Paper
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Initial Configuration Layout Design for 95-Seat Regional Turboprop Aircraft

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Abstract

The initial configuration for 95-seat passenger regional turboprop aircraft, the so called KC950, was designed to meet the market requirements. This paper prescribes the initial design based upon aircraft design guidelines and compared the competitive aircraft configurations after considering the related FAR 25 regulations. More specifically, results of design describe how to select the fuselage cross-sectional area, how to layout the cabin, and how to determine the overall shape and physical dimension of the fuselage. Sizing of wing and empennage areas is estimated using empirical equations and tail volume coefficients in this design. Some design guidelines to determine wing sweep angle, taper ratio, incidence angle and location are also introduced.

Key words: Initial configuration design, regional turboprop

1. Introduction

Configuration layout design is the first step in an aircraft development. The basic geometry of the aircraft is determined throughout this work based on requirements from the market. This paper describes a design process of initial aircraft configuration layout and reviews the results of design based upon configuration design guide references, FAR 25 regulations and compared with other competitive aircrafts geometry such as Q400 and ATR 72. Figure 1 shows the overall shape of the 95-seat aircraft, the KC950.

The general procedure of the initial configuration layout design is as follows:

① Requirements definition
② Fuselage cross section layout
③ Fuselage plan view layout
④ Wing area sizing and plan view layout
⑤ Empennage area sizing and layout
⑥ Aircraft side/front/plan view layout

The design is initiated from aircraft top level requirements (TLARs) which are given by marketing and program management offices. Table 1 summarizes the key design features in TLARs for KC950 development. The cruise speed of the aircraft has a dominant effect on COC (Cash Operating Cost). If the speed goes up, the relative fuel consumption is also increased, results in an increase of COC. However to increase utilization of the aircraft and more turnaround, a high cruise speed is recommended.

This paper shows how to determine the overall fuselage shape, length, and wing and empennage configurations. The physical location of the wings and type of empennage are determined by observing the competitive aircrafts, such as

Fig. 1. 95-seat regional turboprop aircraft

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the Q400 and the ATR72, as well as comparing the pros and cons of different positions. Eventually KC950 adopts high wing configuration to ensure propeller protection and T-tail configuration to minimize the wake and propeller slipstream influences on the empennage.

Table 2 shows key features of the market dominant competitive aircrafts. These aircrafts accommodate up to 80-passenger by reducing seat pitch and may be used as a baseline configuration to expand their capacity to more than 90 passengers.

This paper now introduces how to select major components of an aircraft, such as fuselage, wing, and empennage. The design references, empirical data, regulation, and competitive aircraft data are used to explain those decisions.

Table 1. KC950 top level requirements

Parameter	Target value
Passengers	95
Seat pitch	32inch (standard)
Cargo	6.0 ft^3/passenger
Range	1,000nm
Cruise speed	M0.6 (360knot)

Table 2. Competing aircraft specifications

Parameter	Q400	ATR72
		
Introduction	2000	1989
Passengers	74@31″	68@31″
Range (typical pax)	1,125nm	890nm
Cruise speed	360knots	276knots
MTOW	64,500lb	49,600lb

2. Fuselage

2.1 Cross Section

To design new an airliner class aircraft, the cross sectional definition is the most important factor since it determines the comfortability of passengers, cargo volume, and overall fuselage length. Before deciding the cross sectional shape, an analysis of competitive aircrafts must be done (Table 3). It shows how other aircrafts were designed to provide passenger comfort and utilize fuselage underfloor volume. The possible candidates for the cross section are shown in Fig. 2. The general process for this design is as follows;

① Cabin abreast determination
② Seat and aisle width determination
③ Passenger clearances circle drawing
④ IML drawing for upper fuselage
⑤ Underfloor depth and cargo container space drawing
⑥ Fuselage lower IML drawing
⑦ Connecting two IMLs and OML definition

Table 4 shows the historical data for cabin abreast seating and the total number of passengers. The baseline of KC950

