Design of a New Stratotanker

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By

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The undersigned faculty Committee Approves

Design of a New Stratotanker

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Abstract

Design of a New Stratotanker

By I-Chiang Wu

In this project, a new stratotanker will be designed to replace the current KC-135 fleet of the U.S. Air force in East Asia. The new aircraft will be designed to support three types of missions: aerial refueling, cargo transfer and medical evacuation. The critical mission requirement is to have high cargo capacity and noise reduction during takeoff and landing. A weight analysis was researched and fits all military performance requirements. A stability and control analysis was done to calculate appropriate tail area. The drag polar estimation based on Roskam's method was calculated. Finally, the takeoff weight of this new aircraft is 332,324 lbs and the wing loading is 120 lb/ft^2, thrust to weight ratio 0.23.

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Nomenclature

AR	Aspect Ratio
b	wingspan
β	Mach Constant
c	Chord Length
C_D	Drag Coefficient
C_{Do}	Zero-Lift Drag Coefficient
C_L	Lift Coefficient
$C_{L\alpha h}$	Horizontal Tail Lift Curve Slope
$C_{L\alpha v}$	Vertical Tail Lift Curve Slope
$C_{L\alpha w}$	Wing Lift Curve Slope
$C_{L\alpha wf}$	Wing-Fuselage Lift Curve Slope

$C_{n\beta}$	Yaw Sideslip Moment Coefficient
$C_{n\beta f}$	Fuselage Yaw Sideslip Moment Coefficient
$C_{n\beta wf}$	Wing-Fuselage Yaw Sideslip Moment Coefficient
d_f	Equivalent Fuselage Diameter
e	Oswald Efficiency Factor
ε_h	Horizontal Downwash Gradient
k	Lift Curve Slope Constant
K_A	Aspect Ratio Constant
K_h	Horizontal Tail Constant
K_λ	Taper Ratio Constant
K_n	Factor Accounting for Wing-Fuselage Interference
K_{wf}	Wing-Fuselage Constant
l_f	Fuselage Length

l_n	Fuselage nose Length
λ_f	Fuselage Length to Diameter Ratio
S	Wing Area
S_v	Vertical Tail Area
$S_{wet,e}$	Empennage Wetted Area
$S_{wet,f}$	Fuselage Wetted Area
$S_{wet,fan}$	Fan Cowling Wetted Area
$S_{wet,gas}$	Gas Generator Wetted Area
$S_{wet,plug}$	Plug Wetted Area
$S_{wet,tot}$	Total Aircraft Wetted Area
$S_{wet,w}$	Wing Wetted Area
V	Aircraft Velocity
X_{acA}	Aerodynamic Center Location of Aircraft from Tip of Nose

X_{acwf} Aerodynamic center Location of Wing-Fuselage Combination from Tip of Nose

1.0 Introduction

As the turmoil in East Asia, North Korea plans to attack South Korea by lunching nuclear bombs. The hypothetical battlefield of the next world war is in Korea. South Korea is the largest DRAM and TFT-LCD producer in the world. Once the war begins, the global economy and technology will be hurt seriously. As the leader of the United Nations, The United States has the primary responsibility for the maintenance of world peace.

The U.S. Air Force mainly positioned the Lockheed Martin F-22 in Guam and Okinawa. The distance between Guam and South Korea is 1780 nautical miles and the distance between Okinawa and South Korea is 705 nautical miles. The range of the F-22 is about 1600 nautical miles. Therefore, more than one refueling is required for any mission. In 2011, China had the first test flight for their new stealth fighter J-20. Military capability of the Communist Party is threatening the whole of East Asia.

Currently the U.S. Air Force has the 909th air refueling squadron located in Okinawa which has 15 Boeing KC-135R. Due to the low range and low cargo capacity, the U.S. Air Force is planning to replace its KC-135R. According to the Request for Proposal[1] put out by the USAF on March 15 2010, the new refueling aircraft has to satisfy range, payload as good as the KC-135 and multi-point refueling capability.

In the past, the U.S. Air Force tried to use different engine to increase the range for the KC-135. There are also many research studies to gain the use life of the KC-135. Ishimitsu[2] tried to add winglets for the KC-135, the induced drag is decreased from the experiment result. Gerontakos[3] experienced different dihedral angle for winglets, the negative dihedral was more effective in reducing the induced drag. Halpert[4] tried to add winglets, raked wingtips and a wingspan extension to increase the range and endurance for the KC-135. A raked wingtip with 20° of additional leading edge sweep could increase the most range and endurance. Gold[5] had an experimental study about the dihedral on a raked wingtip. The result showed the raked tip with the lower sweep angle exhibited a lower induced drag. Slofff[6] used flap tip fence to improve the aerodynamic efficiency. An improvement of lift to drag ratio and maximum lift coefficient up to 1%. A reduction of noise during landing is about 7dB.

2.0 Mission

The objective of this project is to design a new military fuel transport aircraft for the United State Air Force. According to the request, the USAF aims to replace its current aerial refueling fleet which consists of Boeing KC-135Rs. Better range and payload requirement is necessary for the new aircraft. Three different tasks competency is also required which are aerial refueling, cargo transfer and medical evacuation. A typical mission for the new aircraft can take off from Guam carrying military personnel to South Korea, transfer military supplies from Guam to South Korea, or take off from Okinawa to prepare for an aerial refueling mission near North Korean airspace.

2.1 Mission Specification

As determined by the USAF, the mission requirement numbers are concerned:

- Passengers: 150 (125 Patients to 25 Medical Personnel; 5:1 ratio)
- Cargo: 18 x 464L Pallets (5,000 lbs/each)
- Crew: 3: Pilot, co-pilot, boom operator
- Fuel Capacity: 150,000 lbs
- Range: 1,500 nmi for aerial refuleing mission

  1,800 nmi for cargo transfer and medical evacution missions
- Cruising Altitude: 40,000 ft
- Cruise Speed: 612.7mph (M=0.83)

2.2 Critical Mission Requirements

The KC-X has two critical mission requirements. The first is large cargo capacity. The U.S. government is planning to move marine troop from Okinawa to Guam in 2014. Large cargo capacity could assist transport large quantities of supplies. The second is the reduction in noise during take-off and landing. Okinawa and Guam are both popular sightseeing place. Noise could affect local residents and vibrations could damage local landscape.

Figure2. 1 – Beach of Okinawa

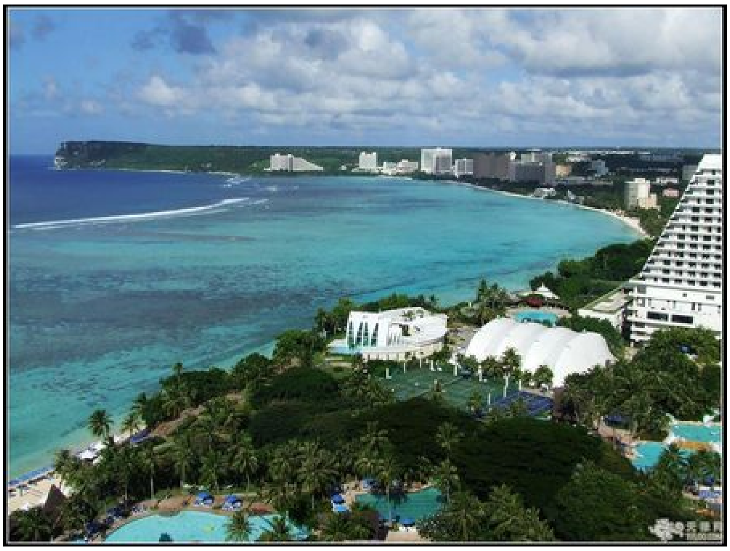

Figure2. 2 – Beach of Guam

2.3 Mission Profile

Figure 2.3 shows a sketch of the aerial refueling mission profile of the KC-X. Firstly taxi on the run way and take off then ascent to cruise altitude 40,000 feet. The KC-X will refuel other aircraft at 40,000 feet then return fly back to the base. When approach the base, the KC-X will do loiter for one hour and then do descent and landing.

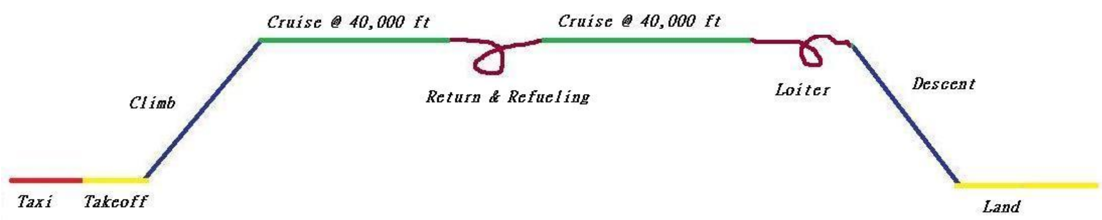

Figure2. 3 –Aerial refueling mission profile

Figure 2.4 shows the sketch of both cargo transfer mission and medical evacuation mission. Taxi one the runway then takeoff climb to 40,000 feet. One hour loiter before landing and then do descent and landing.

Figure2. 4 – Mission profiles for cargo transfer mission and medical evacuation mission

2.4 Comparative Study

This section will compare different refueling aircraft designs. Currently, there are four different refueling jet powered aircrafts service around the world. They are KC-135R, KC-767, KC-30 and KC-10. The KC-135R is the current fleet for the USAF. Figure 2.5 to figure 2.8 shows these four aircrafts. Table 2.1 express specifications of these four aircraft.

Table2. 1 – Specification of similar aircraft

	KC-135R	KC-767	KC-30	KC-10
Crew	3	3	3	4
Capacity	37 passenger+ 6 pallets	200passenger+ 19 pallets	380passenger+ 8 pallets	75 passenger+ 17 pallets
Length	136ft 3in	159ft 2in	193ft	181ft 7in
Span	130ft 10in	156ft 1in	198ft	165ft 4.5in
Height	41ft 8in	52ft	57ft	58ft 1in
Wing Area	2,433 ft^2	3,050 ft^2	3,900 ft^2	3,958 ft^2
Empty Weight	98,466 lb	181,610 lb	275,600 lb	241,027 lb
Takeoff Weight	322,500 lb	395,000 lb	514,000 lb	590,000 lb
Thrust	86,536 lbf	120,400 lbf	144,000 lbf	157,500 lbf
Fuel Load	150,000 lb	160,660 lb	245,000 lb	353,180 lb
Max Speed	580mph(0.87M)	570mph(0.86M)	547mph(0.83M)	619mph(0.84M)
Cruise Speed	530mph(0.8M)	530mph(0.8M)	534mph(0.8M)	560mph(0.76M)
Range	1,500 nmi	6,385 nmi	8,000 nmi	4,400 nmi
Cruise Altitude	50,000 ft	40,100 ft	41,500 ft	42,000 ft
Thrust to Weight Ratio	0.268	0.304	0.28	0.266
Wing Loading	132.55	129.5	131.79	149.06

Figure2. 5 – KC-135R

Figure2. 6 – KC-767

Figure2. 7 – KC-30

Figure2. 8 – KC-10

3.0 configuration design

Combined configurations for existing designs, the KC-X will use the low wing configuration, conventional tail for its empennage, conventional tricycle type landing gear, a high-bypass turbofan propulsion system and two different types (drogue and boom) for the refueling system. The transport fuel could store under-floor of the fuselage. The conventional tricycle landing gear could be landed in very large crab angle in a crosswind. The risk of landing is reduced by this type of landing gear. The KC-X will only use two turbofan engines placed symmetrically on the wing. With this configuration, less maintenance efforts will be required. The configuration sketch is shown in figure 3.1 and figure 3.2.

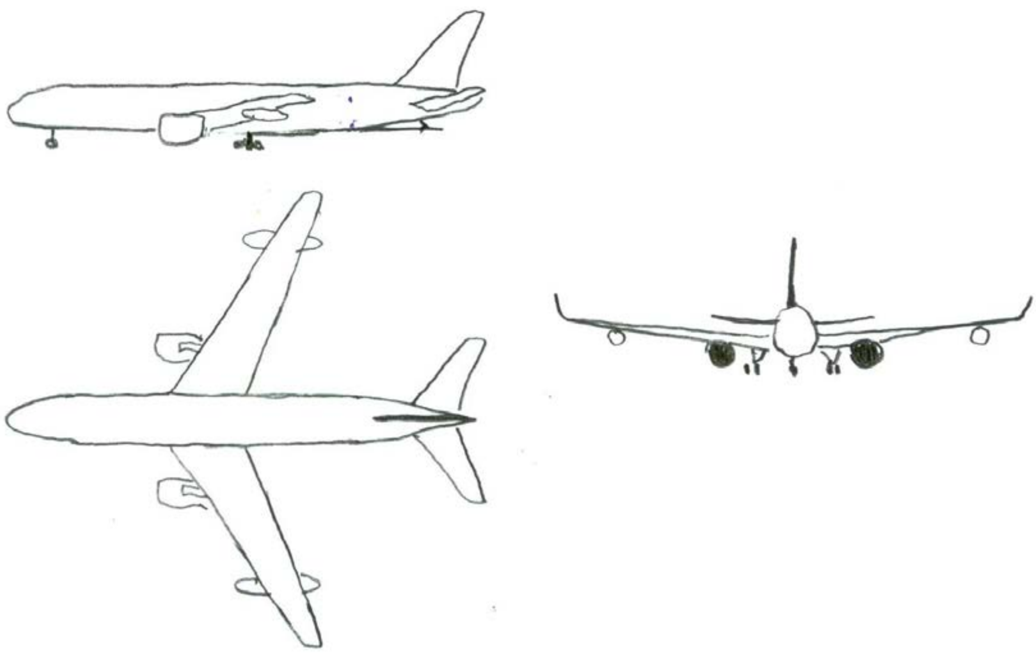

Figure3. 1 – Configuration Sketch

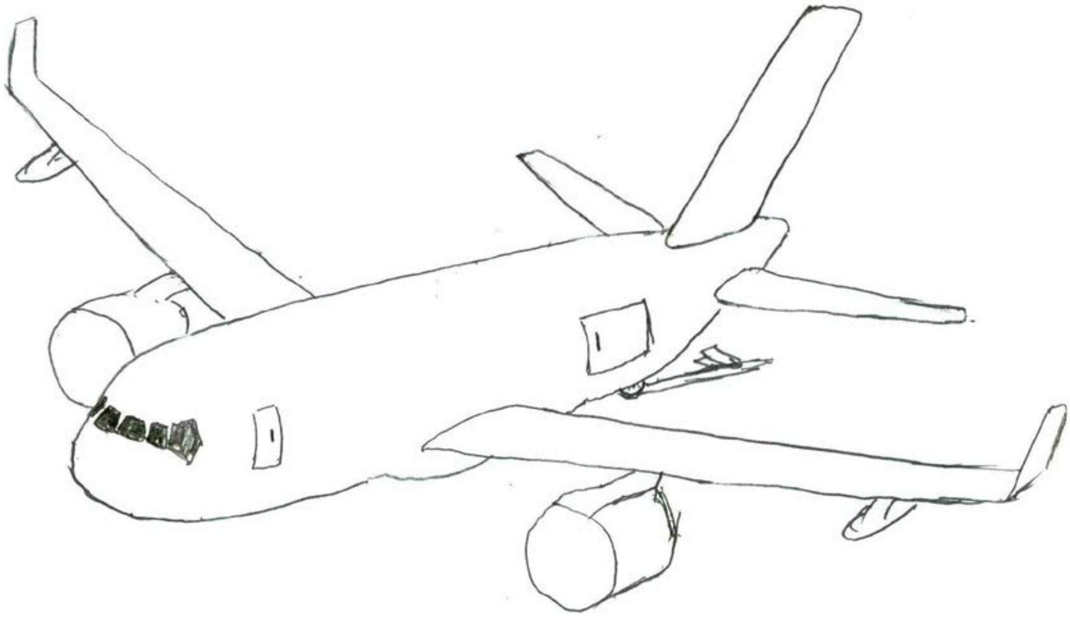

Figure3. 2 – Configuration Sketch

4.0 Weight Sizing

Before estimate the weight, the linear relationship between empty and takeoff weight is required. For a given value of takeoff weight, the allowable value for empty weight can be found from Eq. (4.1). According to four similar design tanker aircrafts, the design empty and takeoff weight relationship was found by AAA. The numerical value for the quantity A is 2.1898, B is 0.6588. The result is shown is figure 4.1.

