International Conference on Mechanical, Industrial and Materials Engineering 2015 (ICMIME2015)
11-13 December, 2015, RUET, Rajshahi, Bangladesh.

Paper ID: RT-49

Design and Optimization of a Long Range Jet Aircraft

Md. Afzal Hossain [1], Md. Abdus Salam [2], Md. Rayhan Afsar[3], Kh. Md. Faisal[4], M. A. Taher Ali[5]
[1-5]Military Institute of Science and Technology, Mirpur Cantonment, Dhaka-1216, Bangladesh
aeroboyrony12@gmail.com, head@ae.mist.ac.bd, rayhan@ae.mist.ac.bd, faisal@ae.mist.ac.bd, matali@ae.mist.ac.bd

Abstract

The design of a long range jet aircraft is presented in this paper. Design requirements were selected from market analysis. The minimum requirements for aircraft design, extracted from market analysis were: - range: 5200 nm, maximum Mach number: 0.8, ceiling: 43000 ft., passenger: 280, load factor: ranging from +3.5 to -1.5. The aircraft should be capable of carrying two crew members. The aircraft had to materialize a certain mission profile. This mission profile contains the flight segments like taxi, take-off, climb, cruise, loiter, descend, climb, cruise to alternate destination, descend and landing. In addition to, the complete aircraft design was accomplished through three basic phases like conceptual, preliminary and detail design. Initially in conceptual design phase, configuration of the basic components of aircraft were selected through figure of merit analysis. After that preliminary design, detail design has been done. At last weight of different components was calculated.

Keywords: Aircraft design, Aerodynamics, Thrust, Figure of merit analysis, Mission Profile.

1. Introduction

From first flight of the Wright Flyer I, December 17, 1903 to the first flight of the Boeing 787 Dreamliner December 15, 2009 a lot has changed in the history of aircraft design, construction and maintenance. In between this period so many different methodologies and approaches have been explored by different designers. And a revolutionary advancement has been observed. But in reality, a lot is yet to come. So many are trying to solve different complication related to the design methods standing for a long time. Old complications are being solved and new are coming. Nowadays, aircraft designing is one of the most challenging sectors due to its huge manufacturing costs and sensitivity. A single paper is not enough for understanding all complications and other challenges related to this field. But in this work, the design of long range jet liner is presented optimizing all those complications and challenges. It will be really helpful for a beginner who wants to design a passenger aircraft.

2. Design Requirements

Here the aim is to design and optimize a Long Range Jet Aircraft following these given requirements.

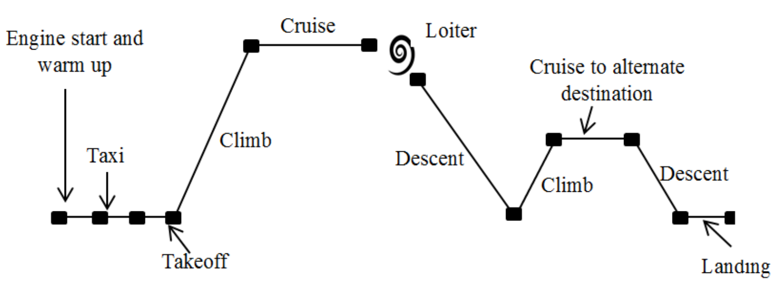


Fig. 1. The mission profile

Parameters	Min. Requirements
Range	9600 km, 5200 nm
Max. Mac	0.8
Ceilling	43000
Pax.	280
Load Factor	+3.5 ; -1.5
Crew	2

Table 1. Design Requirements

3. Conceptual design

Following the design requirements and using figure of merit (FOM) analysis, the following configuration was optimized for the design.