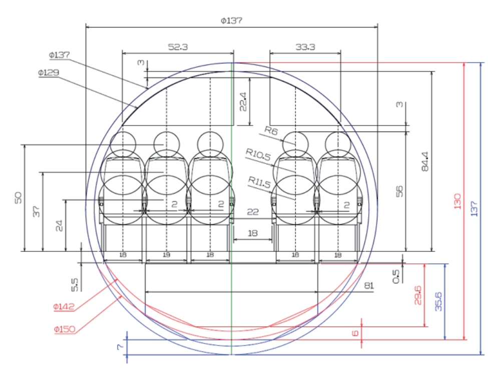

Fig. 2. KC950 fuselage cross section

Table 3. Competing aircraft fuselage cross section dimensions (unit: inch)

Parameter	CSeries	SSJ100	Q400	ATR72	CRJ900	E190	MRJ90
Cabin abreast	2+3	2+3	2+2	2+2	2+2	2+2	2+2
Fuselage width	141.1	137.8	106.0	112.8	105.9	119.0	114.2
Fuselage height	141.1	137.8	101.0	106.3	105.9	132.0	116.5
Seat width	18.5	18.2	17.3	17.3	17.0	18.25	18.5
Aisle width	20.0	20.0	15.8	18.0	16.0	19.75	18.0
Aisle height	83.9	83.5	76.8	75.2	74.4	79.0	80.0
Underfloor cargo height	42.5	40.2	-	-	22.0	37.0	-

is for 95 passengers and its derivative must hold up to 115 passengers. Therefore, the cabin seat arrangement for KC950 and its derivative shall be 5-abreast. Figure 2 shows 3-passenger LHS and 2-passenger RHS.

After deciding on cabin abreast seating, seats must be sized. Table 3 shows seat width and aisle width of several competitors. A seat width between 17 and 18.5 inch is generally recommended as shown in Table 3. Aisle width should satisfy FAR25.815 regulation (Table 5). KC950 seat width is determined as 18 inches for base except middle seat which is 19 inches wide, which will provide more comfort to a passenger in the middle. The aisle width is determined as 18 inches for the height of less than 24 inches from the floor. Aisle height can also be determined according to human standard selection.

The seat armrest is located 24 inches from the floor including the seat track. Therefore, the overall cabin seat and aisle width becomes 123 inches with 2 inch seat elbow width (four 18″ wide seats, one 19″ wide seat, one 18″ wide aisle and seven 2″ wide elbow rests).

To ensure passenger comfort on the seat, the values used in major OEMs in Table 6 are selected as guidelines. By drawing small circles as models for a head, shoulder, elbow and feet at their specific height location, moveable spaces for a passenger in a seat are defined. Now, a fuselage cabin cross section inner circular arc above the floor line without interception of the model circles can be drawn (Fig. 2).

Large commercial aircrafts such as the B777 and the B747 usually use standard sized containers for efficient cargo handling. However, smaller aircraft cannot use these standard containers; instead they only have space for bulk cargo because of underfloor cargo height limitation. The required cargo volume of the KC950 is 6ft3 per passenger as described in Table 1. Underfloor cargo volume must meet this requirement. However it is not an easy task since the underfloor volume is used for the cargo storage and for system hardware installation, such as avionics, landing gear bay, ECS ducting, and cables. In KC950 underfloor volume calculation, 20% of the underfloor volume is allocated for use by systems.

Fuselage frame depth can be estimated using Eq.(1) (Roskam, 2002).

$$Frame\ depth = 0.02D_f+1.0 \quad (1)$$

where, D_f is fuselage diameter. Equation (1) gives approximately a 4.0 inch frame depth. Therefore, the KC950 fuselage outer width is 137 inches, as shown in Fig. 2.

Fuselage floor beam depth could be estimated using Eq.(2).

$$Floor\ beam\ depth = 1.8 + 0.04*cargo\ width \quad (2)$$

Initial width of the cargo bay supporting structures is assumed to be 81 inch. Then, Eq. (2) gives 5.04 inch. For convenience the floor beam depth is 5.5 inches including seat track supporting structure with a depth of 0.5 inches.

The blue curve in Fig. 2 is a circular arc that has the same radius as the upper fuselage cabin radius. The red curve has a larger radius in Fig. 2, it provides less height in the lower fuselage section. Eventually the fuselage section consists of two circles or double bubble shape. In general, two different circles forming a double-bubble would have to intersect at the passenger floor to support hoop tension efficiently.

To decide which circles are more efficient, trade-off studies for manufacturing costs, cargo volume requirements, weight variation, and aerodynamic penalty due to increased wetted area must be performed. The KC950 fuselage cross section is determined as a circle, not a double-bubble shape, mainly due to cargo volume requirement.