$$W_e = \text{inv.}\log_{10}\{\frac{\log_{10} W_{To} - A}{B}\} \tag{4.1}$$

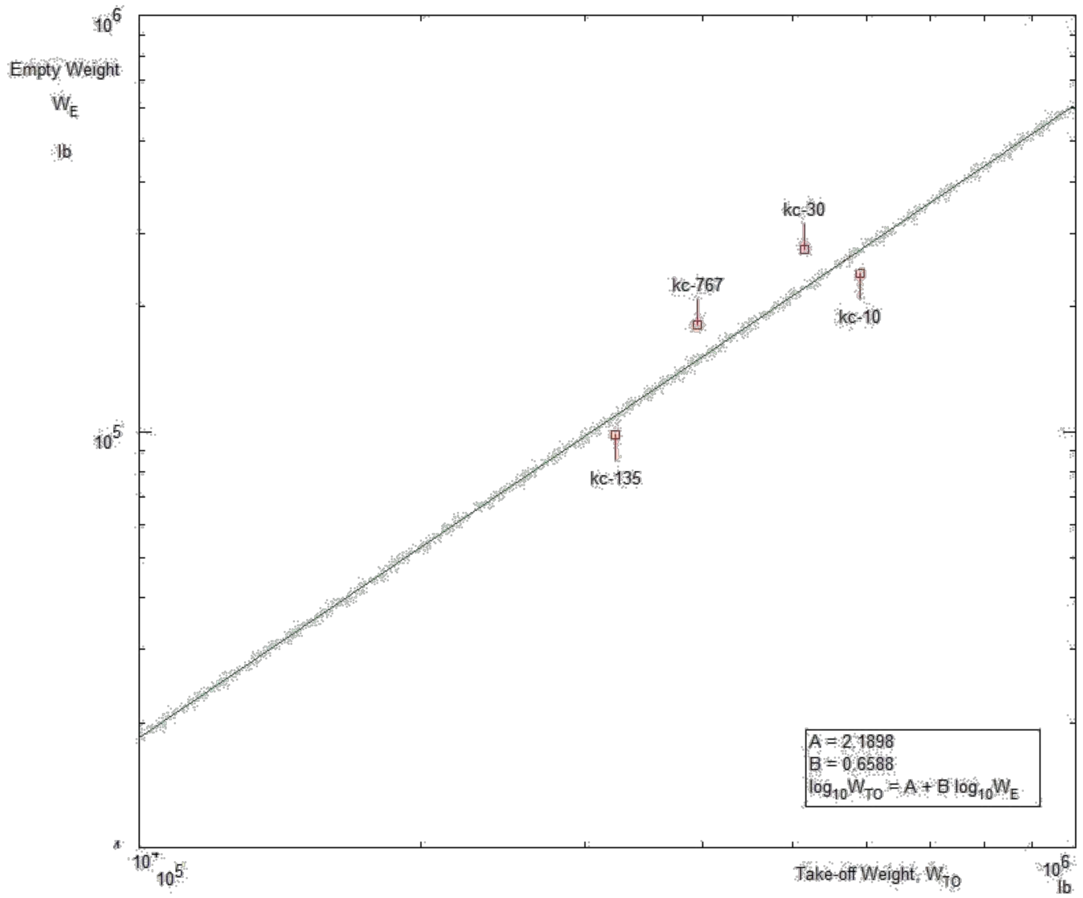

Figure4. 1 – Empty weight vs. takeoff weight relationship for tankers

4.1 Mission Fuel Weight

According to the mission profile, the fuel-fraction has 8 phases which includes: warm-up, taxi, takeoff, climb, cruise, loiter, descent and landing. The fuel-fraction for each phase is defined as the ratio of end weight to begin weight. Assume fuel-fraction ratios for warm-up, taxi and takeoff are 0.99. Assume the climb rate is 1500 feet per minute, average climb speed is 275 knots and the fuel-fraction for climb is 0.98. Assume the SFC for the KC-X is 0.5 and the lift to drag ratio is 14 during cruise. Eq. (4.2) shows the fuel-fraction for cruise. Climb to 40,000 feet require 26.6 minutes and the climb range is 122 nautical miles. The cruise range is 1288 nautical miles. The fuel-fraction for cruise is 0.907. Assume SFC is 0.6 during loiter and the lift to drag ratio is 16. The fuel-fraction for loiter is 0.963. Assume the fuel-fraction for descent and landing is 0.99. The overall mission fuel-fraction is 0.814, that means the used fuel weight is 18.6% of the takeoff weight. Assume 5% reserve fuel; the total fuel weight is 19.5% of the takeoff weight.

$$\frac{W_i}{W_{i-1}} = \exp\left(-\frac{RC_j}{V(L/D)}\right) \tag{4.2}$$

$$\frac{W_i}{W_{i-1}} = \exp\left(-\frac{EC_j}{L/D}\right) \tag{4.3}$$

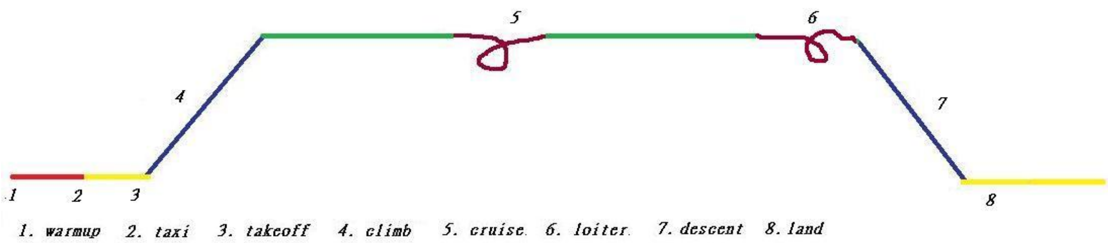

Figure4. 2 – Mission profile

4.2 Weight Estimation

According to Roskam's weight estimation method, the first step is to calculate the tentative value for operating empty weight and the second is to calculate the tentative value for empty weight. Eq. (4.4) and Eq. (4.5) are these two steps. Compare the tentative value empty weight to numerical empty weight shown in figure 4.1. The tolerance for the empty is 0.5% in the design process. The fuel weight is 0.195% of the takeoff weight, mission payload is 15,000 lbs, 200 lbs for each crew and assume 0.5% trapped fuel. The result is shown in figure 4.3, the takeoff weight is 330,000 lbs and the empty weight is 113,300 lbs.

$$W_{OE_{tent}} = W_{To_{guess}} - W_F - W_{PL} \tag{4.4}$$

$$W_{E_{tent}} = W_{OE_{tent}} - W_{tfo} - W_{crew} \tag{4.5}$$

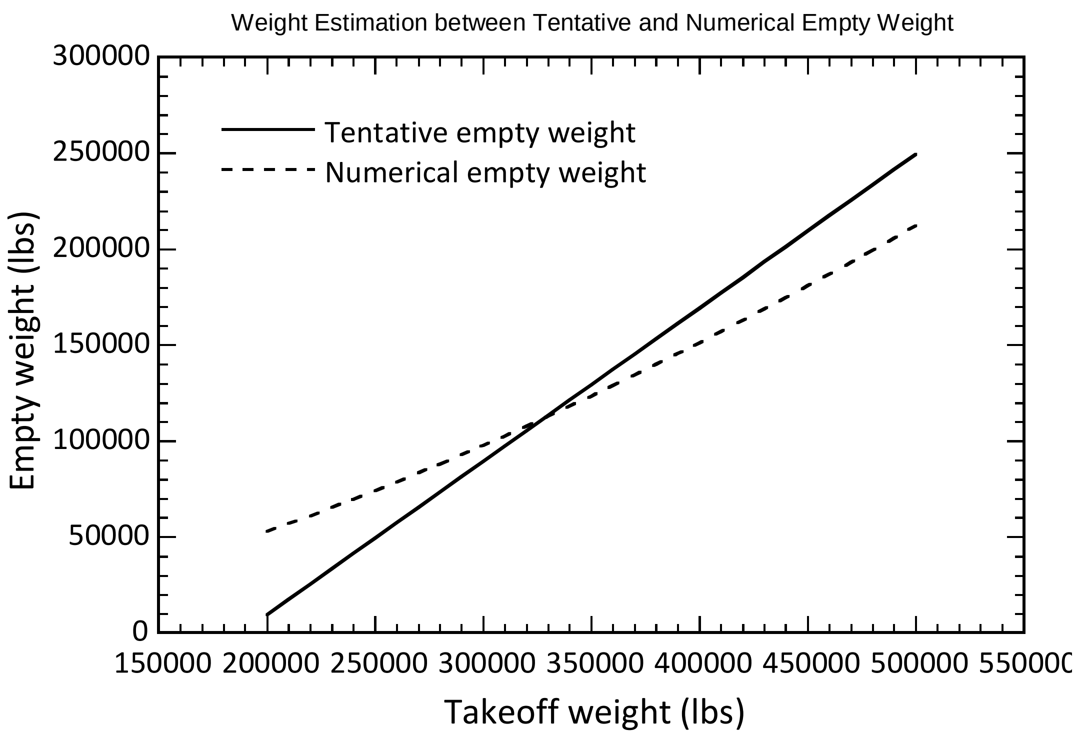

Figure4. 3 – Weight estimation between tentative and numerical empty weight

4.3 Sensitivity Studies

The sensitivity studies will show how aircraft takeoff weight varies with payload, empty weight, range, endurance, lift to drag ratio and specific fuel consumption. These study could assist aircraft adjust the takeoff weight if these parameters change. Here define three values C, D and F for convenient calculation. Eq. (4.9) to Eq. (4.13) are sensitivity equations for jet aircraft. Results are shown in table 4.1.

$$\mathrm{C} = \{1 - (1 + \mathrm{M_{res}})(1 - \mathrm{M_{ff}}) - \mathrm{M_{tfo}}\} \tag{4.6}$$

$$\mathrm{D} = (\mathrm{W_{PL}} + \mathrm{W_{crew}}) \tag{4.7}$$

$$\mathrm{F} = -\frac{\mathrm{BW_{To}^2(1+M_{res})M_{ff}}}{\mathrm{CW_{To}(1-B)-D}} \tag{4.8}$$

$$\frac{\partial \mathrm{W_{To}}}{\partial \mathrm{W_{PL}}} = \frac{\mathrm{BW_{To}}}{\mathrm{D-C(1-B)W_{To}}} \tag{4.9}$$

$$\frac{\partial \mathrm{W_{To}}}{\partial \mathrm{W_E}} = \frac{\mathrm{BW_{To}}}{\mathrm{invlog_{10}}\{\frac{\mathrm{log_{10}W_{To}-A}}{\mathrm{B}}\}} \tag{4.10}$$

$$\frac{\partial \mathrm{W_{To}}}{\partial \mathrm{R}} = \frac{\mathrm{FC_j}}{\mathrm{V(^L/_D)}} \tag{4.11}$$

$$\frac{\partial \mathrm{W_{To}}}{\partial \mathrm{E}} = \frac{\mathrm{FC_j}}{\mathrm{(^L/_D)}} \tag{4.12}$$

$$\frac{\partial \mathrm{W_{To}}}{\partial (^L/_D)} = -\frac{\mathrm{FRC_j}}{\mathrm{V(^L/_D)^2}} \tag{4.13}$$

Table4. 1 – Sensitivities to different parameters

Takeoff weight to payload weight	3.66
Takeoff weight to empty weight	1.92
Takeoff weight to range	77.45 lb/nm
Takeoff weight to lift-to-drag ratio	-8299 lb

4.4 Trade studies

Figure 4.4 shows the trade studies for payload and range. The main payload for the KC-X is fuel. It can be easily stored in the wing, so there is no upper limit for the payload weight. The minimum range requirement is the distance between Okinawa and South Korea which is 705 nautical miles. In this graph, the KC-X has the ability to undertake the refueling mission and the range for eighteen military pallets payloads also fits the cargo mission requirements.

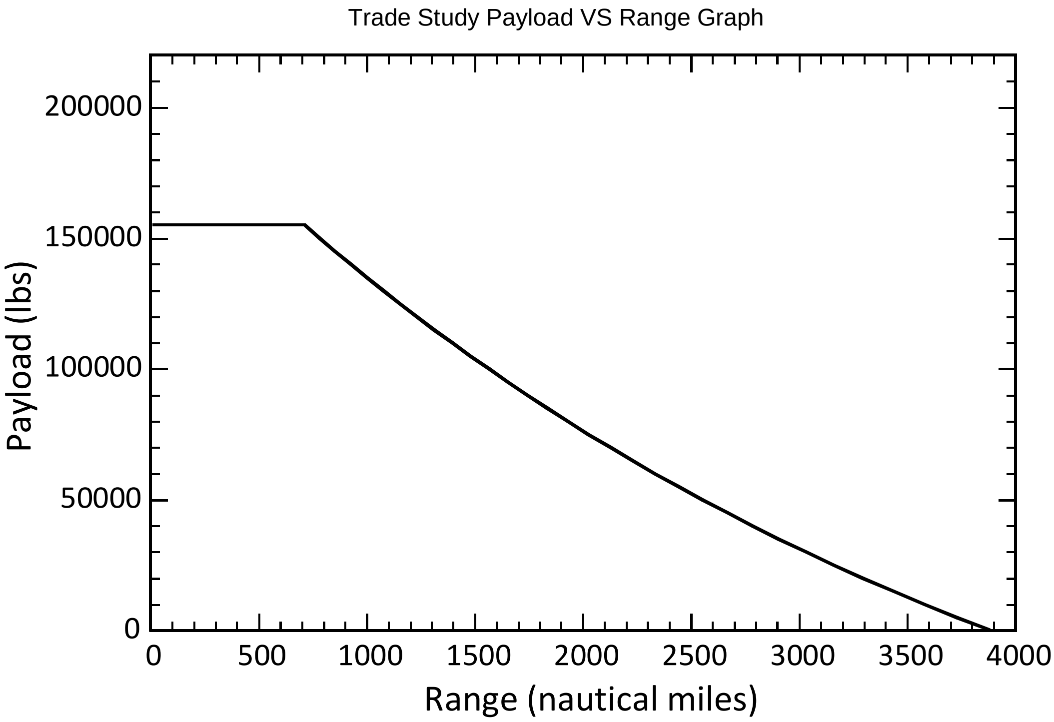

Figure4. 4 – Payload vs. range graph

5.0 Performance Sizing

Airplanes are usually designed to meet performance objectives in stall speed, takeoff field length, landing field length, cruise speed climb requirements. Wing area, takeoff thrust, maximum takeoff lift and maximum landing lift coefficient were affected by these performance. From these data, highest possible wing loading and lowest possible thrust to weight could be found with the lowest weight and the lowest cost.

5.1 Zero Lift Drag Estimation

Before calculate the performance requirements, the zero lift drag coefficient needs to be estimated. Accord to historical aircraft data, Roskam uses the log plot to find a numerical relation between equivalent parasite area and wetted area with different equivalent skin friction coefficient (Eq. 5.2). Figure 5.1 and 5.2 are the log plot from Roskam's. Assume the skin friction coefficient is 0.004, the value for a and b are -2.3979 and 1. The value for c and d is 0.1628 and 0.7316 for military transports. Combine Eq. (5.2) and Eq. (5.3) can get the equivalent parasite area from the takeoff weight. The zero lift drag coefficient for the KC-X is 0.0001921 W/S.

$$C_{D_0} = {}^{f}/_{S} \tag{5.1}$$

$$\log_{10} f = a + b\log_{10} S_{wet} \tag{5.2}$$

$$\log_{10} S_{wet} = c + d\log_{10} W_{To} \tag{5.3}$$

$$f = \mathrm{invlog}_{10}\{a + b(c + d\log_{10} W_{To})\} \tag{5.4}$$

$$C_{D_0} = \frac{\text{invlog}_{10}\{a+b(c+d\log_{10}W_{To})\}}{W_{To}} \times \frac{W_{To}}{S} \tag{5.5}$$

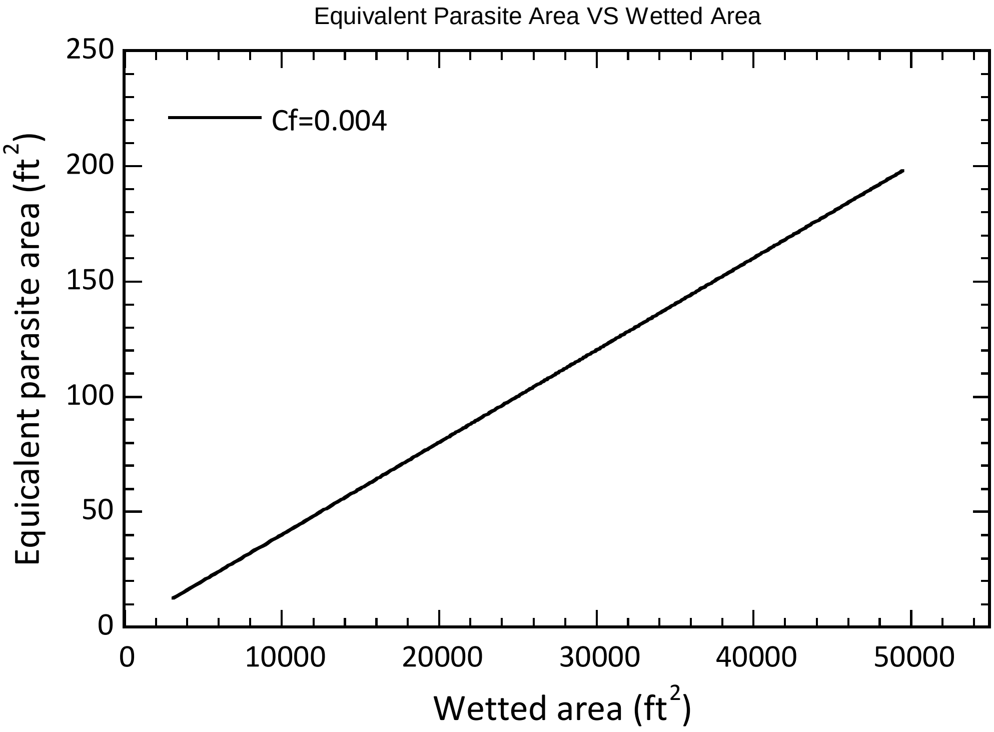

Figure5. 1 – Equivalent parasite area vs. wetted area

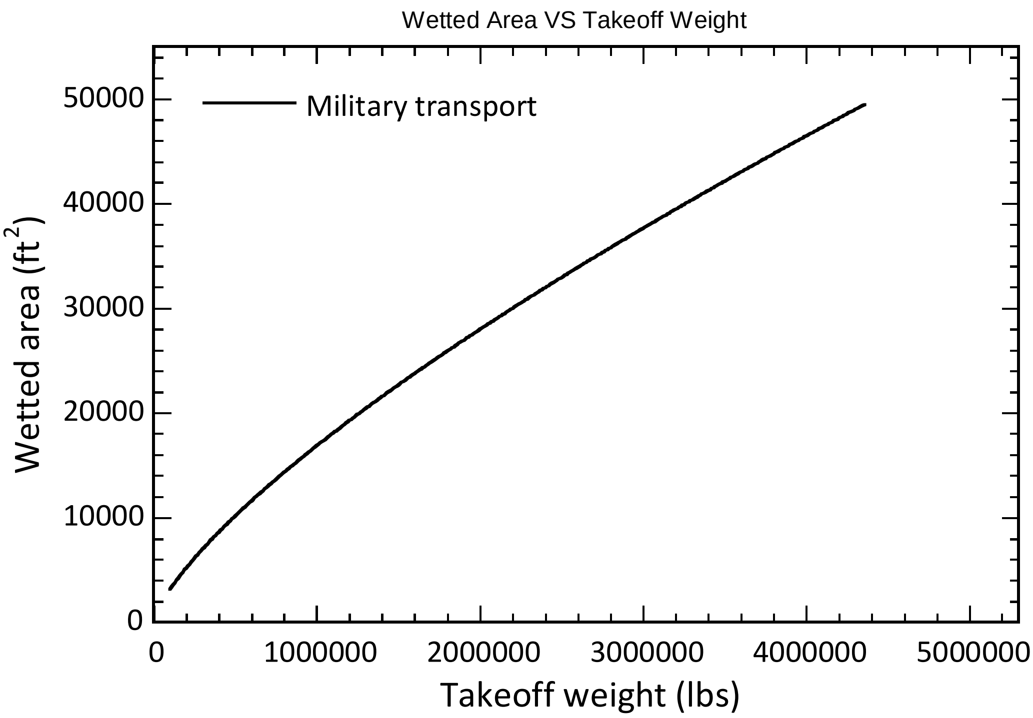

Figure5. 2 – Wetted area vs. takeoff weight

5.2 Takeoff Distance Requirement

The runway of Kadena Air Base in Okinawa is 12,140 feet long; the runway of Andersn Air Base in Guam is 11,155 and 10,555 feet long. The design takeoff distance for the KC-X is 10,000 feet. Eq. (5.6) shows the takeoff distance requirement for military aircrafts. Figure 5.3 shows the result for manual takeoff distance requirement calculations.