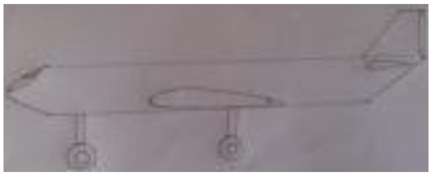


Fig. 2. Conceptual sketch of side view

Fig. 3. Conceptual sketch of top view

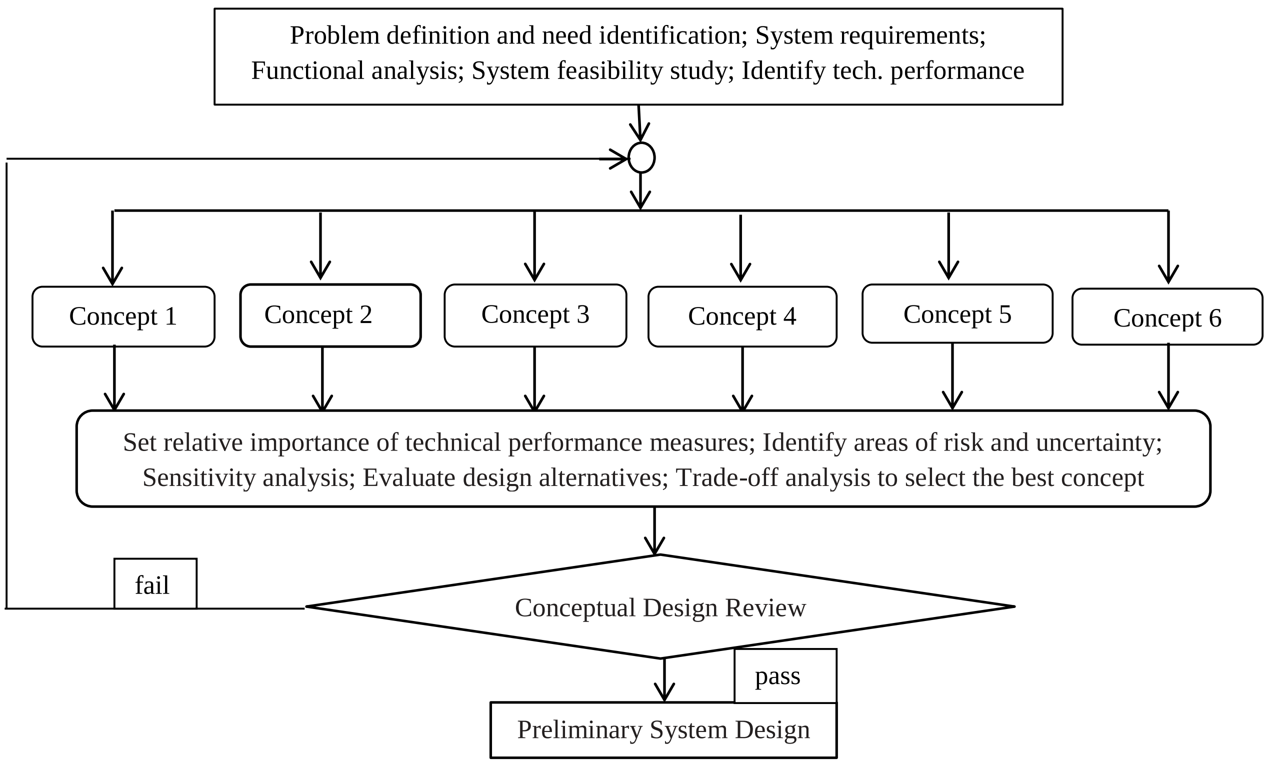


Fig. 4. Conceptual design flowchart

4. Preliminary design

Based on the requirements first the empty weight and the takeoff weight of the aircraft were calculated. Here- Weight of the crew, W_c= 1100 lb; Weight of payload, W_{pl}= 78400 lb; Fuel weight ratio for 1st cruise segment = .834; Fuel weight ratio for loitering = .99 ; Fuel weight ratio for 2nd cruise section = .884 ; Overall fuel weight ratio=.664 ; By calculating, Empty weight, W_e= 342921.82 lb ; And , Takeoff weight, W_{to}= 6.527×10^5 lb ;

The next step is to determine the wing area, S_w and engine size. Here, the matching plot was used for final results.

Five basic equations used for the matching plot are-

(1) Stall speed: $(\frac{W}{S}) = 110.682\ lb/ft^2$; (2) Maximum speed: $(\frac{T}{W})_{max} = (\frac{30.66}{\frac{W}{S}}) + (3.067 \times 10^{-4})(\frac{W}{S})$; (3) Takeoff Run: $(\frac{T}{W})_{Sto} = \frac{.04-.05448[exp\left(\frac{13.949}{\frac{W}{S}}\right)]}{1-exp(\frac{13.949}{\frac{W}{S}})}$; (4) Rate of climb: $(\frac{T}{W})_{ROC} = \frac{1.31}{\sqrt[2]{(W/S)}} + .04762$; (5) Service ceiling: $(\frac{T}{W})_{ROCc} = 0.1133\frac{1}{\sqrt[2]{\frac{W}{S}}} + 0.2226$