Table 4. Single aisle commercial aircraft cabin abreast and passenger capacity (Kundu, 2010)

Cabin abreast	Typical number of passengers (variant type number)
1+1	4~24
1+2	24~45 (20~50)
2+2	44~80 (40~96)
2+3	85~130 (80~150)
3+3	120~200 (100~230)

Table 5. Aisle width regulation (FAR25.815)

Passenger seating capacity	Min. Passenger aisle width	
	Less than 25in from floor	25in and more from floor
10 or less	12	15
11~19	12	20
20 or more	15	20

Table 6. Passenger clearance criteria

	Clearance (circle radius)	Height (above floor)
Head	6.0	50
Shoulder	10.5	37
Elbow	11.5	24
Feet	6.0	0

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2.2 Plan View Layout

The forward fuselage plan view is elliptical in shape (Fig. 3). The ratio of forward fuselage length (*l*) to diameter (*d*) is determined based on statistical data as summarized in Table 7; the aircraft nose cone shape is often made less blunt than a pure ellipsoid. In general, larger aircraft appear to be blunter than smaller aircraft because the nose cone is sufficiently spacious to accommodate pilot positioning including visibility requirement and instrumentation storage in the large aircraft (Kundu, 2010). The pressure bulkhead is usually located 40 inches behind the aircraft nose. A radome is installed in this area. The pilot's eyes are usually located 90 inches behind the aircraft nose. The fuselage width at this position is recommended to be at least 120 inches. The ratio l/d of the K950 was determined as 1.51 based on these design guidelines.

The range of the *l/d* ratio, as shown in Fig. 3, of AFT fuselage plan view is generally from 2.5 to 3.75 for 4 or more seat abreast aircraft. Afterbody drag is increased when the fineness ratio becomes smaller as shown in Fig. 4 due to flow separation. On the other hand, fuselage weight is increased as fineness ratio increases, though the empennage area could become smaller because the moment arm is increased. Some other design variables such as empennage size, after fuselage baggage volume, APU, and after pressure bulkhead must also be considered. The l/d ratio of the K950 was determined as 3.26 based on these design guidelines. In addition, AFT fuselage shape is determined after evaluation of drag variation and depends on enclosure and up-sweep angle effects.

Fuselage main body length is determined according to the number of passengers. Design variables are also door selection, passenger seat arrangement, number of cabin crew, galley and lavatory layout, and requirements for extra baggage compartment size due to the limits of under floor baggage space.

According to FAR25.803, passengers should be able to evacuate from an airplane to the ground under simulated emergency conditions within 90 seconds. To satisfy this requirement, some regulations exist. FAR25.807 defines door type, size, and maximum number of passenger seats permitted for each exit (Table 8). A combination of type C (forward door) and type I (rear door) was adopted for the KC950 which its nominal number of passenger seats of 95. To have commonality between baseline and derivative design, the size of the emergency exits for the derivatives are the same as the baseline.

FAR25.807 regulation also specifies that no passenger emergency exit shall be more than 60 feet from any adjacent passenger emergency exit on the same side of the same deck of the fuselage. The KC950 would not be a problem, however its derivative of 115 passengers would exceed 60 feet in the distance between the two doors. To resolve this regulation issue, an additional exit door, such as type III, should be installed in the middle section at the center of the fuselage.

FAR25.813 defines adequate space to allow crew

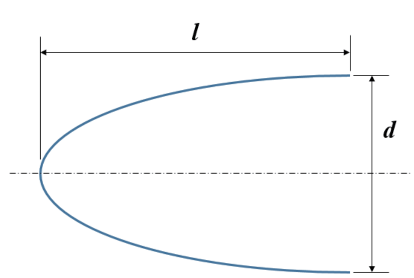

Fig. 3. Forward fuselage elliptic plan view

Table 7. Fuselage front-closure ratio (Kundu, 2010)