$$S_{TOG} = \frac{0.0447(\frac{W}{S})_{to}}{\rho[C_{L_{max}}\left\{0.75\left(\frac{5+\lambda}{4+\lambda}\right)\left(\frac{T}{W}\right)_{to}-0.025\right\}-0.72C_{D_0}]} \tag{5.6}$$

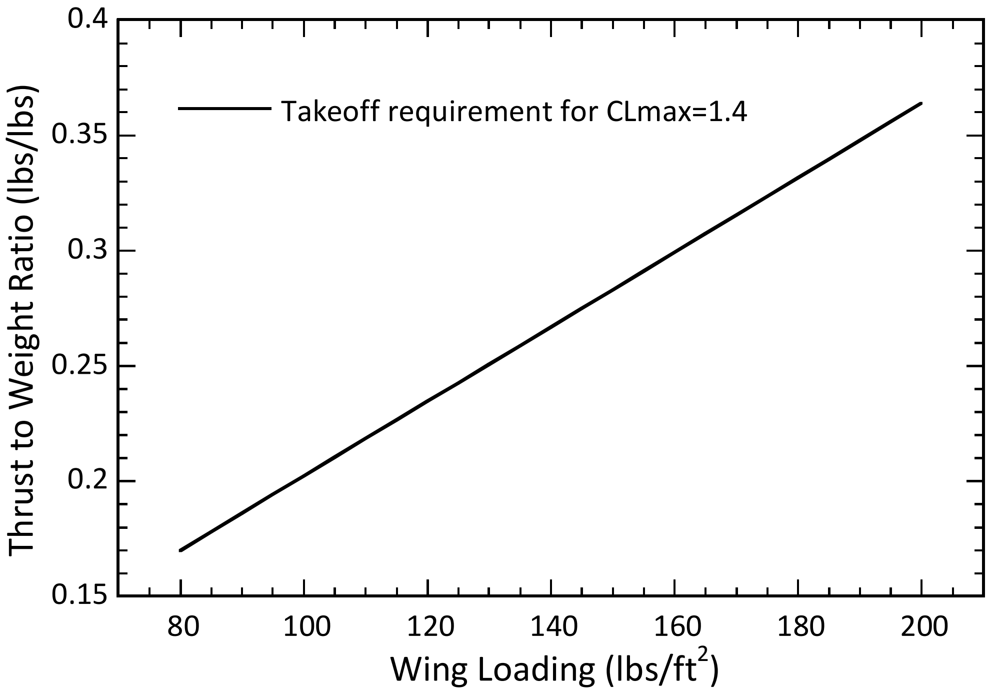

Figure5. 3 – Takeoff distance requirement for CLmax=1.4

5.3 Landing Distance Requirement

The design landing distance for the KC-X is also 10,000 feet. Eq. 5.7 shows the landing distance requirement for military aircrafts. For maximum landing lift coefficient 1.8, the maximum wing loading is 148. Result is shows in figure 5.4.

$$S_{FL} = \frac{2\frac{W}{S}}{\rho C_{L_{max}}} \tag{5.7}$$

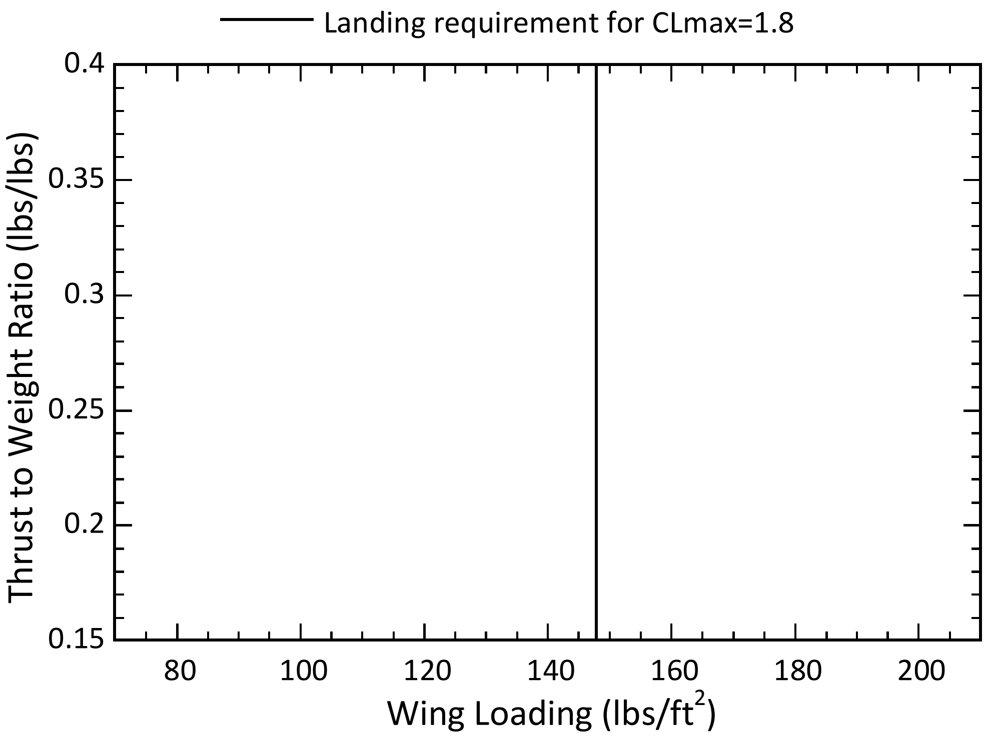

Figure5. 4 – Landing distance requirement for CLmax=1.8

5.4 One Engine Climb Requirement

Eq. (5.8) shows one engine failure climb requirement, N is the engine number and CGR is the climb gradient. The climb rate of the KC-X is 1500 feet minute and the average climb speed is 275 knots. The climb gradient is 0.053, the configuration is gear up, flaps up and maximum continuous thrust on remain engines is 1.25 stall speed. The result is shown is figure 5.5.

$$\frac{T}{W} = N\frac{C_{D_0} + \frac{C_L^2}{\pi A e}}{C_L} + CGR \tag{5.8}$$

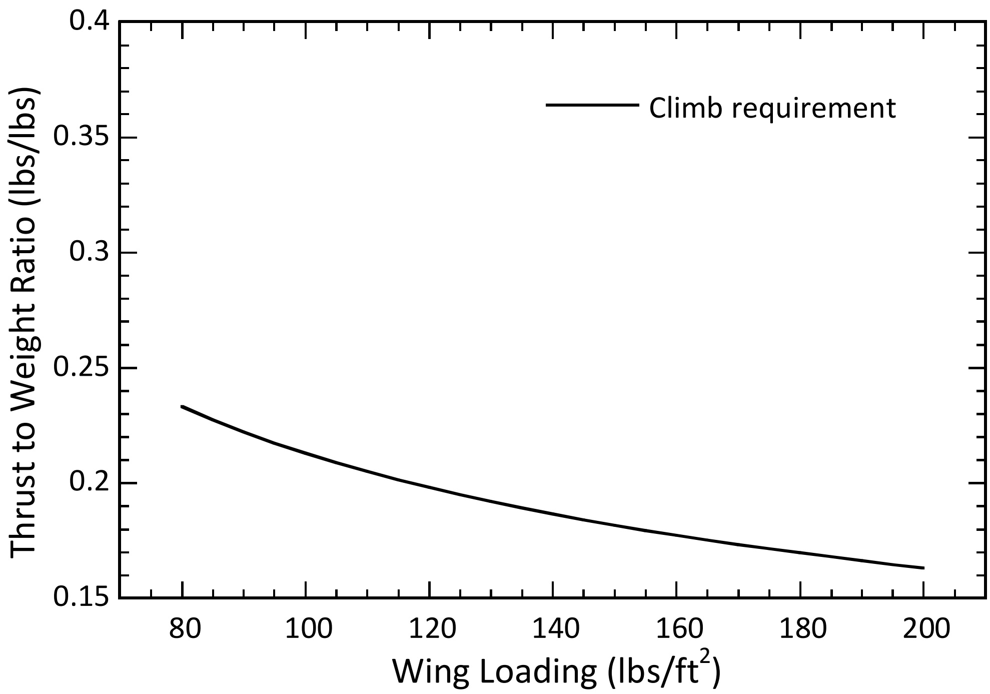

Figure5. 5 – One engine failure climb requirement

5.5 Cruise Speed Requirement

Eq. (5.9) shows the cruise requirement for jet aircrafts. The cruise speed of the KC-X is 0.83 and the aspect ratio use 10. Result is shown in figure 5.6.

$$\frac{T}{W} = C_{D_0} q \frac{S}{W} + \frac{W}{qS\pi Ae} \qquad (5.9)$$

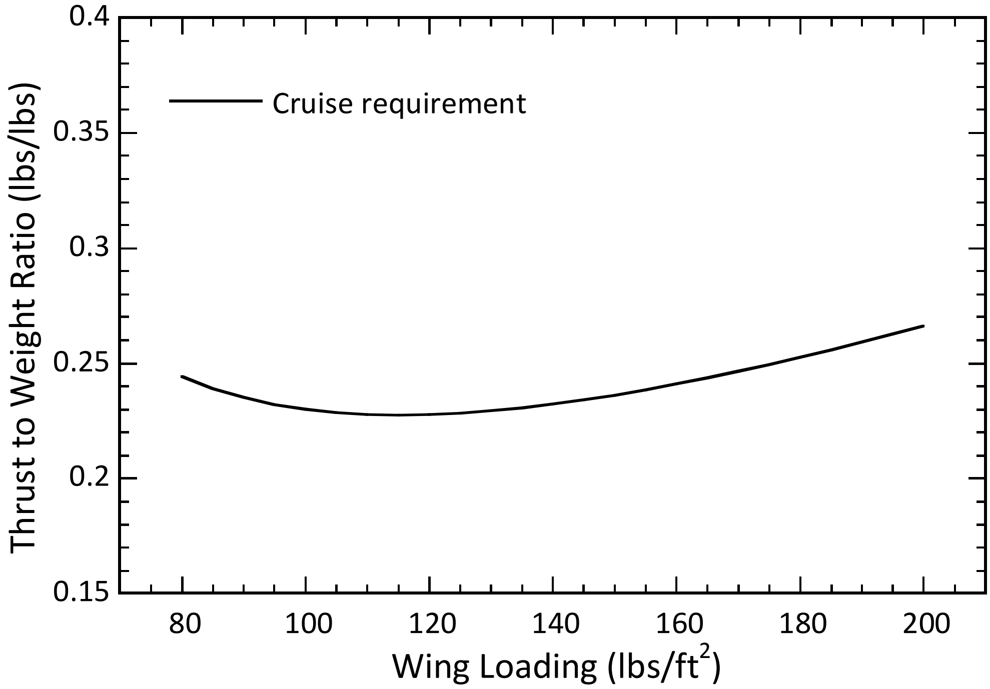

Figure5. 6 – Cruise speed requirement for aspect ratio 10

5.6 Matching for All Requirements

Combine figure 5.3 to figure 5.6, takeoff distance, landing distance, one engine failure climb and cruise speed requirements are all shown in figure 5.7. The best design point P is takeoff lift coefficient 1.4, the lowest thrust to weight ratio 0.23 and the highest wing loading 120. Figure 5.8 shows the AAA results.

