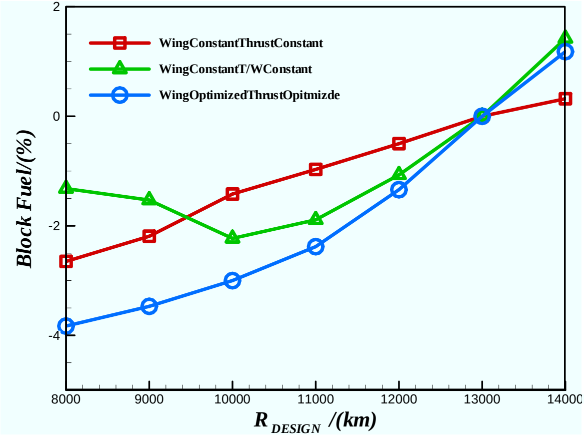

Fig. 8 Variation of block fuel with design range

4.3 DOC analysis

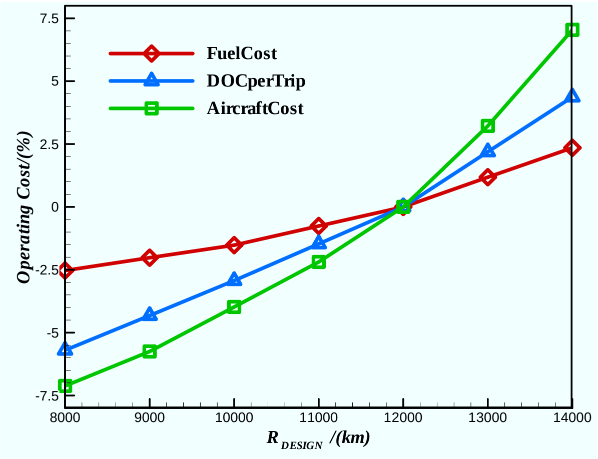

Fig. 9 Variation of operating cost with design range

Civil aircraft generally use direct operating cost as the final economy index, and the evaluation of DOC can be divided into three main parts: fuel costs, maintenance costs and other expenses, aircraft purchase or lease cost. Among them, the aircraft's price does not have universal pricing standards; different pricing strategies will have a greater difference to DOC. In this paper, the formula of aircraft price is calculated and analyzed by fitting the formula on the pricing rules which is proposed by Massachusetts Institute of Technology [8]:

$$Price = \left[k_1 \left(\frac{Seats}{Seats_{ref}} \right)^{\alpha} + k_2 \left(\frac{Range}{Range_{ref}} \right)^{\beta} \right] \times Price_{ref} \qquad (1)$$

k_1 is 0.8942 , α is 1.426 , k_2 is 0.1158 , β is 2.82. Figure 9 shows the variation of aircraft costs, fuel costs, and direct operating costs with range, the wings and engines of aircraft is under the optimized conditions. Aircraft cost decreased more apparently than fuel cost with range reduction. For 3500 nm typical route, DOC decrease amplitude lies between fuel cost and aircraft cost. Under the assumption of the price, DOC reduces by about 3% with the design range decrease 2000 km.

5 Conclusions

(1) Fix seat number and payload, MTOW and OEW decrease almost linearly with the reduction of range, while MTOW decrease more quickly. For a certain wide-body airliner concept design, MTOW decrease 3~4% per 1000km reduction of range, while OEW decrease around 1%;

(2) Fix seat number and payload, range reduction will cause the decrease of wing reference area, then the cruise lift to drag ratio will decrease, and the maximum lift coefficient need for high lift devices will increase, which will raise the difficult of low speed design. When wing reference area decrease, the cruise lift to drag ratio will accelerate to decrease, when wing area reduce relative small, the optimum lift to drag ratio will decrease by 2~3% with 10% reduction of wing area;

(3) Engine reference thrust is mainly determined by performance constraint, such like takeoff field length, one engine inoperative ceiling, second segment climb gradient, but it is necessary to consider the cruise requirement, such like initial cruise altitude, typical cruise altitude etc. Most engines will get the minimum cruise SFC when the ratio between actual cruise thrust and maximum cruise thrust is around 80~90%;

(4)For a certain concept of wide-body airliner, the reduction of range can decrease the block fuel consumption of typical route distance; however the fuel reduction extent is not big. According to different assumptions, a 2000km range reduction of an aircraft with 12000km range, the fuel consumption can decrease by 0.5~2%;

(5) Range reduction will decrease the ability of route coverage, and decrease the competence of

airliner. The reduction of wing area and engine thrust will limit the improve potential of the aircraft. Whether to reduce the range or not depends on the compromised consideration of gains and loss;

(6) In order to make a type of aircraft cover more civil aviation market, also to reduce the cost and risk of engineering development, the family or serial development of a aircraft should be taken into count during the overall design of aircraft concept. The baseline type should aimed to the primary targeting market, while more refined mark can be covered by shorten or extension of fuselage and range.

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