Combining these equations and using Matlab, following matching plot is obtained-

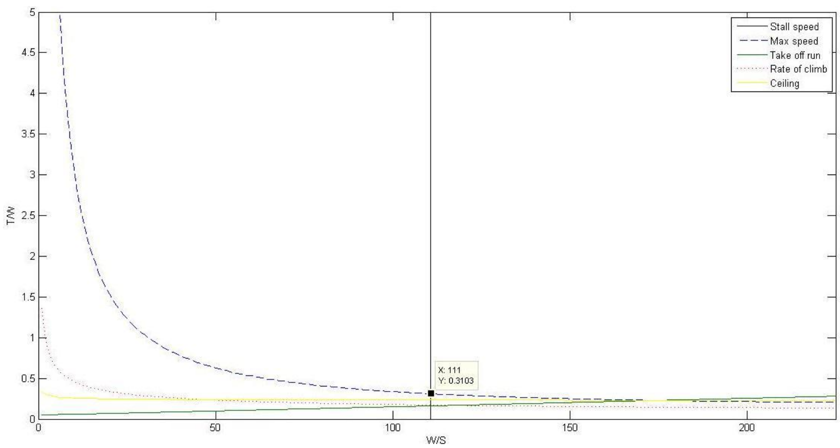


Fig. 5. Matching plot

From matching plot the final results are shown below-
Wing Area, S_w= 5880.18 ft^2 ; Engine thrust, T= 202532.81 lb

5. Detail design

5.1. Wing Design

By using FOM analysis, selected configuration is monoplane, low wing, swept back, tapered configuration for aircraft. Then the aerofoil was selected based on the following results:

Aircraft average weight at cruise, W_{avg} = 2082521.7 N ; Required A/C cruise lift coefficient, C_{lc} = 0.223; Required Takeoff lift coefficient, $C_{l\ t/o}$ = 1.9;

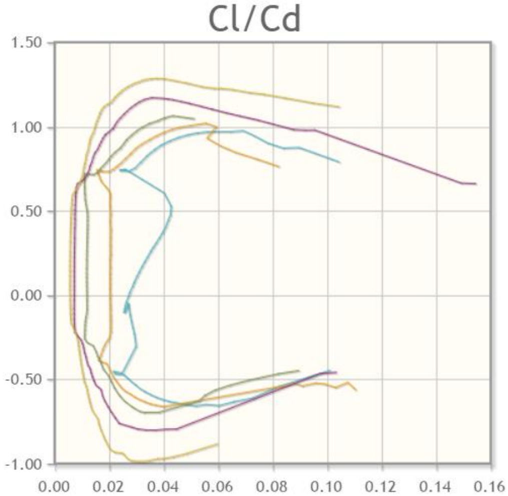
"Trailing edge single slotted flap" was used as high lift device. Now the geometry of wing and HLD is-

AR of the wing, AR_w=11 ; Span of the wing =254.32 ft ; Span of the flap, b_f = 152.592 ft ;
Mean chord of the wing,C_w=23.12 ft ; Mean chord of the flap, C_f = 11.56 ft; Sections ideal lift coefficient, C_{li}=0.26; Sections max lift coefficient,$C_{l\ max\ gross}$= 2.22; Lift coefficient of the high lift devices, $C_{l\ HLD}$= .65;

Then, Maximum lift coefficient, $C_{l\ max}$ = ($C_{l\ max\ gross}$ - $C_{l\ HLD}$) = ***1.57***

Based on this result, ***"NACA 64₁-212"*** was selected from the NACA aerofoil chart [1] for the aircraft.

The characteristic curves [2] of the aerofoil are given below-



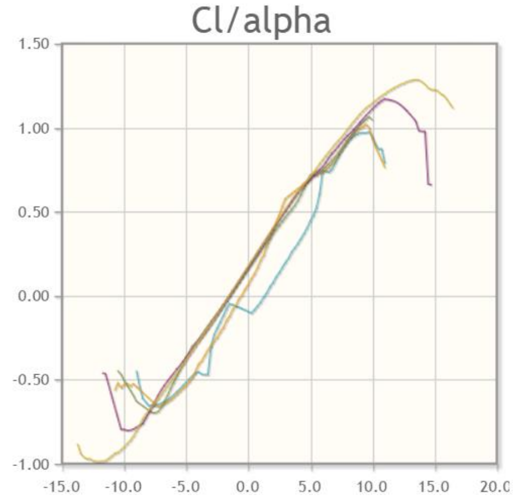


Fig. 6. lift vs drag coefficient curve for diff. reynolds no

Fig. 7. lift coefficient vs AOA curve

Other findings are,
wing incident angle, i_w= 2° ; wing sweep back angle at mid chord= 30°; twist angle= 1.5 ; tapper ratio= 0.2;