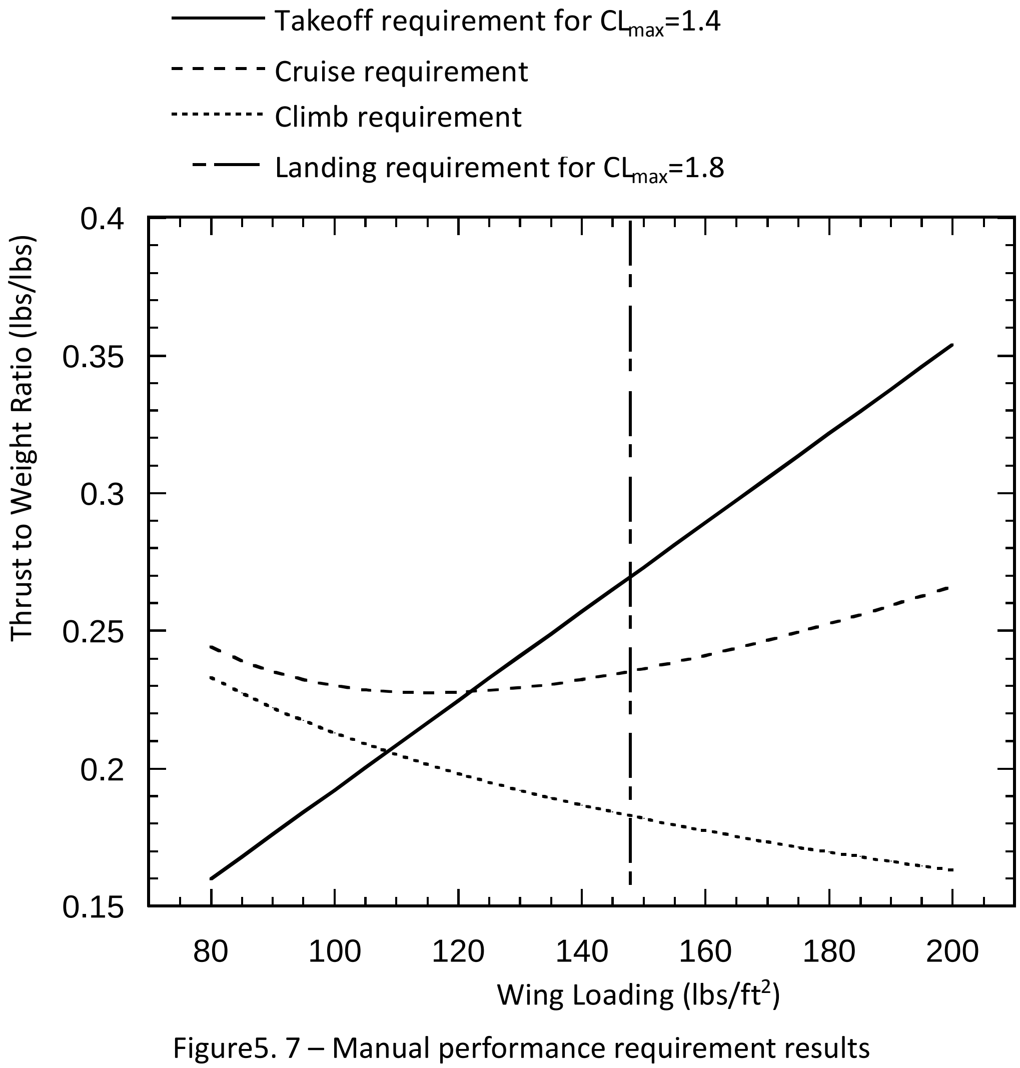

Figure5. 7 – Manual performance requirement results

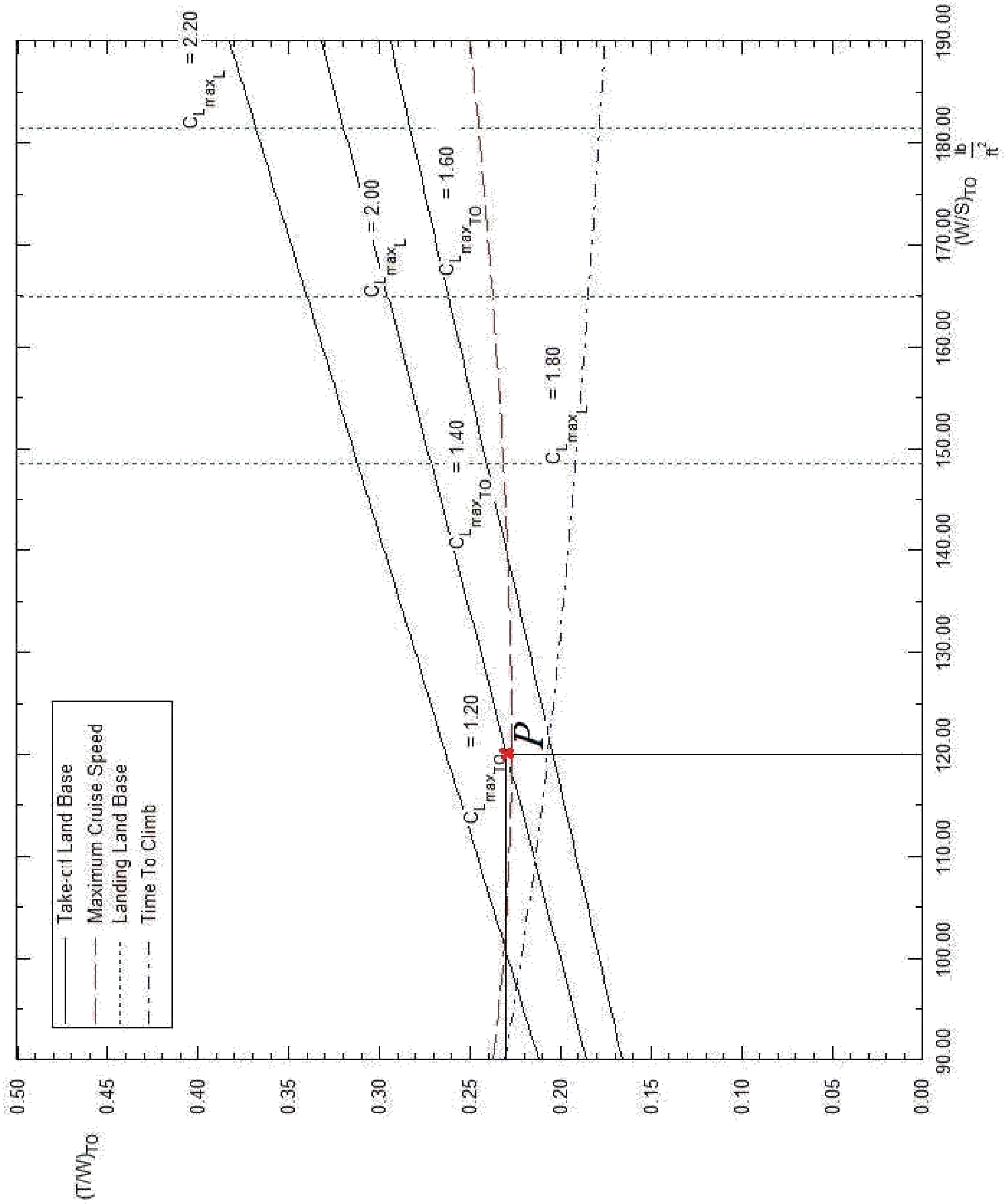

Figure5. 8 – AAA performance requirement results

5.7 Thrust

The thrust could be calculated from the takeoff thrust to weight ratio. 0.23 is the lowest thrust to weight ratio fit all performance requirements. The total thrust for the KC-X is 75900 pounds, 37950 pounds for each engine. Model CF6-6 engine (shown in fig 5.9) from GE Company has maximum power of 41500 lbs. It was also select for the DC-10. SFC at maximum power is 0.35, the dry weight is 8200 pounds, the length is 16 feet and maximum diameter is 8.75 feet.

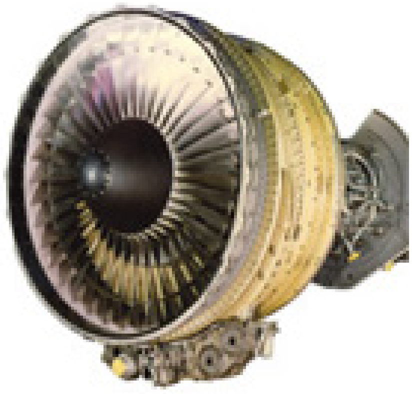

Figure5. 9 – CF6-6 engine

Table5. 1 – Properties of CF6-6 engine

Max Diameter (inch)	105
Length (inch)	188
Dry Weight (lb)	8200
SFC	0.35
Max Power at sea level(lbf)	41500
Pressure Ratio	25-25.5
Bypass Ratio	5.76-5.92

6.0 Fuselage

According to different missions, the fuselage length should allow 150 passengers or 18x464L military cargo pallets. The total length of the fuselage is 150 feet, the maximum diameter of the fuselage is 18.75 feet and th length of the fuselage cone is 65.625 feet. The definition of geometric fuselage parameters are shown in figure 6.1. The thickness of the fuselage is 5.5 inches.

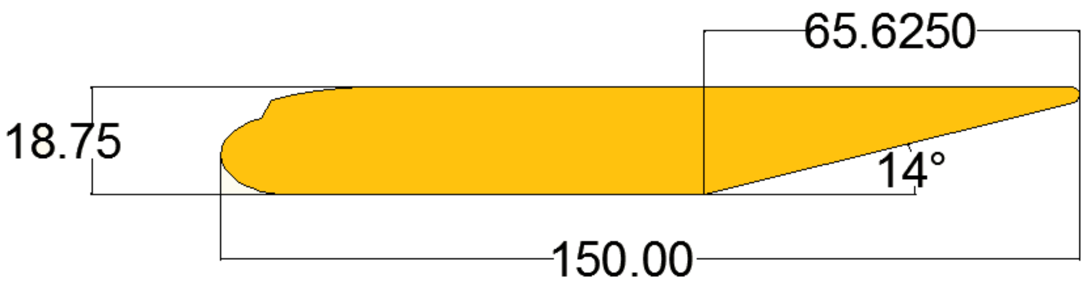

Figure6. 1 – General arrangement of the fuselage

6.1 Cabin

Figure 6.2 shows the top view of the cabin for cargo and medical evacuation mission. For the medical evacuation mission, comfert is the the first requirement. The cabin will have two level classes. The first class will contain enght wide and comfert seats for officers and serious injuries. The first class have two rows, four seats per row. Seats in the first class could adjust 45 degrees, requireed length is 50 inches. The other cabin has 143 seats, 17 rows for minor injuries, seven seas per row, four rows for medical staff, six seats per row. All seats could bend 30 degrees for rest and the require length is 47 inches. For cargo mission, the length of the 464L military is 108 inches and 88 inches in width. 150 feet is an enough length for nine pallets and the width could allow two pallets, 18 pallets is the total carrying number. Figure 6.3 shows the cabin cross section area. The first level is 8 feet high and 18.14 wide. The thickness of the handling floor is 1 feet in order to handle heavy cargos in cargo mission. The hight of the lower level is 9.3 feet for the wing and extra fuel tank mounted in the fuselage.

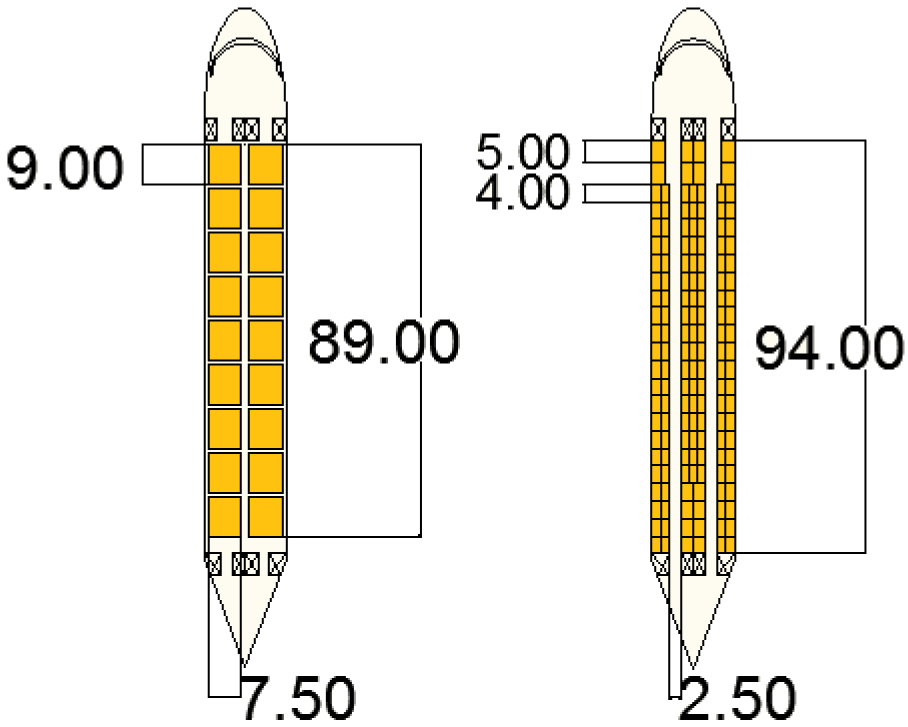

Figure6. 2 – Cabin top view

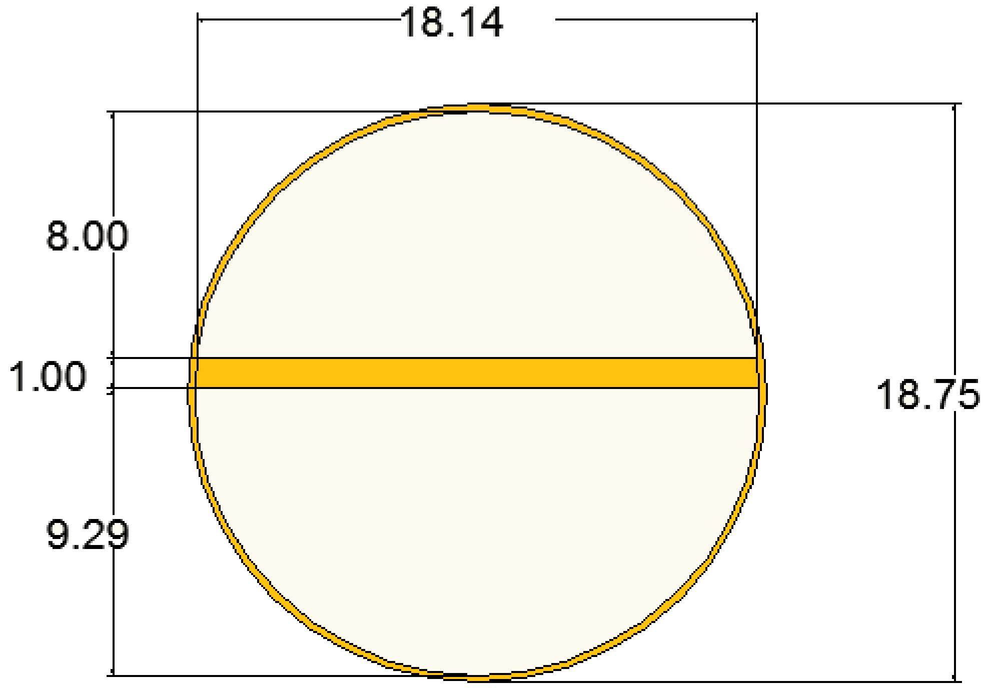

Figure6. 3 – Cabin cross section

6.2 Cockpit

Figure 6.4 illustrate the visibilities for the cockpit. The horizontal visibility ranges are from 136 degrees port to 114 degrees starboard. The vertical visibility range is 16 degrees up and down.

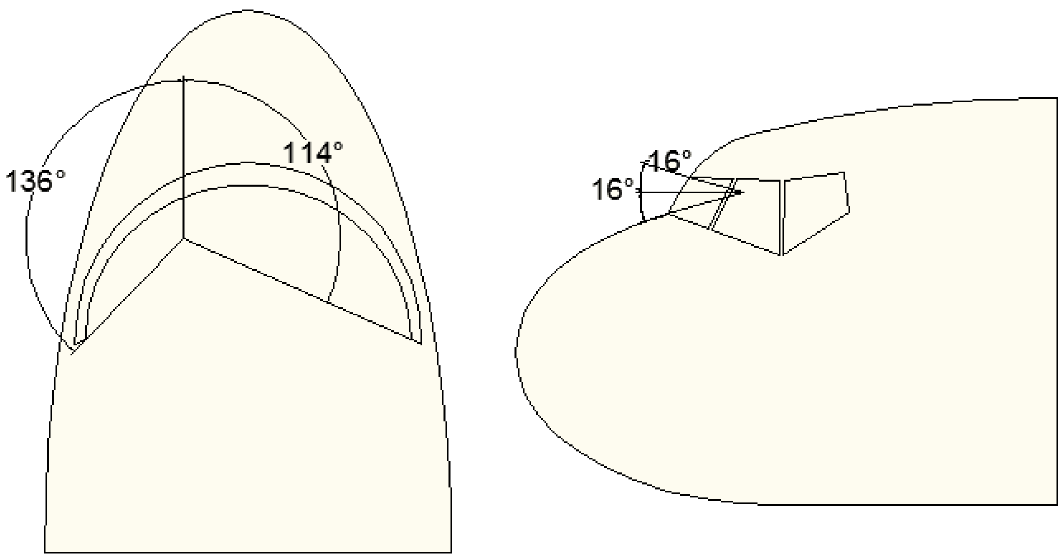

Figure6. 4 – Visibilities for the cockpit

7.0 Wing

From the performance requirements, the wing loading for thrust to weight ratio 0.23 is 120. The wing area calculated form that is 2750 ft^2. The aspect ratio used for the cruise requirement is 10. The KC-X will use this aspect ratio to calculate the span and chord length. The tapper ratio selected for the KC-X is 0.35. The span length is 165.83 feet. The root chord length is 24.56 feet and the tip chord is 8.6 feet.

$$b_w = \sqrt{AR \times S_w} = \sqrt{10 \times 2750} = 165.83 \text{ ft}$$

$$C_r = \frac{2b}{(1+\lambda)AR} = \frac{2 \times 165.83}{(1+0.35) \times 10} = 24.56 \text{ ft}$$

$$C_t = \frac{2b\lambda}{(1+\lambda)AR} = \frac{2 \times 165.83 \times 0.35}{(1+0.35) \times 10} = 8.6 \text{ ft}$$

7.1 Thickness ratio and sweep angle

The thickness ratio will follow Roskam's sweep angle relation figure. Eq. (7.1) shows the relationship between Mach number, cruise lift coefficient, thickness ratio and sweep angle. Thickness ratio cannot be less than 0.1 to allow enough room for the wing structure and the fuel. It also should not be over 0.2 because the profile drag of the wing is going to be too high. According to Roskam's preliminary design part, Eq. (7.2) provides the approximate cruise lift coefficient. Figure 7.1 shows the result for thickness ratio and sweep angle relation. The Thickness ratio selected for the KC-X is 0.12 and the leading edge sweep angle is 50 degrees.

$$\frac{M_{cc}^2 \cdot \cos^2\Lambda}{\sqrt{(1-M_{cc}^2 \cdot \cos^2\Lambda)}} \cdot \left[\left(\frac{\gamma+1}{2}\right) \cdot \frac{2.64 \cdot \left(t/c\right)}{\cos\Lambda} + \left(\frac{\gamma+1}{2}\right) \cdot \frac{2.64 \cdot \left(t/c\right)\left(0.34 \cdot C_L\right)}{\cos^3\Lambda}\right]$$
$$+\frac{M_{cc}^2 \cdot \cos^2\Lambda}{1-M_{cc}^2 \cdot \cos^2\Lambda} \cdot \left[\left(\frac{\gamma+1}{2}\right)\left(\frac{1.32 \cdot \left(t/c\right)}{\cos\Lambda}\right)^2\right] +$$
$$M_{cc}^2 \cdot \cos^2\Lambda \cdot \left[1 + \left(\frac{\gamma+1}{2}\right) \cdot \frac{\left(0.68 \cdot C_L\right)}{\cos^2\Lambda} + \left(\frac{\gamma+1}{2}\right) \cdot \left(\frac{\left(0.34 \cdot C_L\right)}{\cos^2\Lambda}\right)^2\right] - 1 = 0 \tag{7.1}$$

$$C_{L_{cr}} = \frac{W_{TO} - 0.4W_F}{qS} = \frac{330000 - 0.4 \times 64449}{\frac{1}{2} \times 0.000583 \times 803.412^2 \times 2750} = 0.59 \tag{7.2}$$

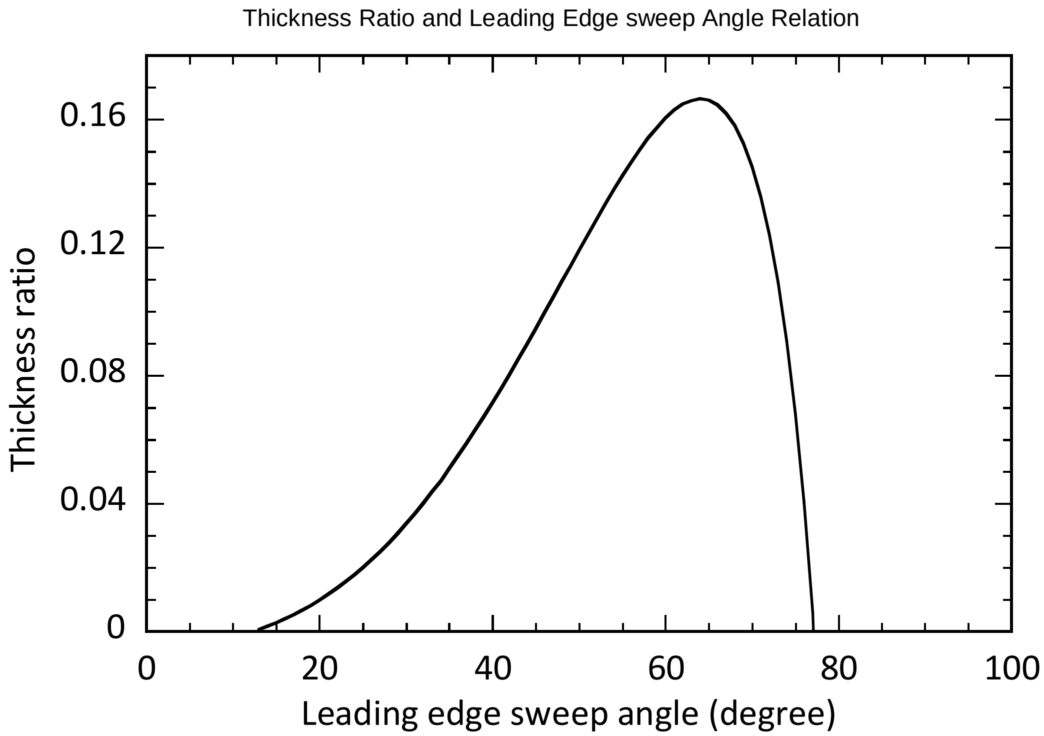

Figure7. 1 – Thickness ratio and leading edge sweep angle relation

7.2 Airfoil

Due to the thickness ratio is 12%, the KC-X will use thickness 12% airfoils for both root and tip for easy calculations. The airfoil selected for the root is NACA 64_1-212 (fig. 7.2), the lift slop for this airfoil is 6.4744, zero lift angle is -2 degrees, stall angle is 15 degrees. NACA 64_1-412 (fig. 7.3) is the tip airfoil for the KC-X. The lift slope for the NACA 64_1-412 airfoil is 6.171, zero lift angle is 1, stall angle is 15 degrees. The incidence angle for the root is 10 degrees and the tip has a -2 degrees twist. The wing has a washout design, the wing root stalls before the wing tip in order to provide the KC-X with continued aileron control. The lifting line method is used to determine the lift distribution of the wing. The zero angle of attack lift coefficient for an unsweep wing is 0.8896. Figure 7.4 illustrate the zero angle of attack lift distribution for the wing. For a 50 degrees sweep wing, the lift coefficient is 0.59 which is high enough to keep the KC-X fly level. The maximum lift coefficient is 0.9, figure 7.5 shows the lift distribution for the maximum lift coefficient at 5 degrees angle of attack.

