DESIGN OF A LOW COST SHORT-TAKEOFF-VERTICAL-LANDING EXPORT FIGHTER/ATTACK AIRCRAFT

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Design of a Low Cost Short Takeoff-Vertical Landing Export Fighter/Attack Aircraft

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AUBURN UNIVERSITY

Abstract

This report presents the design of a supersonic short takeoff and vertical landing (STOVL) aircraft that is suitable for export. An advanced four poster, low bypass turbofan engine is to be used for propulsion. Preliminary aerodynamic analysis is presented covering a determination of CD versus CL, CD versus Mach number, as well as best cruise Mach number and altitude. Component locations are presented and center of gravity determined. Cost minimization is achieved through the use of developed subsystems and standard fabrication techniques using nonexotic materials. Conclusions regarding the viability of the STOVL design are presented.

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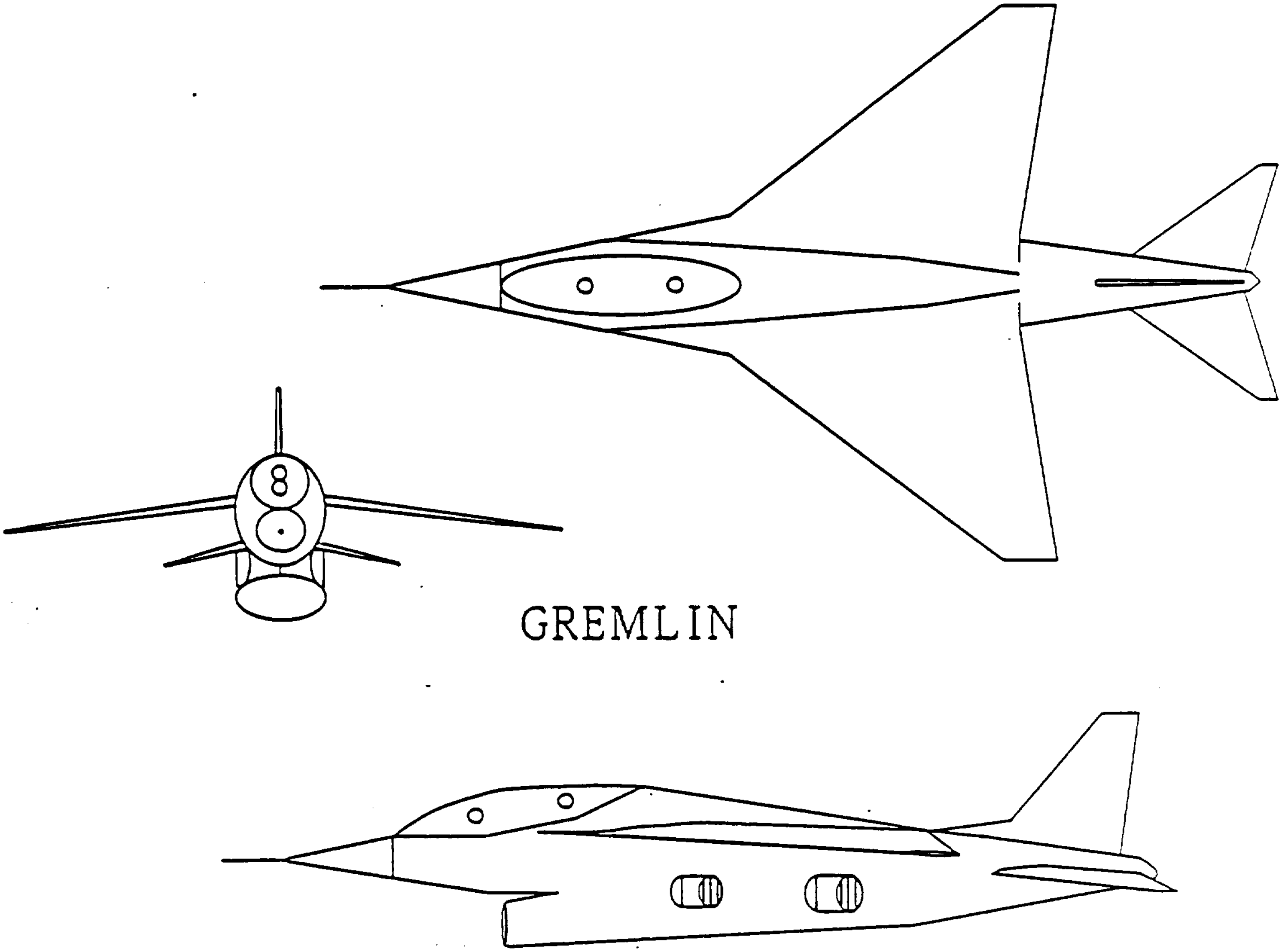