Cabin abreast	The ratio (*l/d*)
≤3	1.7 to 2.0
4 to 6	1.5 to 1.75
≥7	around 1.5

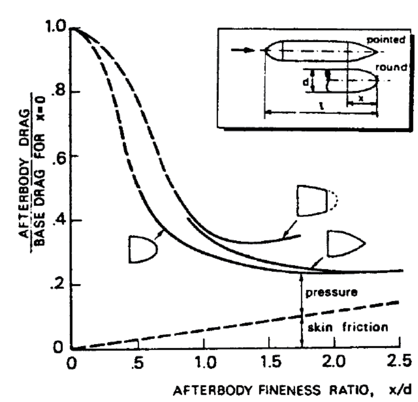

Fig. 4. Afterbody drag of fuselage tail (Torenbeek, 1976)

Table 8. Passenger exits (FAR25.807)

Type	Size (W*H)	Max. passenger
A	42*72	110
B	32*72	75
C	30*48	55
I	24*48	45
II	20*44	40
III	20*36	35
IV	19*26	9

member(s) to assist in the evacuation of passengers. According to this regulation, there must be a passageway leading to type I, type II, or type C exit doors which is unobstructed and at least 20 inches wide.

The length of the cabin is normally determined by multiplying the number of rows by the seat pitch. In single class arrangement, the KC950 cabin length becomes 608 inches (19 rows by 32 inch seat pitch). In addition to this determination, head injury criteria (HIC) should be considered as shown in Fig. 5. There should be sufficient room to avoid head strike to partitions. A minimum acceptable head strike radius of 35 inches from the seat reference point has been used for a number of years. By including this condition in the design, the cabin length is determined to be 623 inches.

The provision of galley and lavatory facilities is essential for aircraft design. Sizes of those facilities are determined based on the number of passengers. Typically galley shape for 60 passengers in economy class (Fig. 6) would be acceptable. Short range transport galley volume is around 1ft^3 per passenger, in general. Therefore, two typical galley units were selected for the KC950. The nominal number of passengers

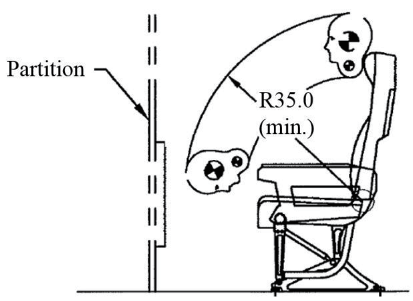

Fig. 5. Head Injury criteria guideline (AC25.785)

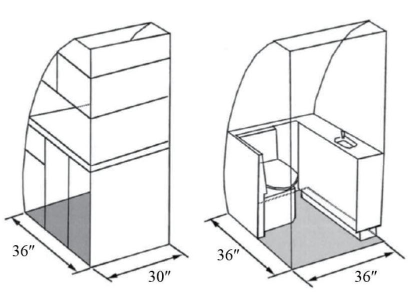

Fig. 6. Typical galley and lavatory units (Jenkinson, 1999)

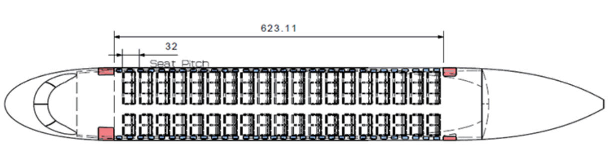

Fig. 7. KC950 cabin layout

for each lavatory is between 40 and 50. This means that two lavatories would be acceptable for the KC950.

FAR121.391 addresses seating capacity for flight attendants. If an airplane has a seating capacity of more than 50 but less than 101 passengers, the operator must provide at least two flight attendants. Therefore, two or more folding seats for cabin crew are included in the KC950 cabin layout design.

Figure 7 shows KC950 cabin layout without service facilities. The galley and lavatory location has not been specified yet. The overall fuselage length in Fig. 7 is 1133.6 inches.

3. Wing

The first step and the most important parameter in wing design is area sizing. There are many methods to estimate initial wing area. In this paper, the KC950 wing area was estimated using the following empirical equations.

$$A_{wet,body} = \pi\sqrt{D_h D_w}\, l_b\left(1 - 0.18\frac{l_n}{l_b} - 0.33\frac{l_a}{l_b}\right) \quad (3)$$

$$A_{wet,total} = \frac{OEW + 27273}{13.6364} \quad (4)$$

$$S_{ref,wing} = 0.37257\, A_{wet,total} - 0.4033\, A_{wet,body} \quad (5)$$

where, $A_{wet,body}$ is fuselage wetted area, $A_{wet,total}$ is aircraft wetted area, $S_{ref,wing}$ is wing reference area. While the fuselage and total aircraft area are wetted area, the wing reference area is a projected one. D is the fuselage diameter (subscript h means height and w means width), l is fuselage length (subscript b means full body, n means nose and a means after body) and OEW is the operating empty weight.