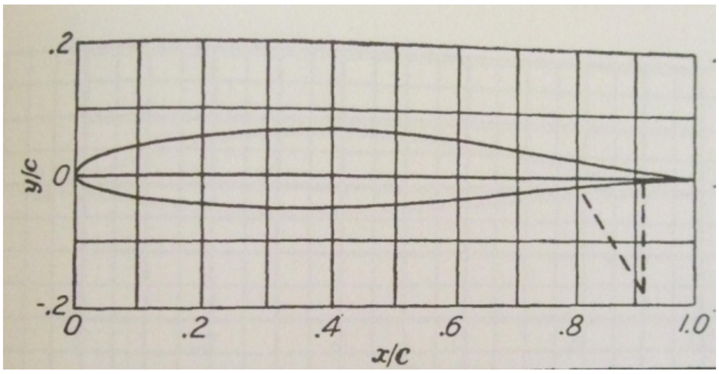

Figure7. 2 – NACA 641-212 airfoil

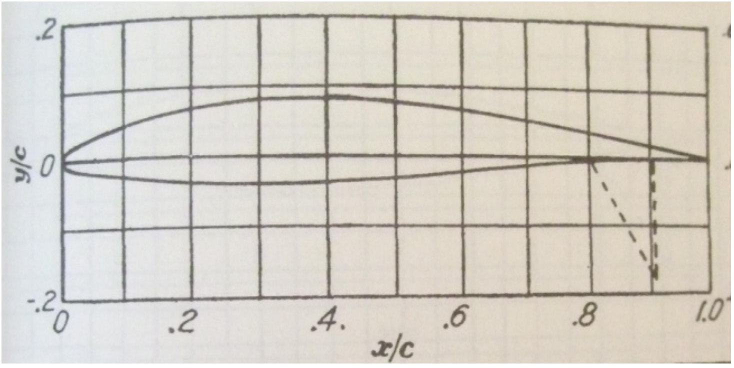

Figure7. 3 – NACA 641-412 airfoil

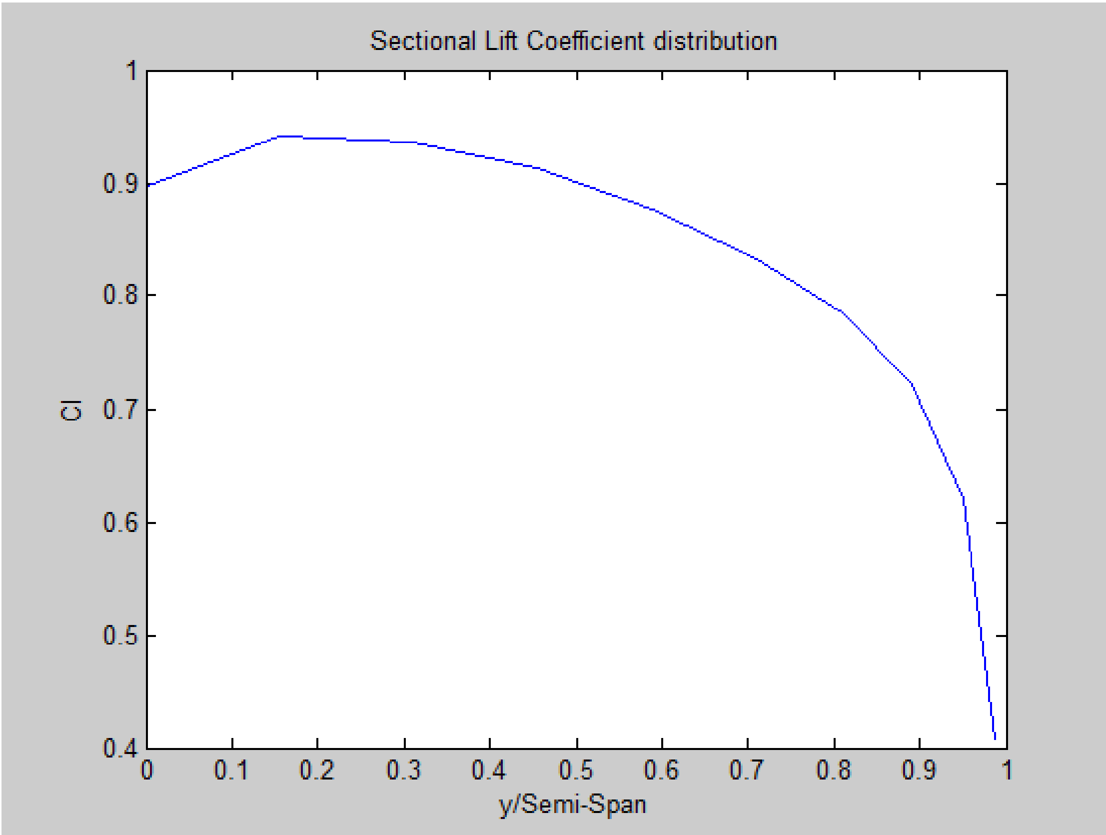

Figure7. 4 – Zero angle of attack lift distribution

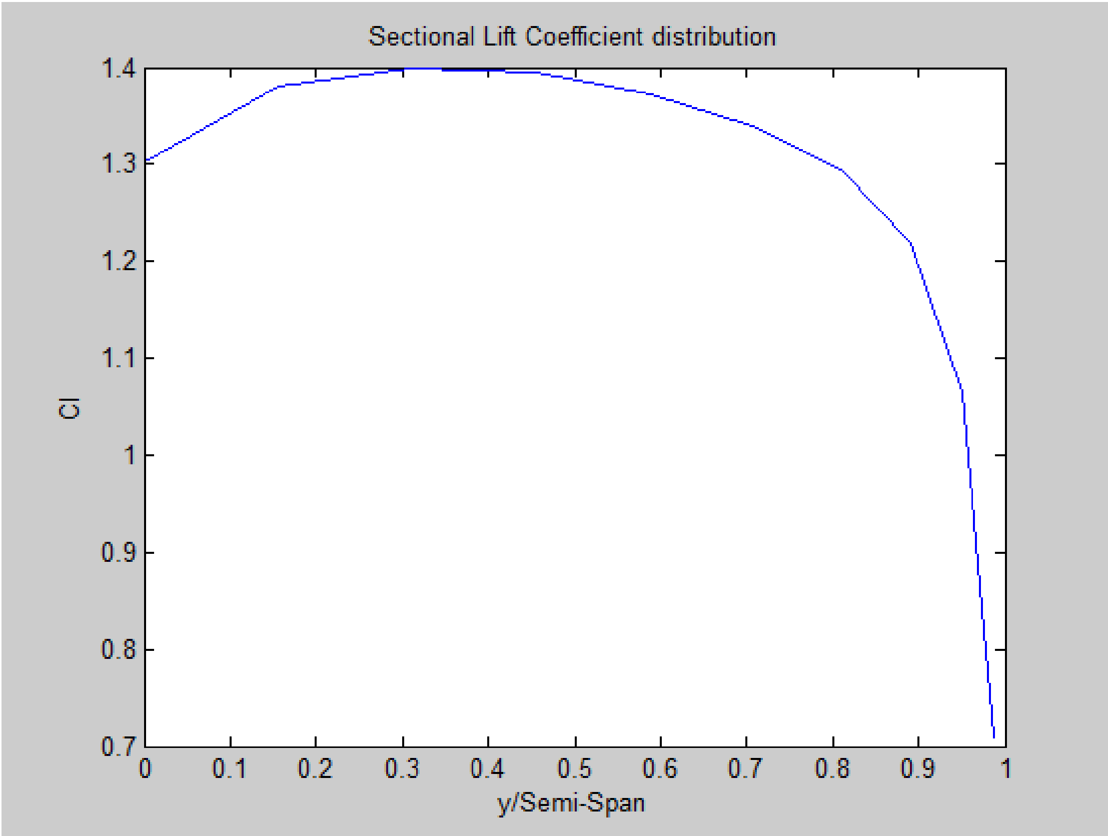

Figure7. 5 – 5 degrees angle of attack lift distribution

7.3 CAD Model

The semi-wing CAD model is shown in figure 7.6. A 50 degrees sweep back straight wing, the semi-length of the span is 82.915 feet, the root chord length is 24.56 feet, the tip chord length is 8.6 feet and the mean aerodynamic chord is 19.04 feet. The lift coefficient is 0.64 at zero angle of attack. The wing will have a 3 degrees dihedral for control and stability.

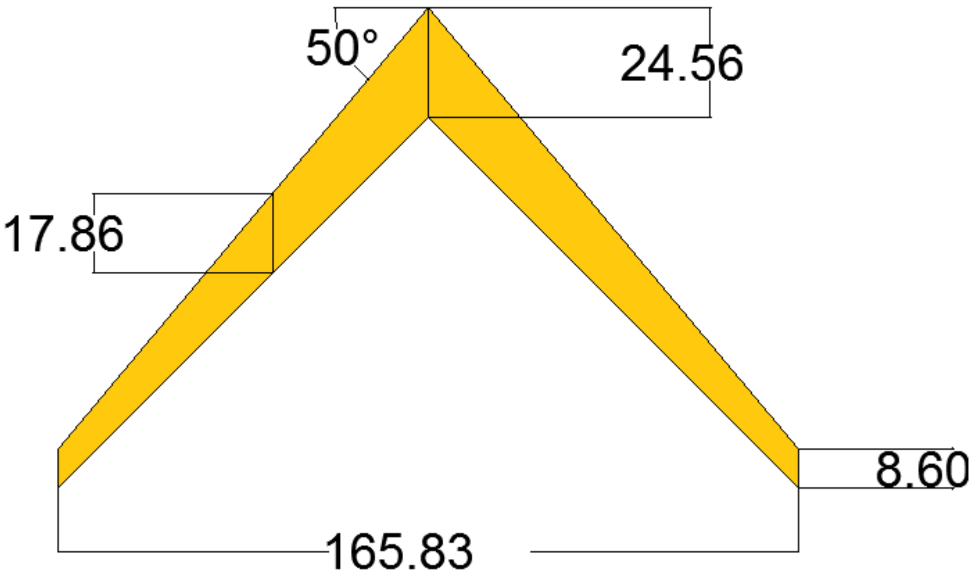

Figure7. 6 – CAD model of the wing

7.4 Flaps

According to the takeoff and landing requirements, the takeoff lift coefficient is 1.4 and the landing coefficient is 1.8 for 10,000 feet runway takeoff and landing. Eq. (7.3) to Eq. (7.5) determined required incremental section maximum lift coefficient with flap down. The wing of the KC-X will include a double-slotted fowler flap on the trailing edge. The flap start from 20% to 50% of the semi-span and the chord is 20% of the airfoil. Eq. (7.6) presents the incremental section lift coefficient due to the fowler flap. Compare results from Eq. (7.1) and Eq. (7.4), the flap deflection angle during takeoff is 13 degrees and 24 degrees during landing. Figure 7.9 shows the CAD model of the flaps.

$$\Delta C_{l_{max}} = \Delta C_{L_{max}} (S/S_{wf}) K_\Lambda \tag{7.3}$$

$$K_\Lambda = (1 - 0.08\cos^2\Lambda_{c/4})\cos^{3/4}\Lambda_{c/4} \tag{7.4}$$

$$S_{wf}/S = (\eta_0 - \eta_i)\{2 - (1 - \lambda)(\eta_i + \eta_0)\}/(1 + \lambda) \tag{7.5}$$

$$\Delta C_l = 2\pi(1 + c_f/c) a_{\delta_f} \delta_f \tag{7.6}$$

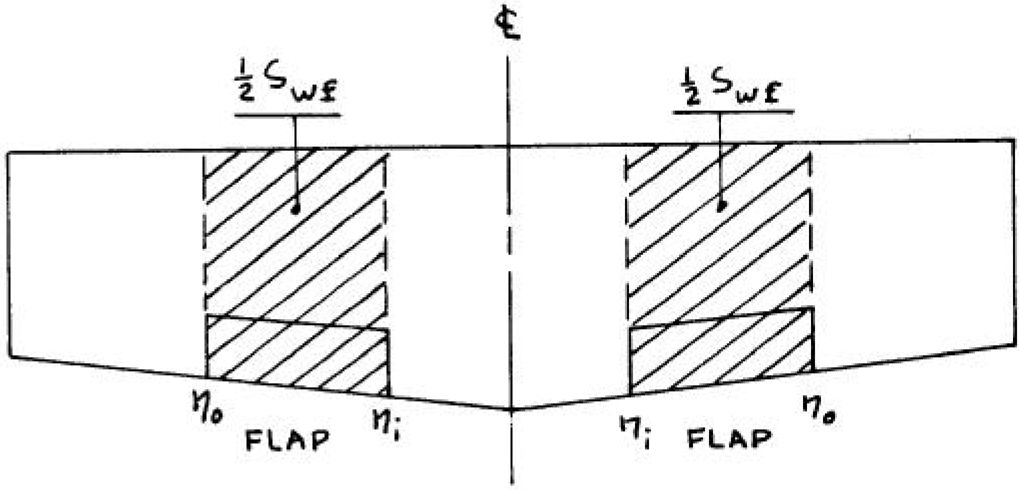

Figure7. 7 – Definition of flapped wing area

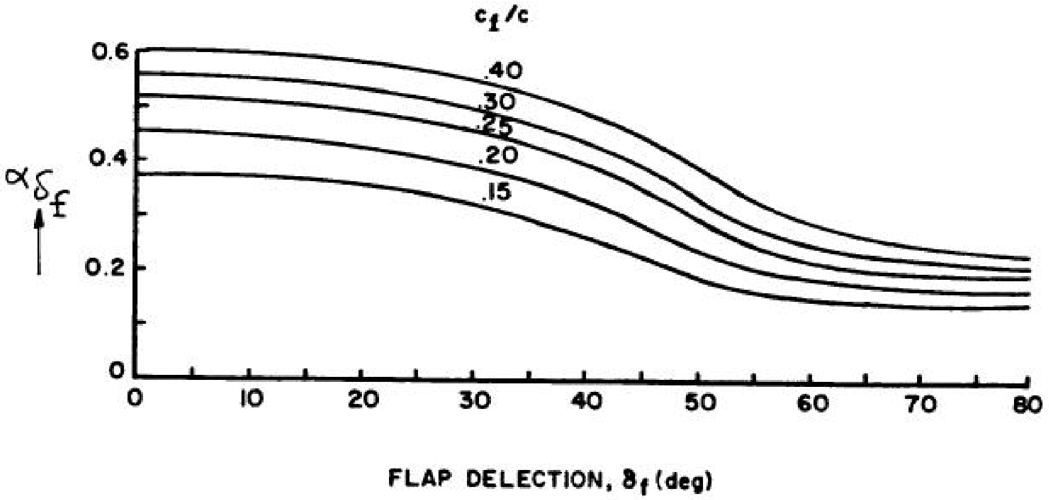

Figure7. 8 – Section lift effectiveness parameter for fowler flap

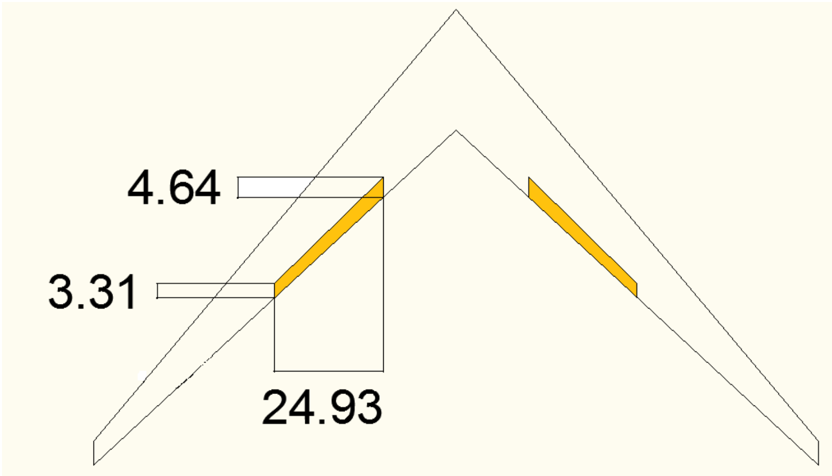

Figure7. 9 – CAD model for flaps

7.5 Aileron

The aileron for thx KC-X will start from 55% to 90% of the semi-span; the chord is 20% of the airfoil. Total aileron area is 134.4 feet square. Compare to similar designs, the aileron to wing area ratio is close. Table 7.1 shows the ratio for KC-767 and KC-10.