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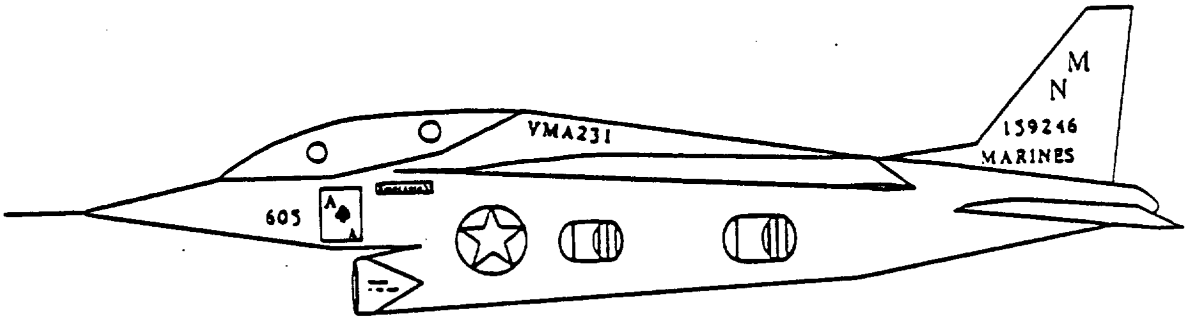
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1. Introduction

In the first few hours of a future war, most military fortifications will be attacked by nuclear, chemical or extremely accurate conventional weapons. Airbases, with their command, communications and control centers as well as airstrips for aircraft operations, will be prime targets. Because of this accepted fact, NATO has adopted a doctrine of aircraft dispersal whereby fighter and light attack aircraft are dispersed to smaller airfields as well as civilian highways and country roads in order to create more targets as well as to confuse the enemy. This strategy in itself creates problems because the smaller airfields are probably already secondary targets. When considering these as well as other problems, the advantages of STOVL fighter/attack aircraft become obvious. Unpaved fields or parking lots could become instantaneous bases. Considerable expense could be avoided and tactical advantage could be achieved all at the same time. Also, as conditions dictate, the STOVL aircraft could be redeployed rapidly in order to take advantage of changing tactical conditions.

The British Aerospace/McDonnell Douglas Harrier Fighter/Recon./Strike aircraft is presently in the U.S. Marine Corps inventory. It is the only operational STOVL aircraft flying with the U.S. military but is also capable of V/STOL (vertical/short takeoff and landing). The Harrier I first entered British service in 1965 and entered U.S.M.C. service in 1971. Through constant redesign and improvement of propulsion, avionics and lifting surfaces, a variant, the AV-8B Harrier II, resulted. This aircraft distinguished itself during the British/Argentine Falkland Island conflict in 1982. Because of its extreme agility in air combat, not a single British

Harrier was lost in air combat (although nine were lost to ground fire). However, a major disadvantage of the Harrier I and II aircraft is its inability to go supersonic in cruise flight. Any fighter/attack aircraft of the future will be required to sustain a Mach number much greater than one for several reasons. The need to fly to the target quickly (low response time) is a must. Also, the faster an aircraft flies, the smaller amount of time is spent above hostile ground fire. Another point is that even though dogfights between combat fighter aircraft usually occurs in the transonic regime or slower, a supersonic aircraft would have an advantage because of the increased power available as well as potential acceleration as opposed to a purely transonic aircraft such as the Harrier.

In response to the need for a supersonic STOVL aircraft, AIAA has sponsored a request for proposals (RFP) for an aircraft meeting the above criteria as well as many others. This aircraft was required to be designed as a short takeoff or vertical landing low cost export fighter. This design proposal will pose a unique set of challenges. Because of the weight minimization needed for the vertical aspect of flight (thrust=weight) lightweight, and oftentimes exotic materials, will be needed for the construction of this aircraft. A new generation of vectored thrust engines will have to be developed since there are no jet engines on the market at the present time capable of producing the performance needed for this aircraft.

Since the cost of an aircraft is a function of the amount of new technology that is involved in its development and construction, it is obvious that it will be a major challenge to keep cost within the range of "low cost". Since the low cost STOVL fighter/attack aircraft (dubbed 'Gremlin') will have a multirole capability, this aircraft could be sold to European as well as friendly third world allies for their air defense needs. The STOVL capability of this aircraft would be a great advantage to lesser developed countries. Fixed airbases are expensive to construct, maintain, and defend; therefore an aircraft that can takeoff and land in an undeveloped area would be much more cost effective as well as tactically effective.

One way to reduce cost in aircraft development is to rely heavily on developed systems. Also, since tomorrow's aircraft will rely much more on costly electronics, an easy way to contain costs is to place only the bare necessities in the way of avionics in the aircraft. Many times avionics are designed for every possible combat theater. This increases cost and complexity. By designing theater specific avionics packages (i.e. European theater would be much different than African or Middle East theater etc.) and installing each during final assembly and delivery to the customer, the extremely high avionics cost could be reduced.