From following result, using Matlab it was checked that if the lift distribution over the wing is elliptical or not. And a positive result was found. The lift distribution curve is shown below,

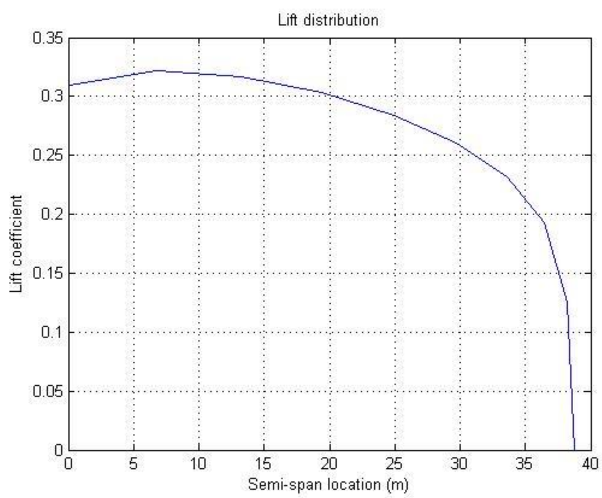


Fig. 8. Elliptical lift distribution over a wing

Other important findings were, α_{flap}= -20° ; wing drag, D_w= 308789 N ;
wing pitching moment, M_{0w}= -9166458.64 ; Root chord,C_r = 10.23m ; Tip chord, C_t= 2.042 m .

Other important results are :
Flap angle, α_{flap}=-20° ; wing drag, D_w=308789 N ; wing pitching moment, M_{ow}= - 916645.64 N-m ;
root chord, C_{root} =10.23 m ; tip chord, C_{tip}= 2.042 m.

5.2. Tail design

5.2.1. By using FOM analysis conventional Aft tail was selected.

5.2.2. Horizontal tail Design: Important finding in the tail sections were, HT volume coefficient, V_h=1.1 [3] ; Optimum tail moment arm, L_{opt}=38.59m ; HT planform area,$S_h = \frac{VhCs}{Lopt}$ = 109.74 m^2; Wing fuselage Aerodynamic pitching moment coefficient, C_{mowf} = -0.0389 Horizontal tail lift coefficient at cruise, C_{lh}= -0.051 Based on these results and other general considerations, **NACA 0009** was selected for the tail section.

Other findings for Horizontal tail are-
Sweep angle, $\wedge_{.5c}$ =30^0 ; Dihedral angle = 6^0 ; Aspect ratio, A_{HT} =7.3 ; Tapper ratio, λ= 0.2; Span, b_h = 92.8 ft ; AR_{HT}= 7.3; Chord, C_h=12.72 ft; Root Chord, C_{root}=18.47 ft; Tip Chord, C_{tip}=3.69ft; Lift curve slope, $C_{l\alpha\text{-}h}$=4.79 ; AOA at Cruise, α_h=-0.613^0 ; Downwash Angle = 1.5^0; Incident angle I_h=-1.56^0 ; $C_{m\alpha}$ =-4.51 rad^{-1} ; As the value of $C_{m\alpha}$ is negative so it has static longitudinal stability.
Finally iteration, optimization, stall checking as well as dynamic longitudinal stability was checked.

5.2.3. Vertical Tail Design:
The important findings were,
VT volume co-efficient, V_v= .009 [4] ; VT Moment Arm, L_v=126.6ft ; VT Planform area, S_v=1063 ;
Aerofoil NACA0009; Aspect ratio,AR_{VT}=2 ; Tapper ratio, λ= 0.3; Incident angle,i= 0°; Sweep angle, $\Lambda_{c/2}$ =30^0 ;
Dihedral angle = 0^0; Tip chord,C_t= 9.7 ft; Root chord, C_r=32.33 ft

Finally directional trim, Directional Stability and Optimization has been done.