Fuselage wetted area can be calculated by using Eq.(3) based on the fuselage design values of the previous section. OEW is around 60% of MTOW (Maximum Take-Off Weight). MTOW estimation is calculated by iterative process. Variables required for MTOW estimation include payload definition, mission profile, and fuel weight fraction assumption. The current value of the KC950 shown in Fig. 1 is 74,200 lb. Equation (5) gives the wing reference area as 818 ft^2 when the OEW is assumed to be 60% of MTOW.

The calculated wing loading becomes 90.7 lb/ft^2. This is an

Table 9. Wing loading of regional turboprop

Aircraft	Wing loading (lb/ft^2)
Q400	96.0
ATR72	73.9
SAAB2000	84.5

acceptable value comparing with other turboprops as shown in Table 9.

Wing location is determined considering aircraft center of gravity position. However, wing MAC (Mean Aerodynamic Chord) quarter chord location is determined at about 50% of the passenger cabin (from flight deck partition to after pressure bulkhead) without sufficient information about CG in initial layout design phase. This assumption is very close to the ball park number compared with other aircrafts. 47% of overall aircraft length could also be used for this purpose. The current KC950 wing is located at 47.2% of the fuselage length.

Wing aspect ratio is determined considering many design considerations such as aerodynamic performance, structural manufacturability, stability, and control. Typical values of wing aspect ratio are 6-9 for low-subsonic transport and 8-12 for high-subsonic transport (Sadraey, 2013). Table 10 shows wing aspect ratio for several regional turboprops. The current initial aspect ratio for KC950 maximizes wing efficiency and is decided to 11.55 by observing other aircrafts .

Swept wing design is generally applied to high subsonic transport to reduce compressibility drag. On the other hand, no sweep angle is recommended for low speed vehicles (less than mach 0.65) because sweep angles imply both structural and possible handling penalties. (Howe, 2000) For this reason, the KC950 adopts straight wing.

The taper ratio which gives the minimum lift-induced drag is slightly dependent on the aspect ratio and more significantly dependent on the wing sweep angle. Figure 8 plots taper ratio as a function of sweep angle. (Corke, 2003)

Table 10. Wing aspect ratio of regional turboprop

Aircraft	Wing aspect ratio
Q400	12.81
ATR72	12.00
SAAB2000	11.00

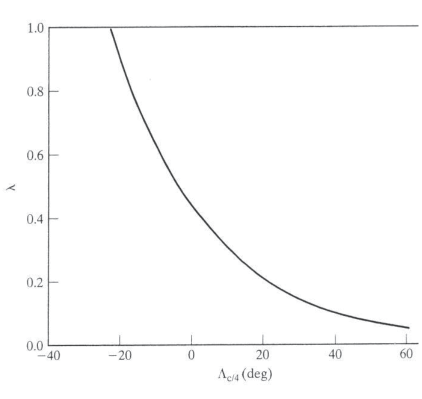

Fig. 8. Taper ratio of trapezoidal wing (Corke, 2003)

This gives initial design value for zero-swept wing as 0.45.

Wing root section thickness of transport aircraft is chosen for to create a good cantilever ratio and maximum lift values. Recommended wing root thickness ratio is between 15 and 20 percent when using relatively simple trailing edge high lift devices. Typical tip sections are between 10 and 15 percent considering structural weight reduction and adequate room for control system elements. (Torenbeek, 1976) Figure 9 shows the effect of the maximum thickness to chord on the maximum lift coefficient for a variety of 2D airfoil sections. These data indicate that the largest maximum lift coefficient occurs at about 14%. (Corke, 2003) The wing section thickness ratio of KC950 is 16% and 12% for the wing root and the wing tip, respectively. The detailed geometry of each airfoil section along the wing station is determined by using CFD analysis.