The fabrication and construction of this aircraft will rely heavily on subcontracting. Existing systems, when permissible, will be used to avoid development and associated cost. The air frame assembly will be undertaken by the main contractor and subsequent subsystems will be installed with subcontractor support.

2. Statement of the Problem

In 1982 the need for V/STOL was proven in the Falkland Islands. England relied heavily on the Harrier, a V/STOL aircraft, for its air combat and air-to-ground strikes. The response time, maneuverability, and ability to land in a small area were great advantages the Harrier possessed over conventional aircraft. Harriers were attributed with downing 28 Argentinian aircraft, while no Harriers were shot down by Argentinian aircraft.

The destruction caused by nuclear and conventional weapons must be a major consideration in a conflict. NATO and American military airfields as well as aircraft carriers are primary targets. To prudently prepare for this loss, aircraft are needed that are capable of landing in a small area. Often in a combat situation, pilots will takeoff for a mission, then return to find their base or aircraft carrier has been destroyed. They then will be forced to land on a damaged runway, a road, a forest clearing, a small naval vessel, or a cargo ship. This capability is found in a STOVL aircraft.

A large market currently exists for a low-cost STOVL fighter/bomber since it will be a high technology aircraft at a comparatively low price. The airplane will primarily be designed as an export for less developed countries. It will be a multi-purpose aircraft capable of air combat and air-to-ground strikes which makes it a desirable asset to any country's armed forces. Its supersonic speed, high degree of maneuverability, and vertical landing capabilities will give it advantages over conventional aircraft. The low cost will make the STOVL aircraft available to third world countries. Also, it will be useful as a trainer to more developed countries who wish to train their pilots for higher technology aircraft.

Another possible market will be military aerobatic teams since the STOVL aircraft will have aerobatic capabilities which conventional aircraft do not possess.

One V/STOL aircraft is in use by American and British military forces today, the Harrier or AV-8B. The Harrier not only has STOVL capabilities, but also has vertical takeoff capabilities. The Harrier was developed by British Aerospace and in recent years, vastly upgraded by McDonnell Douglas. The Harrier's top speed is Mach 0.93 which limits its performance against faster enemy jets and for long range missions. The Soviets have developed a supersonic VTOL (vertical takeoff or landing) fighter/ bomber, the Yak-36 Forger which is capable of flying at Mach 1.2. No strictly STOVL aircraft has yet been developed.

The prototype to the Harrier, the Hawker P.1127 first appeared in 1960. It was the first vertical takeoff and landing aircraft developed. The latest American version of the Harrier is the AV-8B which replaces the AV-8A. Currently, four navies employ the Harrier—United States, Royal, Spanish, and Indian. In the United States, the Marines use the AV-8B since it fits their needs both in the field and at sea. It is capable of responding in eight to ten minutes and landing in a small area. Although the Harrier is capable of vertical takeoff, it usually takes-off with a short taxi enabling it to increase its payload and range.

The Rolls-Royce Pegasus turbofan engine is utilized to power the Harrier by exhausting the cold stream through two front nozzles and the hot stream through two rear nozzles. The nozzles are capable of rotating through greater than 90 degrees. They are pointed down and slightly back for takeoff, then rotated aft for cruise. The Harrier possesses a jet reaction control system which consists of a puffer at the nose, tail, and at each wing tip. The reaction control jets are used for control during takeoff and landing. The United States Marine Corp added an option to the Harrier, VIFF (vectoring in forward flight). By rotating the nozzles during combat, vectored aircraft have significant advantages during dogfights. They are capable of many more maneuvers than conventional aircraft.

The USSR's vectored thrust aircraft, the Yak-36 Forger, is much less sophisticated than the Harrier. It is strictly a vertical takeoff aircraft without the short takeoff capability of the Harrier. This fact limits its maximum payload to approximately one-fourth of the Harrier's payload. The Forger utilizes two engines forward of the center of gravity strictly for lift and one engine at the rear for lift and cruise. The main engine located in the rear is an unreheated turbojet engine. Like the Harrier, the Forger has puffer jets at the wing tips to control yaw and roll. To control the pitch, the Forger depends on selective throttling by the engine. It does not possess VIFF capabilities. Although takeoff and landing are completely computer controlled, the change between vertical and horizontal flight is a slow process in comparison to the Harrier. A large amount of fuel is burned during the transfer.

3. Requirements

The Gremlin was designed as a multi-role, lightweight, high thrust to weight ratio aircraft with a top speed of Mach 1.5. It has a high instantaneous turn rate provided by its main and trim thrusters. The avionics used in the aircraft were chosen for their reliability and ease of maintenance since the aircraft will be exported to third world countries. Since a basic radar is considered essential in a supersonic military aircraft, the Gremlin employs a reliable system which is capable of performing in either and air superiority or ground support role. The capabilities of the Gremlin in the air superiority mission are demonstrated in Figure 3.1 and the capabilities in the air-ground mission are demonstrated in Figure 3.2.