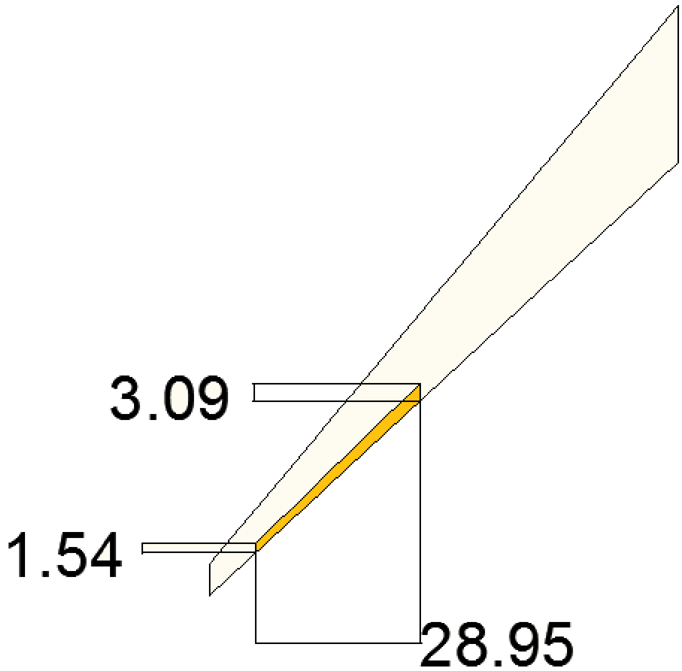

Figure7. 10 – CAD model of aileron

Table7. 1 – Similar aircraft aileron area

	Wing Area	Aileron Area	Aileron to Wing ratio
KC-767	3,050 ft^2	125.05 ft^2	0.041
KC-10	3,958 ft^2	186 ft^2	0.047
KC-X	2,750 ft^2	134.4 ft^2	0.048

7.6 Fuel Volume

The KC-X will transport 150,000 lbs of JP-4. For the transport fuel mission, the KC-X has to carry total 214450 lbs fuel. In the preliminary design, Torenbeek wing fuel volume equation is used to estimate the wing fuel volume. Eq. (7.7) is the Torenbeek wing fuel volume equation. The root and tip thickness are both 0.12. The KC-X could carry total 2544.68 cubic feet (19035 gallons) of JP-4. Convert to weight; the total weight is 124678.25 lbs. 89770 lbs fuel will be stored in the fuselage.

$$V_{WF} = 0.54\left({S^2}/{b}\right)({t}/{c})_r\{(1+\lambda_W\tau_w^{1/2}+\lambda_w^2\tau_w)/(1+\lambda_w)^2 \qquad (7.7)$$

$$\tau_w = \frac{(\frac{t}{c})_t}{(\frac{t}{c})_w}$$

8.0 Empennage

The area of the empennage was determined using the tail volume coefficient method. The recommended horizontal stabilizer volume coefficient for military cargo aircraft is 1 and the vertical stabilizer volume coefficient is 0.08. The KC-X will use all moving vertical stabilizer so the vertical volume coefficient could be reduced 15%. Eq. (8.1) and Eq. (8.2) express the volume coefficient; the moment is an important factor for the volume coefficient. The length of the moment arm is the distance from the wing quarter mean chord to the horizontal stabilizer or vertical stabilizer quarter mean chord. The moment arm for the horizontal stabilizer is 57% of the fuselage length and 50% for the vertical stabilizer.

$$\mathrm{C_{HT}} = \frac{\mathrm{L_{HT}S_{HT}}}{\mathrm{C_w S_w}} \tag{8.1}$$

$$\mathrm{C_{VT}} = \frac{\mathrm{L_{VT}S_{VT}}}{\mathrm{b_w S_w}} \tag{8.2}$$

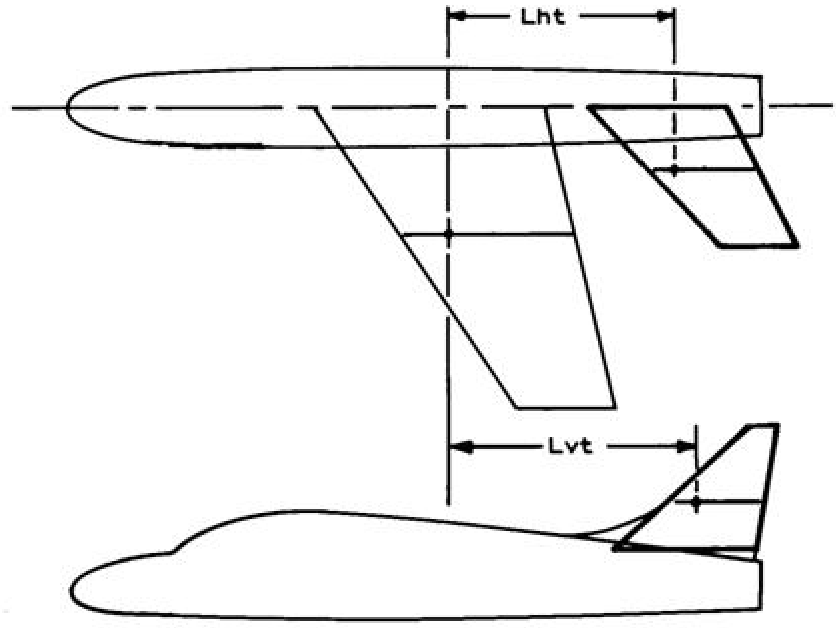

Figure8. 1 – Moment arm for the tail volume coefficient

8.1 Horizontal Stabilizer

Rewrite Eq. (8.1), the area of the horizontal stabilizer is 574.6 square feet. The sweep angle for the horizontal stabilizer is 45 degrees, the aspect ratio is 4 and the tapper ratio is 0.4. The span length is 47.94 feet, semi-span length is 23.97 feet, the root chord length is 17.12 feet, the tip chord length is 6.85 feet and the mean aerodynamic chord is 12.72 feet.

$$S_{Ht} = C_{Ht}C_{w}S_{w}/L_{Ht} \tag{8.3}$$

$$S_{HT} = \frac{1 \times 17.86 \times 2750}{0.57 \times 150} = 574.6\ \mathrm{ft}^2$$

$$b_w = \sqrt{AR \times S_w} = \sqrt{4 \times 574.6} = 47.94 \text{ ft}$$

$$C_r = \frac{2b}{(1+\lambda)AR} = \frac{2 \times 47.94}{(1+0.4) \times 4} = 17.12 \text{ ft}$$

$$C_t = \frac{2b\lambda}{(1+\lambda)AR} = \frac{2 \times 47.94 \times 0.4}{(1+0.4) \times 4} = 6.85 \text{ ft}$$

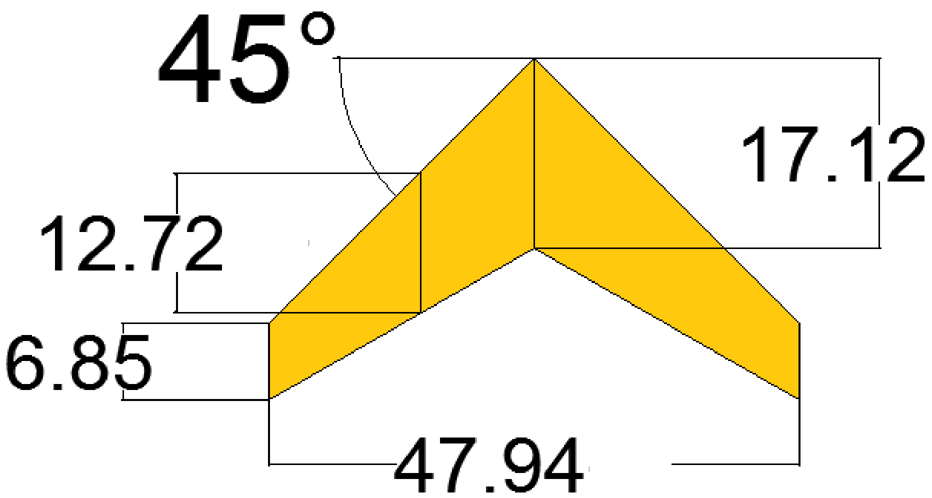

Figure8. 2 – CAD model for the horizontal stabilizer

8.2 Vertical Stabilizer

The area of the Vertical stabilizer is 413.47 square feet. The sweep angle for the horizontal stabilizer is 45 degrees, the aspect ratio is 1.3 and the tapper ratio is 0.6. The span length is 23.18 feet, the root chord length is 22.29 feet, the tip chord length is 13.37 feet and the mean aerodynamic chord is 18.2 feet.

$$S_{vt} = C_{vt} b_w S_w / L_{vt} \tag{8.4}$$

$$S_{VT} = \frac{0.068 \times 165.83 \times 2750}{0.5 \times 150} = 413.47\ \text{ft}^2$$

$$b_w = \sqrt{AR \times S_w} = \sqrt{1.3 \times 413.47} = 23.18\ \text{ft}$$

$$C_r = \frac{2b}{(1+\lambda)AR} = \frac{2 \times 23.18}{(1+0.6) \times 1.3} = 22.29\ \text{ft}$$

$$C_t = \frac{2b\lambda}{(1+\lambda)AR} = \frac{2 \times 23.18 \times 0.6}{(1+0.6) \times 1.3} = 13.37\ \text{ft}$$

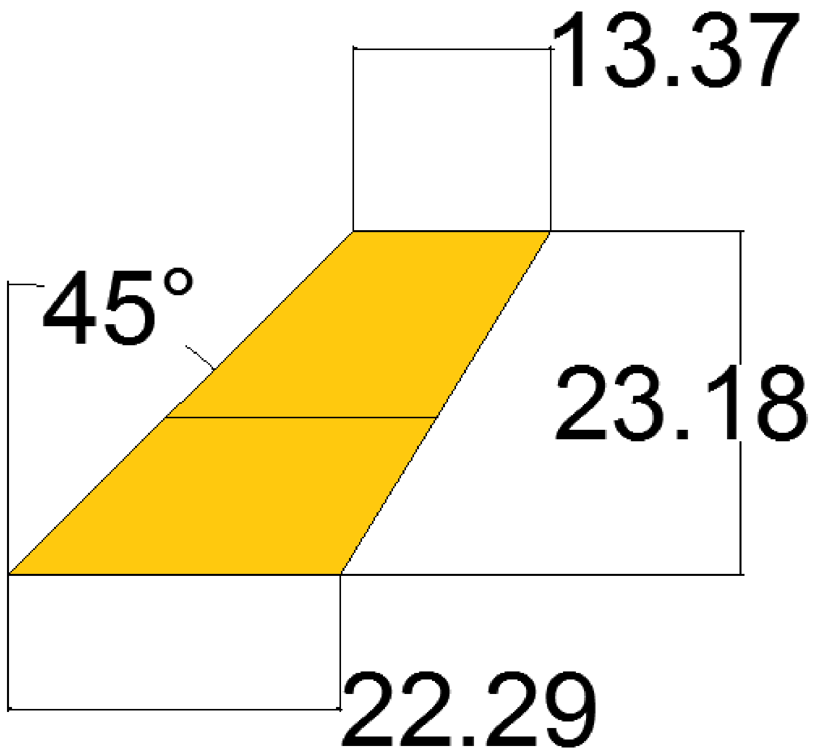

Figure8. 3 – CAD model for the vertical stabilizer

8.3 Elevator

The elevator for the KC-X will start from 20% to 95% semi-span of the horizontal stabilizer; the chord is 35% of the airfoil. Total elevator area is 185.9 feet square.

Compare to similar designs, the aileron to wing area ratio is close. Table 8.1 shows the ratio KC-767 and KC-10.

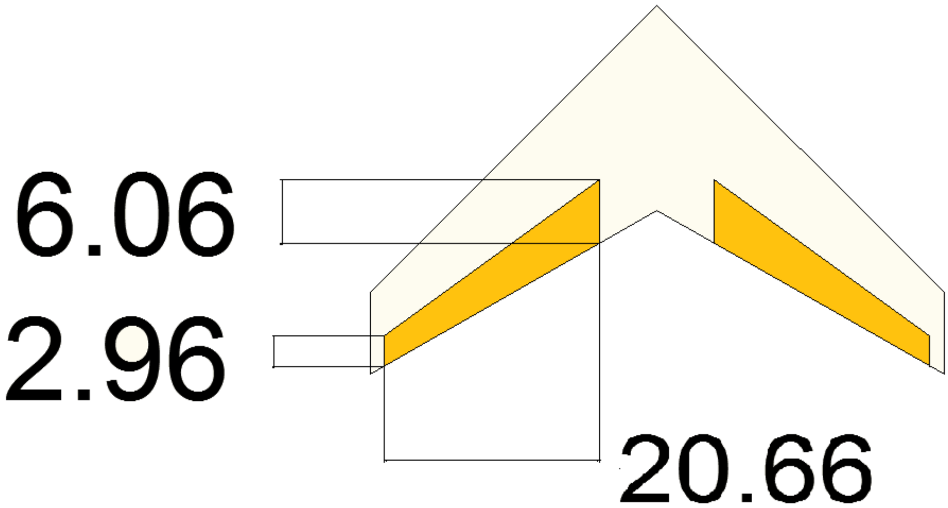

Figure8. 4 – CAD model of elevator

Table8. 1 – Similar aircraft elevator area

	Wing Area	Elevator Area	Elevator to Wing ratio
KC-767	836 ft^2	192.28 ft^2	0.23
KC-10	1338 ft^2	294.36 ft^2	0.22
KC-X	574.6 ft^2	140.7 ft^2	0.245

9.0 Weight and Balance

The maximum takeoff weight of the KC-X is 330,000 pounds. Table 9.1 shows a roughly estimated weight. All weight components are from GD weight method or Torenbeek method from Roskam's Class II weight estimation. Some of the components were using USAF weight method. The distances where the moments were computed were taken with respect to the front of the airplane, towards the cockpit nose, and measured along an access parallel to the approximate center of gravity distance of a particular component. The same procedure is carried out with the useful load for each mission's center of gravity. Table 9.1 shows the weight and distance to the nose for each component. Figure 8.1 shows the C.G. diagram, point 1 is the empty C.G. location. Point 2 add 3 crews, at point 3 and 4 add transport fuel and mission fuel. Point 5 finish refueling with half mission fuel then landing.