5.3.Propulsion system design

In case of propulsion system design part, a/c performance, Engine manufacturing cost, Engine operating cost, Flight safety, Engine efficiency, maintainability, manufacturability, maximum thrust needed are the most important criteria what were needed to be considered.

Considering those the result and using FOM analysis the following were obtained,

> Turbofan (High bypass ratio) is more suitable for this a/c.

> Required thrust is more so four engines can be taken.

> It was decided to mount the engine under wing.

> We used “GE engine” for this a/c.

> Determined thrust for each engine =$\frac{953.66}{4}$ =238.4kN

> Based on thrust required, “GE CF6-50E2” engine was selected.

5.4. Fuselage design

Based on A/C type, payload, range, cruise ceiling, crew and passengers, fuelling, wingspan, mechanical and electrical system landing gear and other considerations the fuselage was designed and following were obtained.

Instrument for cockpit suggested by FAR part 25 section 25.1303 ; Optimum length to diameter ratio, L_f/D_f=12.21 ; Length of cabin, L_c=44.2 m; Total luggage volume , V_l=287*2*0.146 =83.8 m^3; No of LD1 container =17.1 17 cont;

Volume of fuel V_f=109.97 m^3; Fuselage available space, V_{avl} =62.848 m^3 ; Wing box volume, V_{wbox} = 45.53 m^3 ; Fuselage maximum diameter D_f=3.62 m ; Fuselage length will be L_f=188 ft ;Final fuselage length to diameter ratio, L_f/D_f=15.8; Upsweep angle, α_{us} =13.25°; Overall length $L_{overall}$=57.32 m ;

Finally lofting, Iteration and optimization are done.

5.5. Landing gear design

The main Considerations are ground clearance, tip back angle, take off rotation, overall angle, structural integrity, A/C ground stability, ground controllability, low cost maintainability and manufacturability. Based on the requirements and design considerations by FOM analysis we selected 'Tricycle landing gear", Retractable landing gear is selected. Height of the landing gear is H_{lg}= 4.17 m ; Distance between the main gear and the A/C forward CG is, X_{mg}= 7.8 ft ; Tip back angle is α_{tb}=22.27 ° which satisfy The clearance angle which is α_c=10 °>α_{to} ; wheel base, B=45.88 ; wheel track ,T=26.68 ft ; Overturn angle φ_{ot}=30.16 °>25 °;

5.6. weight of Component

1. Wing weight, W_w=3672074.254 N
2. Weight of HT, W_{ht}=355639.5 N
3. Weight of VT, W_{vt} =238841N
4. Weight of fuselage, W_f=766058.99 N
5. Weight of landing gear, W_{lg}=9676.97 N
6. Installed engine weight, W_{engine}=856883.7 N
7. Fuel system weight, W_{fs}=745.55 N

6. Conclusion

As the historical values are used for so many calculations, the results found sometimes were deviated from the exact result. In the preliminary design step, for determining required engine thrust and wing area we used matching plot as we are designing in the premature stage. More precise methods is used by the designer in the higher level. Scope is there to improve lift distribution over the wing as there is no limitation of betterment in this section. In the case of tail design, deviation of larger portion of air flow due to the disturbance created by the wing and fuselage, was not considered. That definitely affected the result. In case of propulsion system design, improvement can be done in case of thrust required due to change in altitude. Finally, it can be concluded that, though there are scopes of improvement in this design, but it represents the entire design and optimization of a long range jetliner, which will serve as a useful resource for the design enthusiasts.

7. Nomenclature

T- Engine thrust; S- Wing Area; W- Empty weight; C- Engine specific fuel consumption; Vc- Cruise speed; ROC- Rate of climb; HLD- High lift device; AR- Aspect ratio; μ- frictional coefficient; ʌ- sweep angle; λ- Tapper ratio; b- Wing span; n- Load factor.

8. References

[1] Mohammad H. Sadraey, AIRCRAFT DESIGN A Systems Engineering Approach, Page-192, Figure 5.23.
[2] UIUC Airfoil Coordinates Database Source dat file, http://airfoiltools.com/airfoil/details?airfoil=n64212-il.
[3] Mohammad H. Sadraey, AIRCRAFT DESIGN A Systems Engineering Approach, Page-303, Table 6.4.
[4] Mohammad H. Sadraey, AIRCRAFT DESIGN A Systems Engineering Approach, Page-303, Table 6.4.