The aircraft also meets the following requirements carrying a full weapons load with sixty percent of internal fuel:

1. Accelerate from Mach 0.9 to 1.5 at 30,000 feet in less than sixty seconds.
2. Have specific excess rate of climb powers of:
    a. 750 feet per second at 10,000 feet and Mach 0.8.
    b. 500 feet per second at 30,000 feet and Mach 0.8.

The wing of the Gremlin is able to meet the following criteria:

1. Sized to generate a 9.0g load factor at combat load and speed.
2. Capable of performing a wing-lift only landing in a rare event failure of the vectoring drive. The aircraft will be able to meet the following specifications during such an emergency landing:
    a. No more than a 140 knot touchdown speed.

b. At least five percent of internal fuel still aboard.

c. No armaments left onboard.

d. An angle of attack of less than twenty-five degrees.

e. Clear vision over the nose for the pilot.

3. Capable of being folded to a nominal semi-span of 10 feet for storage.

4. With control in flight being achieved with the main and trim thrusters, moveable surfaces on the wing will usually not be warranted, however use of such surfaces on the wing was necessary for safety.

Horizontal and vertical stabilizers are usually used for stability and control, however, since control is provided by the main and trim thrusters, only stability need be considered. The stabilizers are sized to generate neutral stability between 140 knots and the maximum design speed.

The airframe of the Gremlin aircraft is capable of withstanding a maximum load factor of at least +9.0g's and a minimum load factor of at least -3.0g's in the air superiority mode and sixty percent internal fuel. These two values include a safety factor of 1.5 over mission requirements. The airframe is also constructed to withstand a maximum dynamic pressure of at least 2133 pounds per square foot (Mach 1.2 at sea level).

The landing gear of the Gremlin is able to meet the following requirements:

1. Capable of operating perfectly in a fully naval environment.

2. Capable of withstanding a vertical speed of twenty feet per second when the aircraft is making a vertical landing.
3. Capable of withstanding a routine landing at sixty knots and a vertical speed of fifteen feet per second.
4. Capable of withstanding an emergency landing at 140 knots and a vertical speed of 10 feet per second.

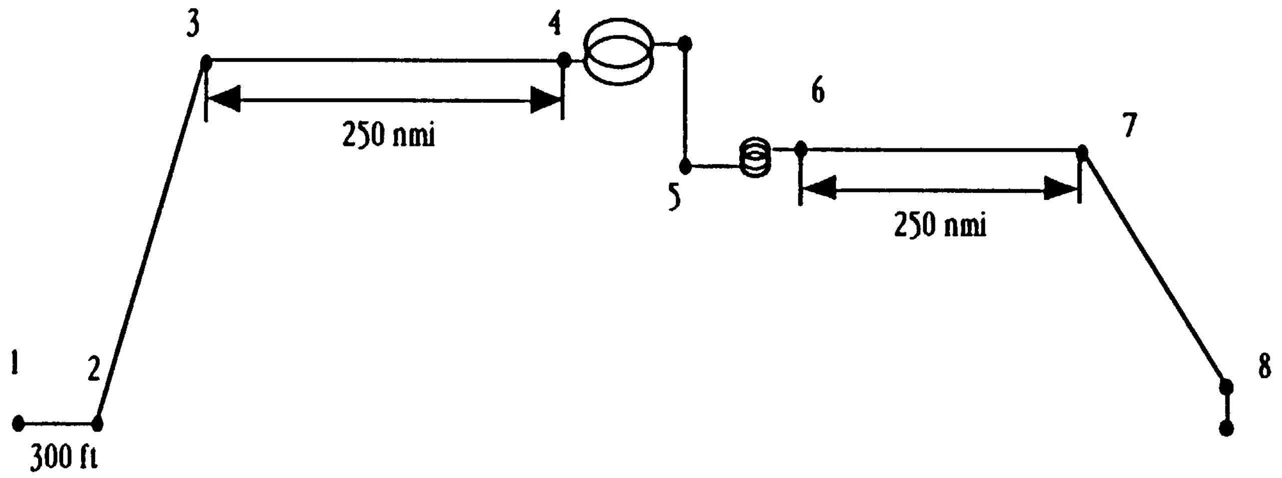


Figure 3.1 Air Superiority Mission

1. Warm-up and taxi for five minutes at ground idle.
2. Takeoff at sea level with a ground roll of 300 feet with 20 knots of wind over the deck.
3. Accelerate to Mach 1.5 at best cruise altitude and cruise to a point 250 nautical miles from take-off.
4. Perform two 360 degree 4.5g sustained turns at Mach 1.5 and 30,000 feet firing two AIM-9L Sidewinder missiles.
5. Perform three 360 degree 4.5g sustained turns at Mach 0.9 and 15,000 feet firing two AIM-9L Sidewinder Missiles and the M61A1 Vulcan 20mm cannon.
6. Return 250 nautical miles at best cruise Mach number and altitude.
7. Descend to sea level.
8. Land vertically with at least five percent internal fuel left.