Table9. 1 – Component weight

Name	Weight	Distance to nose	Moment
Wing	28,859 lb	68 ft	1962407 lb-ft
Horizontal Stabilizer	1,868.66 lb	154 ft	287773.6 lb-ft
Vertical Stabilizer	2,236.2 lb	142 ft	317545.5 lb-ft
Fuselage	30,549 lb	70 ft	2138439 lb-ft
Nacelle	3,202.4 lb	52 ft	166525.9 lb-ft
Main Gear	15,694 lb	70 ft	1098580 lb-ft
Nose Gear	1,896 lb	15 ft	28440 lb-ft
Engine	16,350 lb	52 ft	850304 lb-ft
Fuel System	1,055.3 lb	40 ft	42213.16 lb-ft
Flight Control	4,320 lb	10 ft	43200.63 lb-ft
Avionic	2,311 lb	10 ft	23110 lb-ft
APU	2,640 lb	145 ft	382800 lb-ft
Furnishing	184 lb	15 ft	2764.125 lb-ft
Electrical System	2,149.5	75 ft	161211.9 lb-ft
Total	113,315.66 lb	66.23 ft	7504896.16 lb-ft

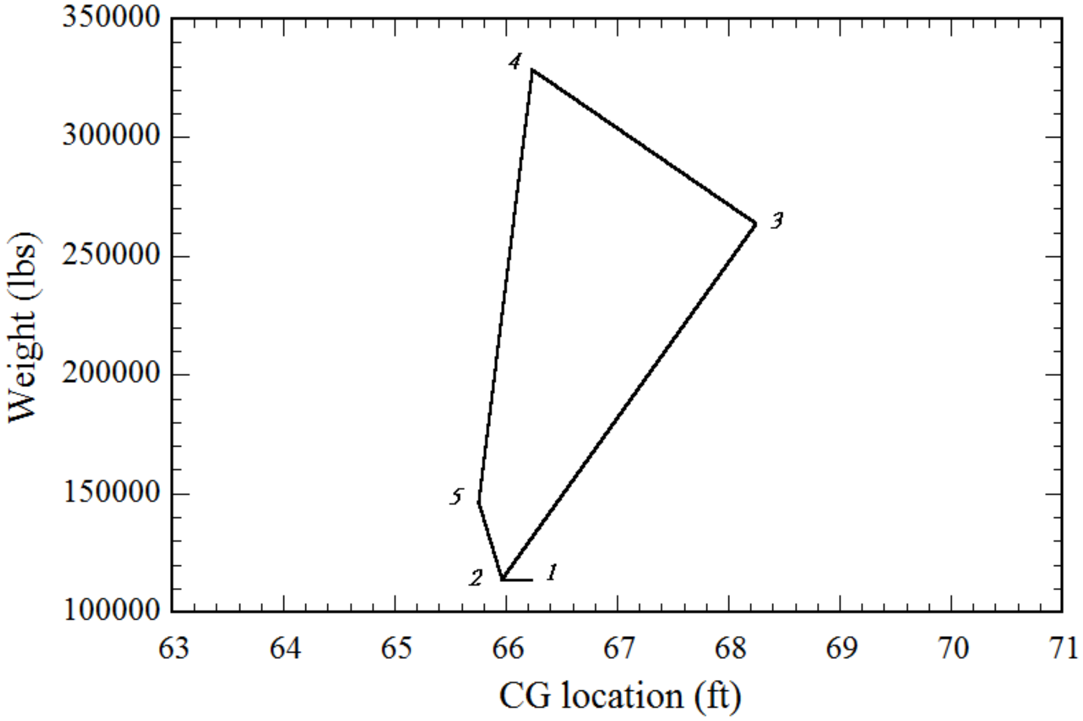

Figure9. 1 – C.G diagram for refueling mission

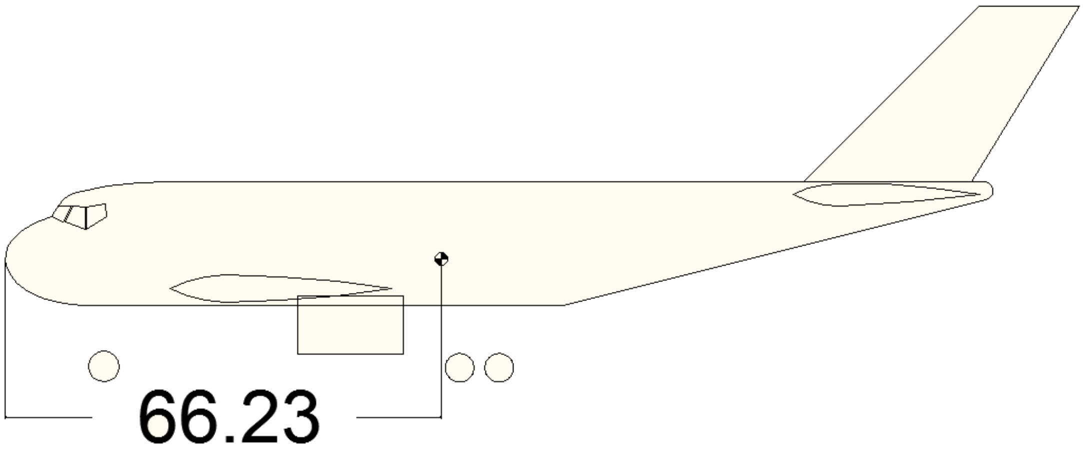

Figure9. 2 – Empty weight C.G location

10.0 Landing Gear

The KC-X uses the tricycle fuselage mounted gears. The main gear with two struts, four wheels per strut and two wheels for the nose gear strut. According to different center gravity locations, the gear would bear different loads. The maximum load for the main gear wheel is 39,270 lb when the C.G. location is at 68.25 feet from nose and the maximum load for the nose gear is 28,900 lb when the C.G. location is at 65.75 feet from the nose. Table 10.1 shows the wheel information; selected wheel for the main gear is type VII with maximum load of 41,700 lb in 44 inches diameter and 18 inches wide. The wheel for the nose is new design type with maximum load of 29,300 lb in 37 inches diameter and 13 inches wide.

$$P_n = \frac{W_{to} l_m}{(l_m + l_n)} \tag{10.1}$$

$$P_m = \frac{W_{to} l_n}{n_s (l_m + l_n)} \tag{10.2}$$

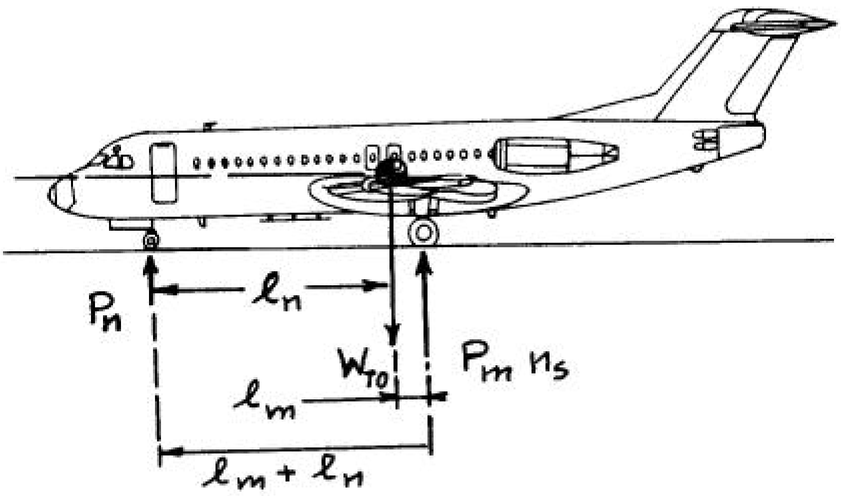

Figure10. 1 – Static load geometric for tricycle gears

Table10. 1 – Selected wheel data

	Gear Type	DoxW	Maximum Load
Nose Gear	New Design Type	37”x13”	29300 lb
Main Gear	Type VII	44”x18”	41700 lb

11.0 Stability and Control Analysis

In order to find appropriate horizontal stabilizer are and vertical stabilizer area, longitudinal stability and directional stability will be analyzed via longitudinal X-plot and directional X-plot in this chapter.

11.1 Static Longitudinal Stability

The static longitudinal stability will be based on Roskam's method. The longitudinal X-plot is used to define the ideal horizontal stabilizer area. The GD method from Roskam is used for the center gravity graph shown in Eq. (11.1).

$$W_h = 0.0034\{(W_{TO}n_{ult})^{0.813}(S_h)^{0.584}\left(\frac{b_h}{t_{r_h}}\right)^{0.033}\left(\frac{C}{l_h}\right)^{0.28}\}^{0.915} \tag{11.1}$$

A relationship between horizontal stabilizer area and weight is determined from Eq. (11.1). Using weights from chapter 9, the relationship between the center gravity location and horizontal stabilizer area can be found. To calculate the aerodynamic center location, Roskam use Eq. (11.2) and Eq. (11.3) to determine the horizontal stabilizer area and aerodynamic center relationship.

$$X_{acA} = \frac{X_{ac_{wf}} + \frac{C_{L_{\alpha h}}\left(1-\frac{\partial\varepsilon_h}{\partial\alpha}\right)\left(\frac{S_h}{S}\right)X_{ac_h}}{C_{L_{\alpha wf}}}}{F} \tag{11.2}$$

$$F = 1 + \frac{C_{L_{\alpha h}}\left(1-\frac{\partial\varepsilon_h}{\partial\alpha}\right)\left(\frac{S_h}{S}\right)}{C_{L_{\alpha wf}}} \tag{11.3}$$

Eq. (11.4) to Eq. (11.8) can be used to solve the wing-fuselage coefficient, wing lift curve slope, Mach constant and Mach variable for the wing-fuselage lift curve slope.

$$C_{L_{\alpha wf}} = k_{wf} C_{L_{\alpha w}} \tag{11.4}$$

$$k_{wf} = 1 + 0.025\left(\frac{d_f}{b}\right) - 0.25\left(\frac{d_f}{b}\right)^2 \tag{11.5}$$

$$C_{L_{\alpha w}} = \frac{2\pi A}{2+[\left(\frac{A^2B^2}{k^2}\right)+4]^2} \tag{11.6}$$

$$\beta = \sqrt{(1-M^2)} \tag{11.7}$$

$$k = \frac{(C_{l_\alpha})_M}{\frac{2\pi}{\beta}} \tag{11.8}$$

To calculate the horizontal lift curve slope, replace Eq. (11.6) aspect ratio and airfoil lift curve slop values for the horizontal stabilizer. Eq. (11.9) to Eq. (11.12) are the Roskam's method to solve the aspect ratio coefficient, the taper ratio coefficient and the horizontal stabilizer coefficient for the downwash gradient at the horizontal stabilizer.

$$\frac{\partial \varepsilon_h}{\partial \alpha} = \frac{4.44(K_A K_\lambda K_h \sqrt{\cos\Lambda_{1/4}})^{1.19}}{\sqrt{(1-M^2)}} \tag{11.9}$$

$$K_A = \frac{1}{A} - \frac{1}{1+A^{1.7}} \tag{11.10}$$

$$K_\lambda = \frac{(10-3\lambda)}{7} \tag{11.11}$$

$$K_h = \frac{1-\frac{h_h}{b}}{\sqrt[3]{(\frac{2l_h}{b})}} \tag{11.12}$$

Figure 11.1 shows the result combine Eq. (11.2) to Eq. (11.12). Assume a 10% static of margin which is commonly used for aircrafts, the required horizontal stabilizer area from figure 11.1 shows 570 ft^2. The initial design horizontal stabilizer area is 574.6 ft^2. These two values are very close. The horizontal stabilizer area will not change.

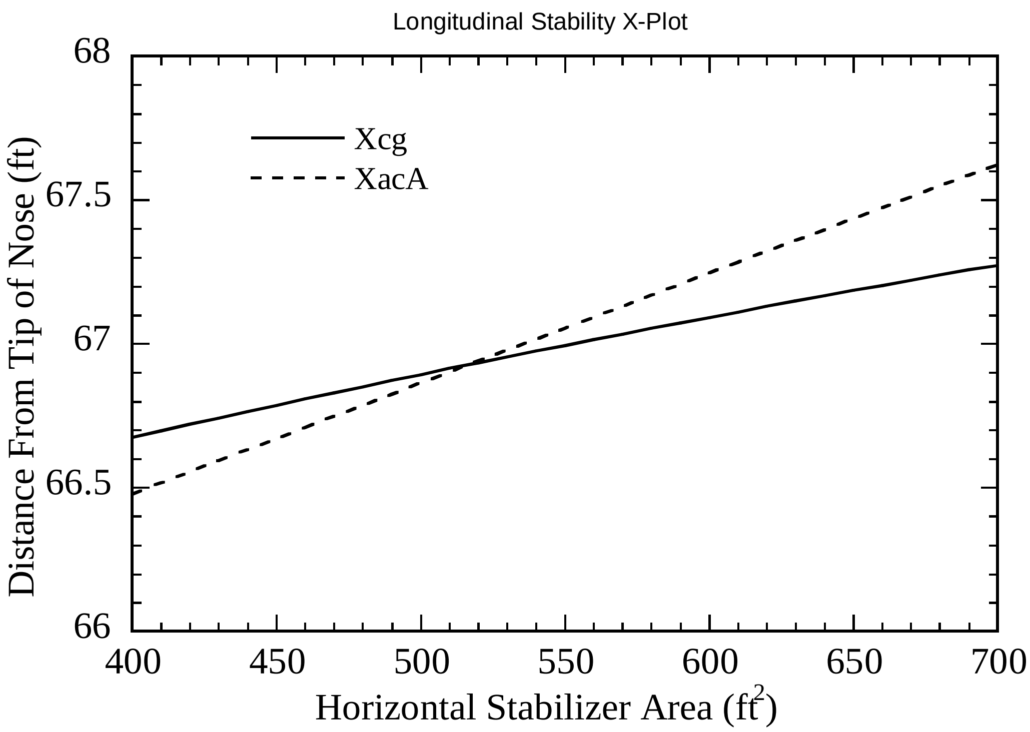

Figure11. 1 – Longitudinal stability X-Plot

11.2 Static Directional Stability

A relationship between the yaw side-slip moment coefficient and the vertical stabilizer area from Roskam were shown in Eq. (11.13):

$$C_{n\beta} = C_{n\beta_{wf}} + C_{L_{\alpha V}} \left(\frac{S_v}{S}\right)\left(\frac{X_v}{b}\right) \tag{11.13}$$

Assume the wing yaw side-slip coefficient be zero at high angle of attack, the fuselage yaw side-slip coefficient is defined in Eq. (11.14):

$$C_{n\beta_f} = -57.3K_N K_{R_l}(\frac{S_{f_s} l_f}{Sb}) \tag{11.14}$$

The value of K_N is empirical factor determined from figure 11.3 and K_{Rl} is a factor depends on Reynold's number from figure 11.4. Figure 11.2 shows the directional stability X-plot result from Eq. (11.13) and Eq. (11.14). When the yaw side-slip moment coefficient is equal to 0.001, the recommended vertical stabilizer area is 321 ft^2. The initial design vertical stabilizer area is 413.47 ft^2. The appropriate vertical stabilizer area from this chapter is 77% of the initial design. The smaller vertical stabilizer area number from t his chapter will be used in order to reduce the tail weight.

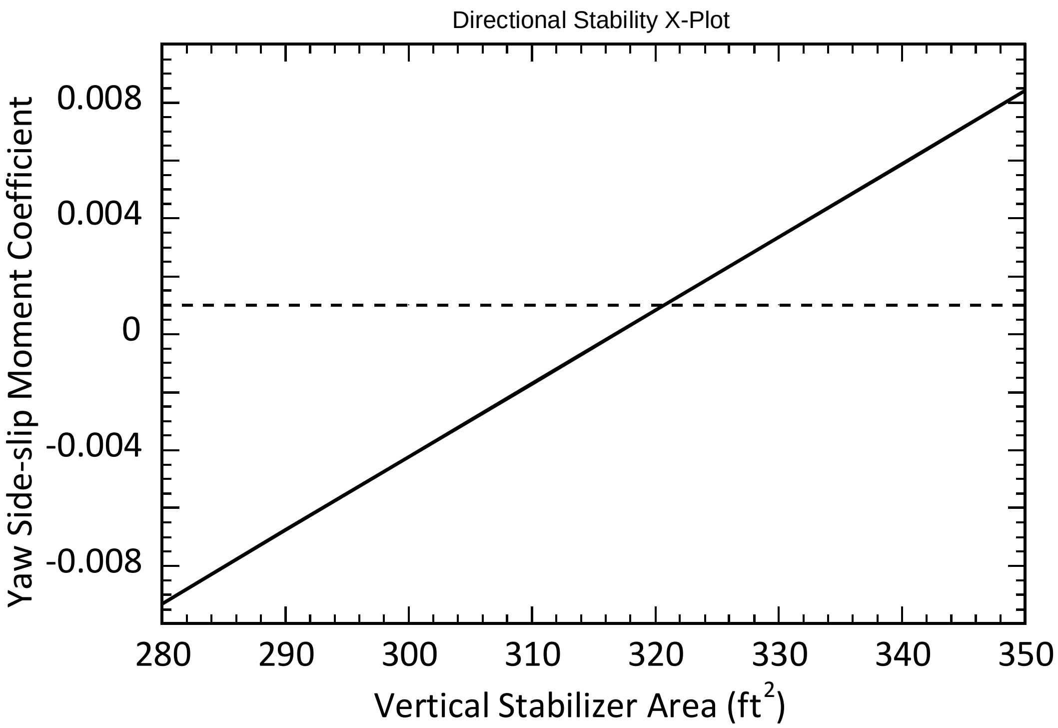

Figure11.2 – Directional stability X-Plot

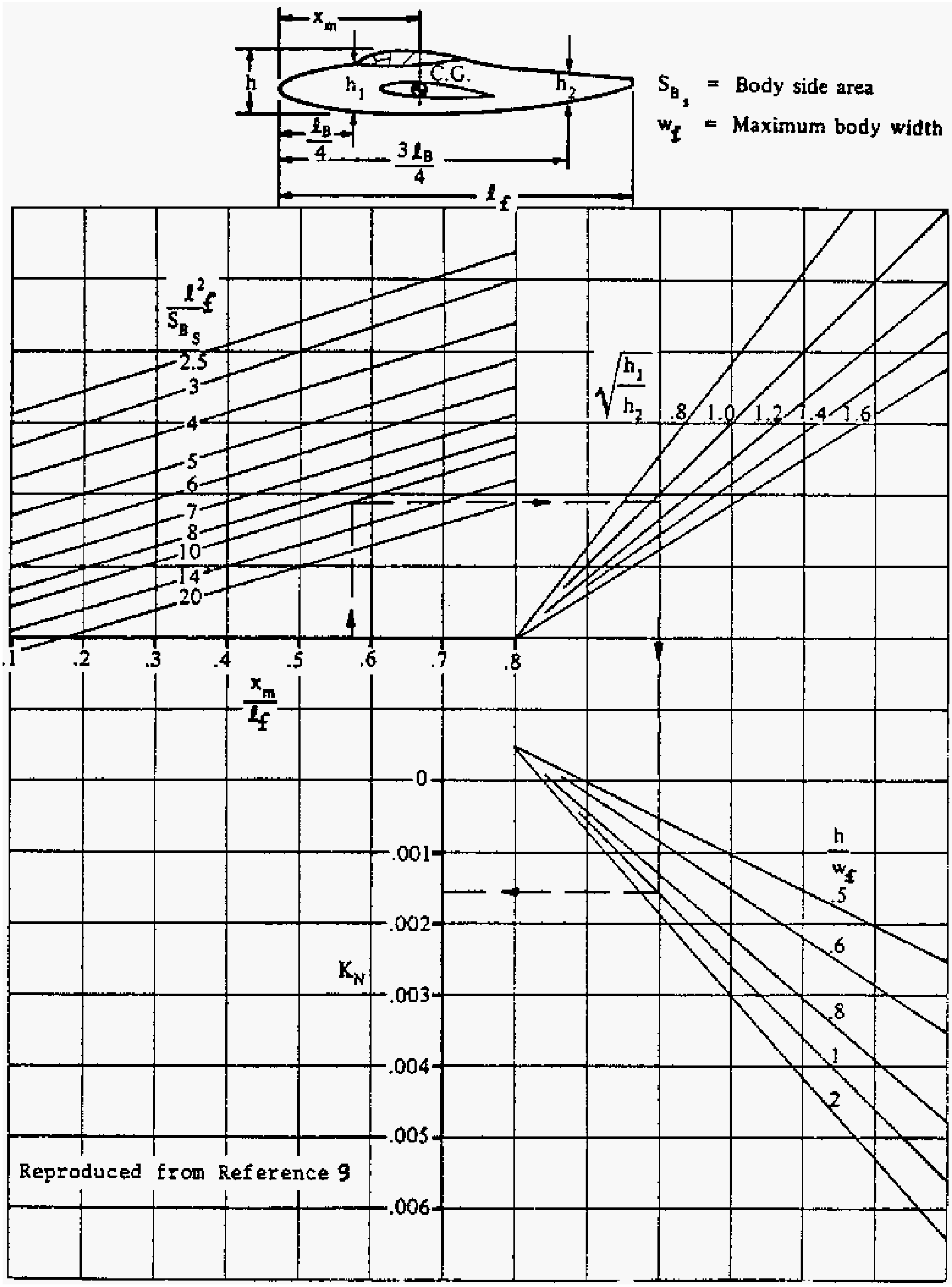

Figure11. 3 – Factor accounting for wing-fuselage interference with directional stability