Wing dihedral angle is applied to improve the the lateral stability of the aircraft. Low-wing aircraft generally have a dihedral anle of 5 to 7 degrees, while high-wing configurations require a lower value of up to 3 degrees. (Torenbeek, 1976) The dihedral angle of the KC950 was set to 2.5 degrees with reference to the competitive turboprops Q400 and ATR72 which have 2.5 degrees and 3.0 degrees wing dihedral angle, respectively.

Wing incidence angle and twist angle are another design

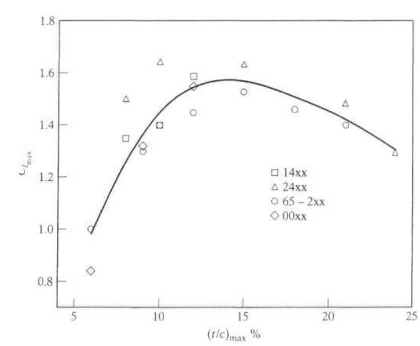

Fig. 9. Effect of the thickness ratio on the maximum lift coefficient (Corke, 2003)

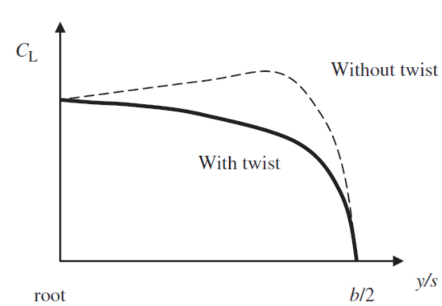

Fig. 10. Typical effect of a (negative) twist angle on the lift distribution (Sadraey, 2013)

variables to be determined. Wing incidence angle must satisfy design requirements for minimum drag during cruise flight and deviation of less than 2 degrees from a level cabin in cruise flight. The goals of applying wing twist angle are avoiding tip stall before root stall and modification of the lift distribution to an elliptical one. Fig. 10 shows lift re-distribution with twist. In this initial design phase, typical angle of +2 degrees at root and -1 degree at tip were applied to KC950.

4. Empennage

To determine the optimum tail moment arm (the distance between the aircraft center of gravity and the empennage aerodynamic center), the following equation is used. (Sadraey, 2013)

$$l_{opt} = K_c \sqrt{\frac{4MAC_w S_w C_{HT}}{\pi D_f}} \quad (6)$$

where, K_c is a correction factor (varying between 1.0 and 1.4 depending on the aircraft configuration). This is assumed to be 1.4 for a transport aircraft. MAC_w is wing mean aerodynamic chord length and S_w is wing area. C_{HT} is volume ratio coefficient of the horizontal tail. In this paper, an average value of the volume ratio coefficients of regional transports was used, which is 1.39. Although this value is larger than the typical value in the reference book (Sadraey, 2013), it is closer to the current large turboprops. Equation (6) gives an acceptable value of 564.0 inch which is nearly 50% of the fuselage length. The typical distance of the tail arm is 50~55% of the fuselage length for an aircraft that has engines mounted on the wings. Although the tail arm from Eq. (6) is an estimation for horizontal tail, it is assumed as same for vertical tail in the initial design phase.

After determination of the tail arm, the initial area of the vertical and the horizontal tail could be estimated by the following equations.

$$S_{VT} = C_{VT} \frac{b_w S_w}{l_{VT}} \quad (7)$$

$$S_{HT} = C_{HT} \frac{MAC_w S_w}{l_{HT}} \quad (8)$$

where, C_{VT} and C_{HT} are volume ratio coefficients, bw is wing span length, l_{VT} and l_{HT} are tail arm length which are same as l_{opt} in Eq. (6).

The vertical tail volume ratio coefficient of 0.10 is also an average value of regional transports. Based on this assumption and design values of the fuselage and the wing, Eq. (7) gives 166.9 ft^2 as vertical tail area and Eq. (8) gives 215.0 ft^2 as horizontal tail area.

Symmetric and thinner airfoils than wings are recommended for vertical and horizontal tails. The other configuration related design variables such as aspect ratio, sweep angle, taper ratio, incidence angle, and dihedral angle could be determined through stability analysis.

5. Performance Evaluation

Based on the initial configuration, the aircraft component weight, operating empty weight, and maximum take-off weight were estimated for performance analysis (Table 11). Empirical equations suggested by Torenbeek and Howe were applied for this estimation. (Torenbeek, 1976 and Howe, 2000)

Performance analysis was carried out to evaluate if the designed configuration is satisfactory to top level aircraft requirements. Fig. 11 shows the mission profile for the 95-seat turboprop. Aerodynamic data were calculated using an empirical formula. Engine performance was assumed to be 15% improved compared with a PW150A which is used for the Q400.