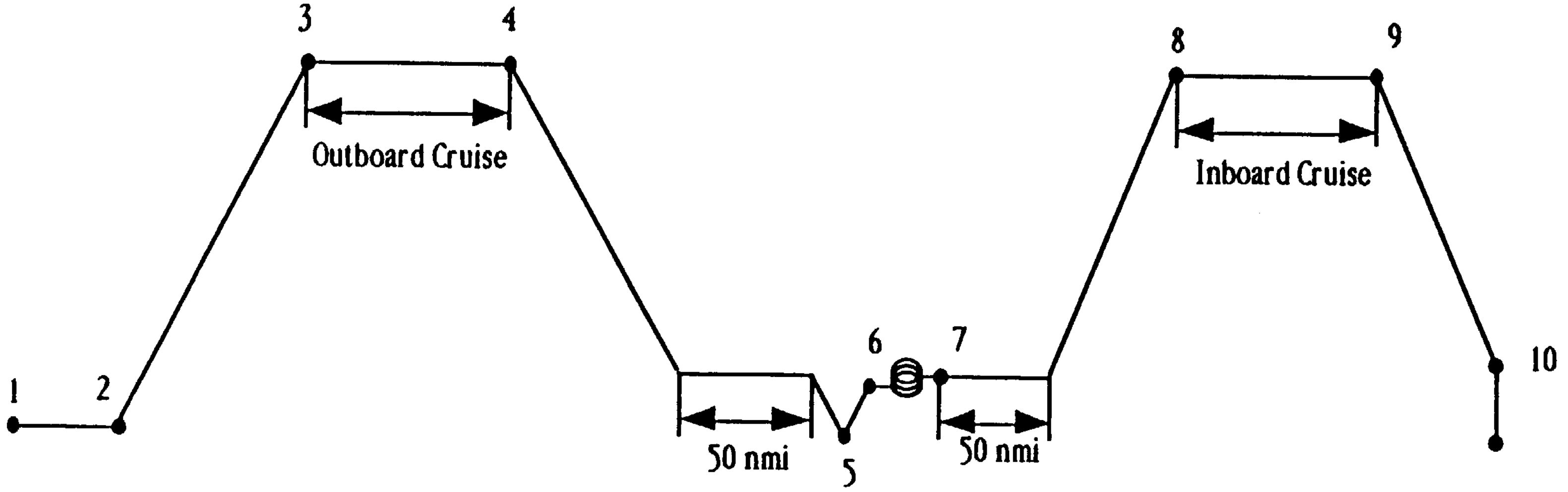


Figure 3.2 Ground Superiority Mission

1. Warm-up and taxi for five minutes at ground idle.
2. Takeoff at sea level with a ground roll of 300 feet with 20 knots of wind over the deck.
3. Accelerate and climb to best cruise Mach number and altitude for outboard cruise.
4. Descend to 250 feet and penetrate 50 nautical miles at Mach 0.8.
5. Drop 6 Mk82 500 pound bombs.
6. Perform three 360 degree 6.5g sustained turns at Mach 0.8 and sea level firing the M61A1 Vulcan 20mm cannon.
7. Egress at 250 feet for 50 nautical miles at Mach 0.8.
8. Climb and return to best cruise Mach number and altitude.
9. Descend to sea level.
10. Land vertically with at least five percent internal fuel left.

4. Technical Information and Configuration

4.1 Initial Sizing

Once the takeoff gross weight has been calculated, the fuselage, wings and tails can be sized. The front, side, and top views of the Gremlin are shown in Figures 4.1.1, 4.1.2, and 4.1.3 respectfully.

Fuselage

The fuselage length is based on the function and mission of the aircraft. A passenger aircraft bases its fuselage length and diameter on the number of passengers it must carry, while a fighter aircraft must be as light and compact as possible and still perform all its mission specifications.

For the Gremlin, using a gross takeoff weight of 24,111 pounds, the fuselage length was determined to be 47.5 feet.

The aircraft fineness ratio is the ratio of the fuselage length to the widest diameter of the fuselage. For a nonvarying internal volume, a fineness ratio of approximately 3.0 minimizes subsonic drag. For supersonic flight, to have minimum drag, a fineness ratio of approximately 14.0 is desired. Using a maximum diameter of 4.9 feet, the Gremlin's fineness ratio was determined to be 9.7.

Wing Sizing

The wing reference size can be calculated by the takeoff gross weight divided by the takeoff wing loading. This was determined to be 353.3 square feet.