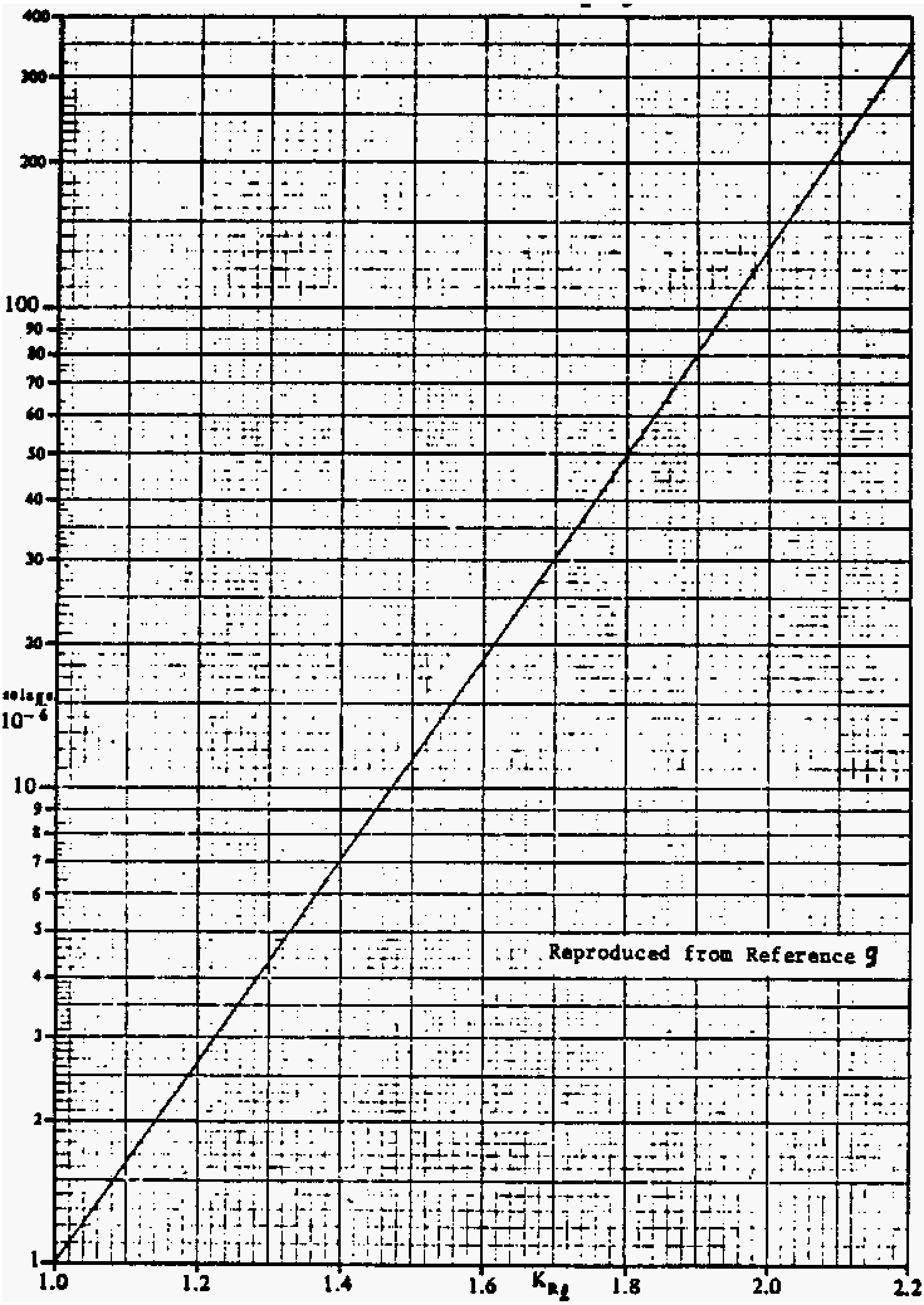

Figure11. 4 – Effect of fuselage Reynolds number on wing fuselage directional stability

12.0 Drag Polar Estimation

In section 5.1, an assumption of drag polar is made for the military aircraft performance requirement. In this chapter, the drag polar will be calculated based on Roskam's method then compare to the drag assumed in chapter 5.

12.1 Zero Lift Drag

To calculate the zero lift drag, the wetted area is required to be calculated. The wetted area is split into different components include: wing, empennage, fuselage and nacelles. Eq. (12.1) shows the total wetted area of the airplane is the sum of wetted area from different components.

$$S_{wet,tot} = S_{wet,w} + S_{wet,e} + S_{wet,f} + S_{wet,n} \tag{12.1}$$

Eq. (12.2) to Eq. (12.6) is used to calculate the wetted area for different components. Eq. (12.2) will be specific used for the wing, horizontal stabilizer and vertical stabilizer.

$$S_{wet,w} = 2S_{exp}\left\{1 + 0.25\left(\frac{t}{c}\right)_r \frac{(1+\tau\lambda)}{(1+\lambda)}\right\} \tag{12.2}$$

The fuselage wetted area can be calculated using Eq. (12.3)

$$S_{wet,f} = \pi D_f l_f \left(1 - {}^{2}/_{\lambda_f}\right)^{2/3} (1 + {}^{1}/_{\lambda_f^2}) \tag{12.3}$$

The nacelle includes fan cowling, gas generator and the plug. Eq. (12.4) to Eq. (12.6) shows the wetted area of these components.

$$S_{wet,fan} = l_n D_n \left\{2 + 0.35\, {}^{l_1}/_{l_n} + 0.8\, {}^{l_1 D_{h1}}/_{l_n D_n} + 1.15\left(1 - {}^{l_1}/_{l_n}\right) {}^{D_{ef}}/_{D_n}\right\} \tag{12.4}$$

$$S_{wet,gas} = \pi l_g D_g \left[1 - \left(\frac{1}{3}\right)\left(1 - {}^{D_{eg}}\!/_{D_g}\right)\left\{1 - 0.18\left({}^{D_g}\!/_{l_g}\right)^{\frac{5}{3}}\right\}\right] \tag{12.5}$$

$$S_{wet,plug} = 0.7\pi l_p D_p \tag{12.6}$$

Table 12.1 express the wetted area of these components and the total wetted area is 21,657.7 ft^2. Back to Eq. (12.2), the equivalent parasite area is 82.5 ft^2. The zero-lift drag coefficient can be determined using Eq. (5.1) with the value for the parasite area and the wing area, the zero-lift drag coefficient becomes 0.03.

Table12. 1 – Wetted area for different components

Fuselage	7417.37 ft^2	Fan Cowling	469.48 ft^2
Wing	9502.9 ft^2	Gas Generator	144.14 ft^2
Horizontal Stabilizer	1839 ft^2	Plug	43.96 ft^2
Vertical Stabilizer	2219.11 ft^2	Total	21657.72 ft^2

12.2 Drag Polar

Using the value of zero-lift drag coefficient, the overall drag coefficient can be calculated from Eq. (12.7):

$$C_D = C_{D_0} + \frac{C_L^2}{\pi e AR} \tag{12.7}$$

The drag polar and lift to drag ratio at various lift coefficient are shown in figure 12.1 and figure 12.2:

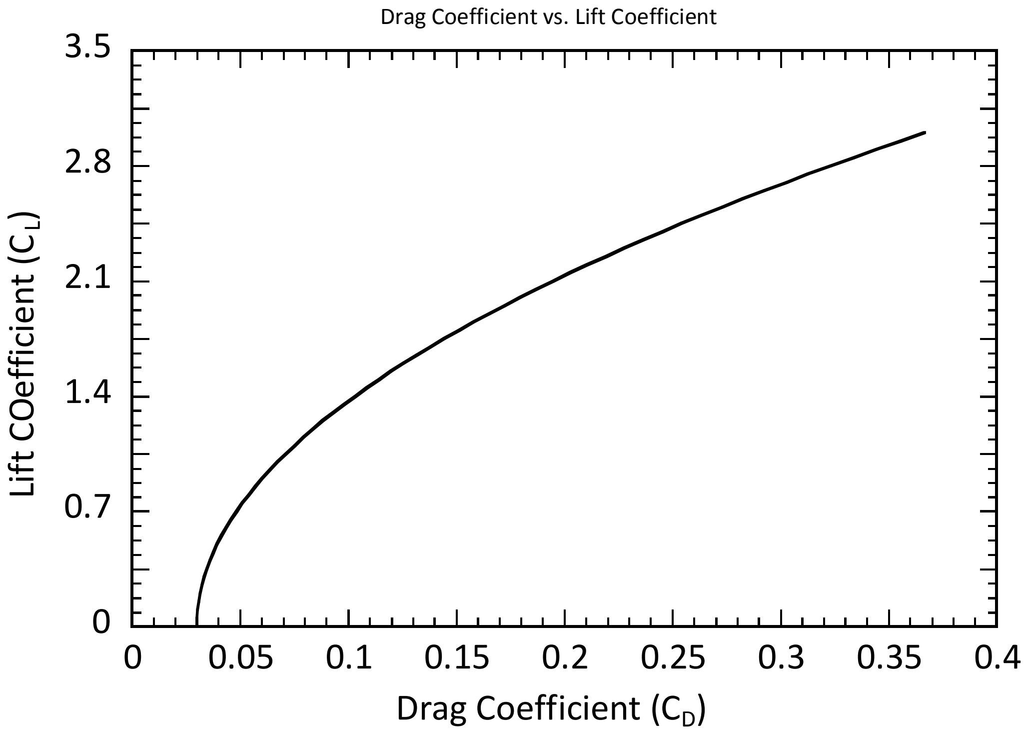

Figure12. 1 – CD vs. CL

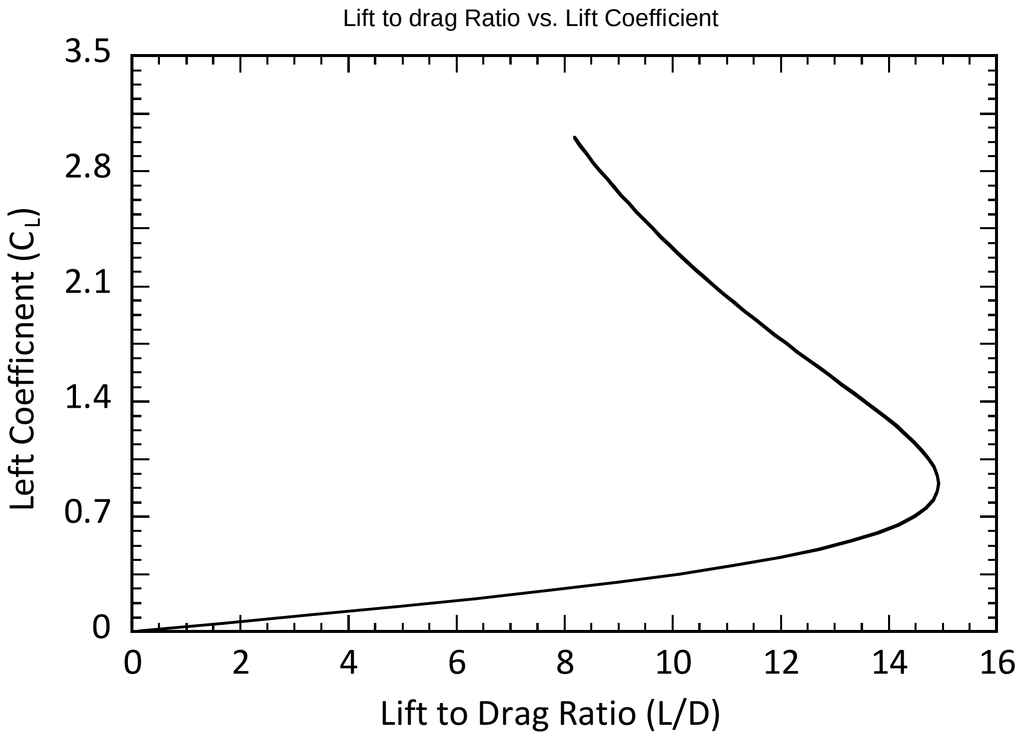

Figure12. 2 – L/D vs. CL

Using the cruising lift coefficient of 0.59 and the Oswald efficient factor of 0.85, the total drag coefficient during cruise is 0.043. Assume the lift coefficient stays constant, the lift to drag ratio can be calculated:

$$\frac{\mathrm{L}}{\mathrm{D}} = \frac{\mathrm{C_L}}{\mathrm{C_D}} = \frac{0.59}{0.043} = 13.72$$

In chapter 5, the preliminary assumptions of the cruising lift to drag ratio is 14 and the calculated lift to drag ratio is 13.72. From the sensitivity analysis data in section 4.3:

$$\frac{\partial \mathrm{W_{To}}}{\partial (\frac{\mathrm{L}}{\mathrm{D}})} = -8299 \text{ lb}$$

The decrease in lift to drag ratio from 14 to 13.72, the takeoff weight needs to be increased by 2324 lbs. This weight will be used for more advanced structural protections for the fuel tank.

13.0 V-N Diagram

The generation of lift during high-G maneuvers typically accounts for the greatest aero load on the airplane. At high speeds the maximum load factor is limited to the chosen value based upon the expected use of the airplane. The V-N diagram, of the airplane describes these basic flight performance limits. The recommended maximum load factors from Roskam for military transporter are positive two and negative one. A V-N diagram for the KC-X is shown in the figure 13.1. Vs is the 1G stall speed at which the KC-X is controllable. V_a is the design maneuvering speed at maximum load factor. V_c is the design cruise speed and V_d is the design diving speed.

$$V_S = \sqrt{\frac{2\frac{W}{S}}{\rho C_{N_{max}}}} = \sqrt{\frac{2\times 120}{0.00237\times 0.923\times 1.1}} = 315.81 \text{ ft/s=187.27 kt}$$

$$V_a = V_S \times \sqrt{2} = 446.62 \text{ ft/s=264.84 kt}$$

$$V_C = 803.41 \text{ ft/s= 476.42 kt}$$

$$V_d = 1.25V_c = 1004.26 \text{ ft/s=595.52 kt}$$

V-N Diagram

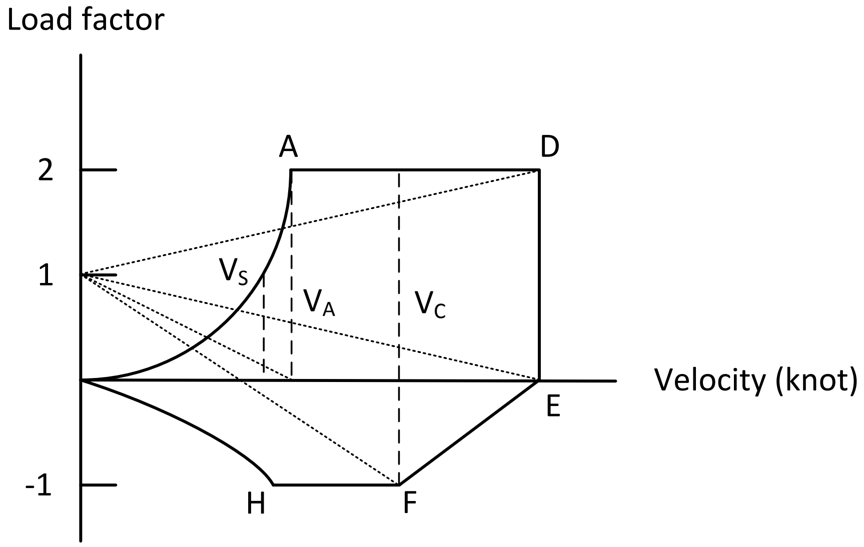

Figure13. 1 – V-N diagram for the KC-X

14.0 Conclusion

East Asia is the heart of the world high technology includes the place of origin of rare earth metals and the key position of development and OEM. Once the war start, the global economic will be inflict heavily and the great depression might come out again. The KC-X is tailored for the East Asia deployment with high cargo capacity and low noise. In the future, the KC-X could assist the movement of marine troop from Okinawa to Guam and also protect the environment for these beautiful islands from military competitions. The government could consider the KC-X, the new stratotanker of environment protector to reduce the environment impacts.

15.0 Reference

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Appendix A. Front, Side and Top Views of the KC-X