Figure 12 shows the aircraft sizing matching chart. According to this chart, the design results represented as power loading and wing loading are within the requirement curves. For the KC950, wing loading of 90.7 lb/ft^2 and power loading of 0.16 shp/lb, satisfies with the design requirements

Table 11. Weight estimation

Designation	Weight (lb)
Wing	6,150
Fuselage	9,570
Empennage	1,220
Structure total	21,790
OEW	43,500
MTOW	74,200

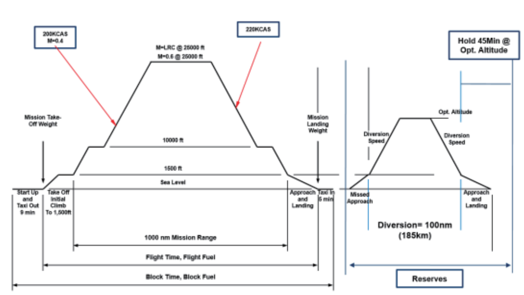

Fig. 11. 95-seat turboprop mission profile

of M0.6 cruising speed, 4,300 ft take-off field length, and 4,000 ft landing field length.

Figure 13 shows payload-range capability. The results are satisfactory for the aircraft requirement which is a 1,000 nm flight range with maximum payload at maximum cruise speed.

The performance evaluation and configuration design are iterative processes for optimal design. However, detail performance analysis was not included in this paper, because that is beyond the scope of this paper.

6. Conclusion

The most efficient method to develop initial aircraft configuration is to refer to the statistical design values of current successful competing aircrafts. This is true especially for conventional shape transport. Similar initial design to well-known transports is logical to determine a starting point. The design could be enhanced through iteration.

This paper introduces initial design processes and illustrates design results of a 95 passengers turboprop aircraft KC950 for the major components, including fuselage, wing, and empennage. In addition to design variables specified in this paper, initial configuration of landing gear, nacelle, and propeller must be included in initial design phase. The KC950 adopted fuselage mounted main landing gear and relatively short nacelles as shown in Fig. 1. Control surface layout considering flap, aileron, spoiler, rudder, and elevator is also important to be determined in this design stage. Sufficient pilot vision during cruising flight as well as take-off and landing is a critical point for cockpit design. Tail strike angle should be reviewed after rear fuselage design. Aircraft structural design is followed by external configuration design such as fuselage frame and stringer layout, wing, and empennage spar and rib layout and conceptual design on the structure assembly.

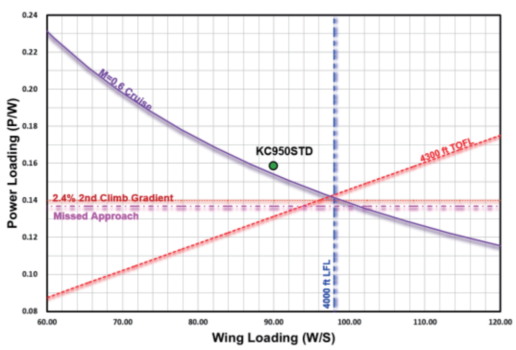

Fig. 12. Aircraft sizing matching chart

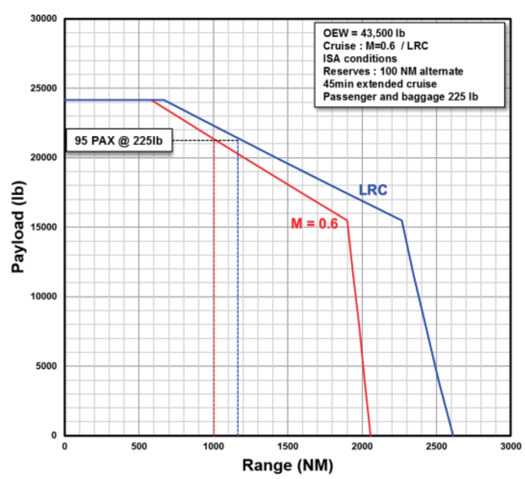

Fig. 13. Payload-range capability

Acknowledgement

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