Tail Sizing

A historical approach is used during the determination of tail sizing. The main purpose of the tail is to counteract the adverse moments that are generated by the wing. Therefore, the greater the distance from the aerodynamic center of the tail to the aerodynamic center of the wing, the smaller the tail area must be. The moment arm of the tail can be determined by historical data which for a mid-mounted engine is 45-50 percent of the fuselage length. Using 48 percent of the fuselage length, the moment arm of the tail was calculated to be 22.8 feet.

The horizontal tail area, S_{ht}, was calculated to be 68.2 square feet. The vertical tail area, S_{vt}, was calculated to be 33.6 square feet. Because of the effect of rotatable nozzles, some of the stability that the tail provides can be provided by the thrust. Therefore, the horizontal tail area is reduced by 15 percent which gives us a new horizontal tail area of 57.97 square feet.

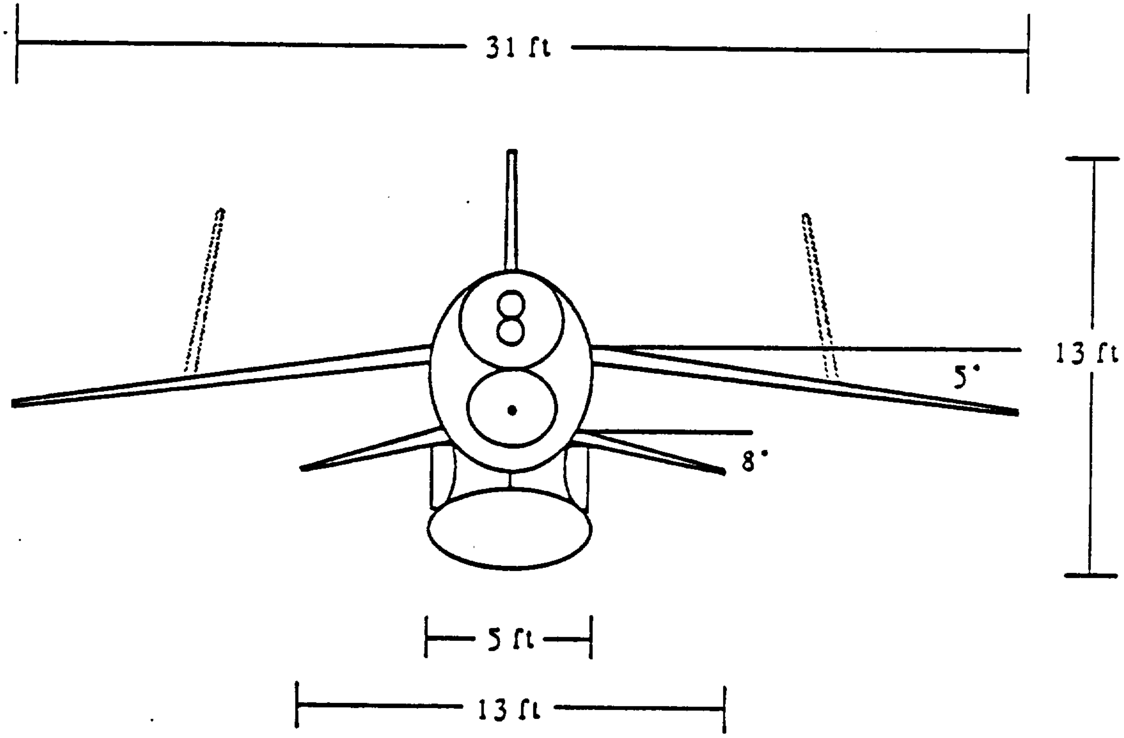


Figure 4.1.1 Gremlin Front View

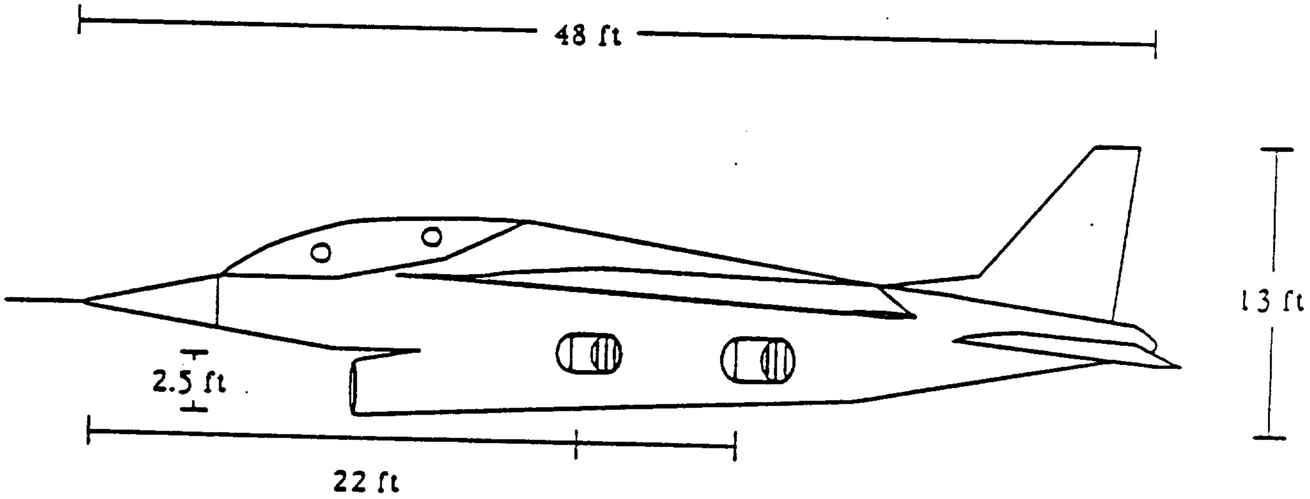


Figure 4.1.2 Gremlin Side View

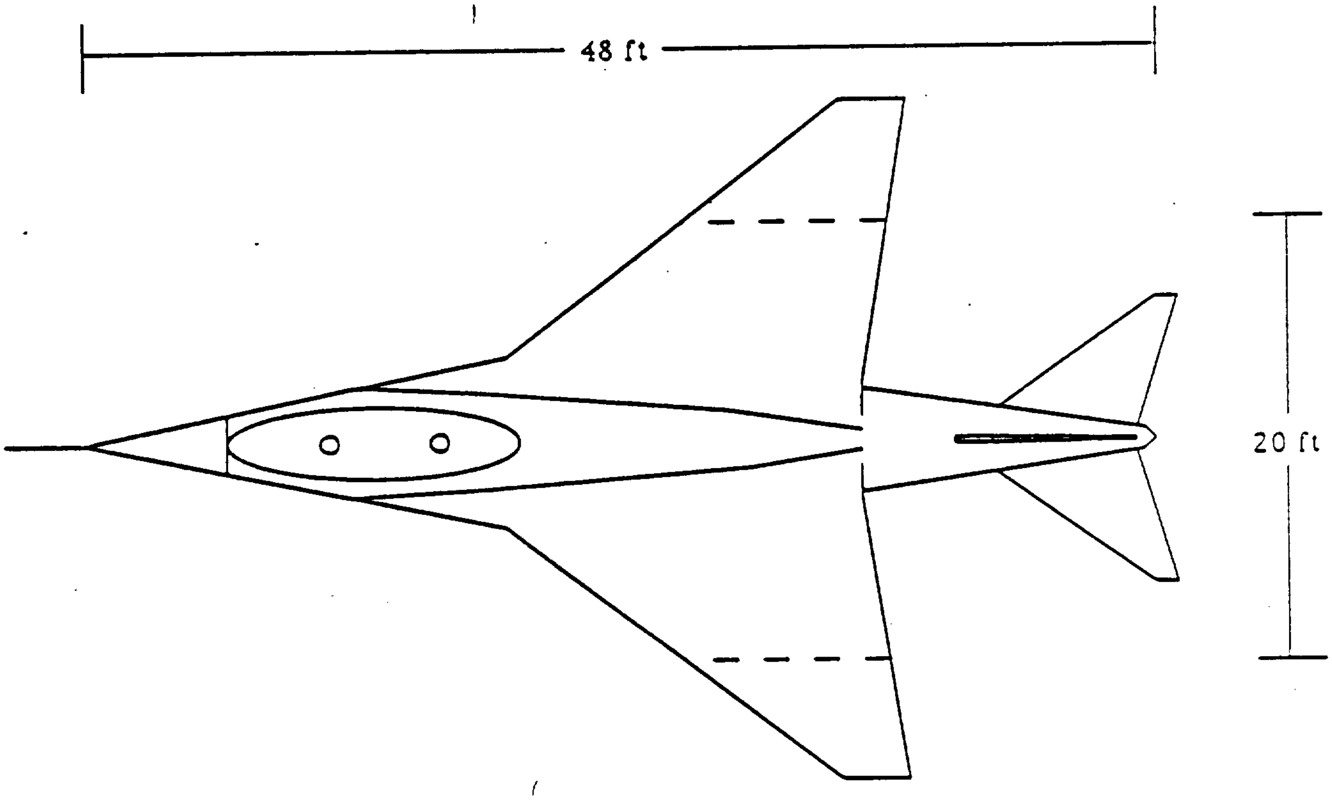


Figure 4.1.3 Gremlin Top View

4.2 Mission Weights

The total gross weight of the aircraft fully loaded for the ground attack mission and the weight ratios for each section of the mission are located in Table 4.2. These are initial estimations needed for future calculations of aircraft performance. They were calculated using mission paramenters and specifications. By interpolation, the initial ground weight was calculated to be 24,111 pounds.

Table 4.2 Mission Weights

Mission Segment Number	Mission Location	Weight Ratios
W_1/W_0	takeoff	0.970
W_2/W_1	climb to cruise altitude	0.985
W_3/W_2	150 n.mi. cruise	0.979
W_4/W_3	50 n.mi. cruise at 250 ft. altitude	0.994
W_5/W_4	dropping bombs	0.834
W_6/W_5	making 3, 6.5 turns	0.982
W_7/W_6	50 n.mi. cruise at 250 ft. altitude	0.994
W_8/W_7	150 n.mi. egress at altitude	0.979
W_9/W_0	landing	0.743

4.3 Component Weights

Although an initial weight sizing was determined based on historical data, a more accurate weight determination is done by adding component weights. The component equations can be found in many references and some of the calculations are shown in the appendix. The results of this data calculations and the c.g. locations of the components within the aircraft are shown below in Figure 4.3.1, Table 4.3.1, and Table 4.3.2.

Table 4.3.1 Weight Determinations

	Air Superiority Mission	Air Ground Mission
Maximum Takeoff Weight (lbs.)	18549	21579
Fuel Weight (lbs.)	4500	4500
Operating Empty Weight (lbs.)	13497	13497
Empty Weight (lbs.)	13002	13002

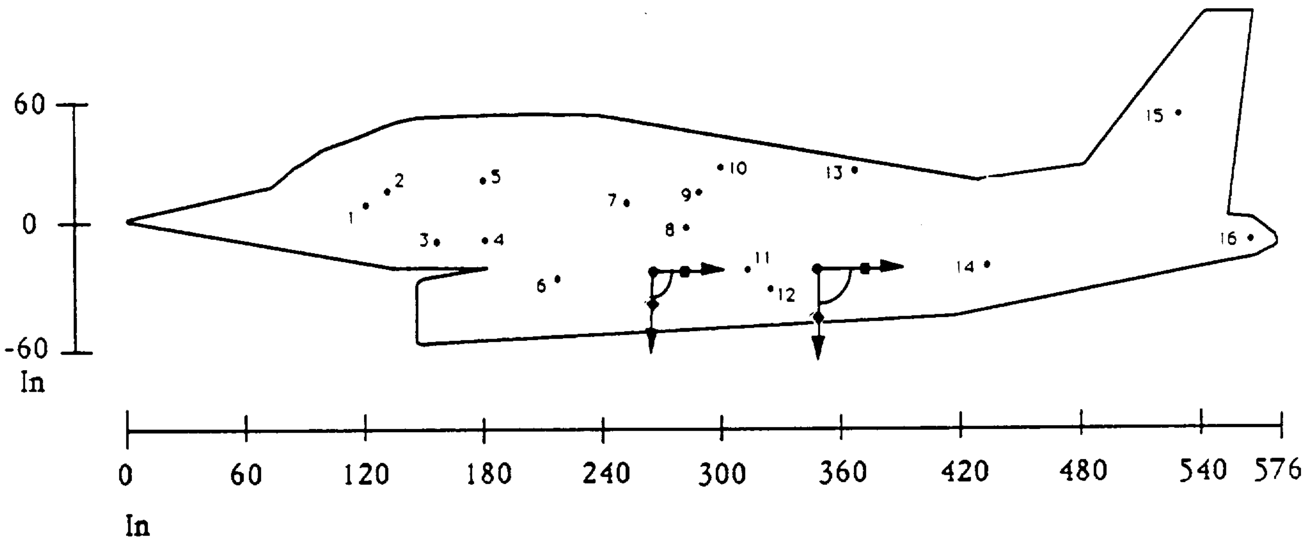


Figure 4.3.1 Weight Distribution

Table 4.3.2 Weight Distribution

Component	Location From Figure	Weight (lbs.)	Fuselage Station (in.)	Center Line Station (in.)	Waterline Station (in.)
Wing	13	2086	368	0	12
Horizontal Tail	16	298	558	0	-12
Vertical Tail	15	470	528	0	48
Fuselage	8	1351	281	0	-6
Main Landing Gear	12	766	324	0	-39
Wing Landing Gear	13	206	368	0	12
Engine Mounts	11	41	324	0	-24
Firewall	11	28	324	0	-24
Engine Section	11	20	324	0	-24
Air Induction	6	418	216	0	-30
Engine Cooling	11	256	324	0	-24
Oil Cooling	11	38	324	0	-24
Engine Controls	2	5	132	0	12
Starter	11	53	324	0	-24
Fuel System & Tanks	10	698	300	0	24
Flight Controls	2	490	132	0	12
Instruments	2	212	132	0	12
Hydraulics	9	172	288	0	12
Electrical	9	681	288	0	12
Avionics	4	1457	178	0	-8
Furnishings	2	435	132	0	12
A/C & Anti-Ice	3	302	154	0	-12
Engine	11	1920	324	0	-24
Gun	7	454	252	-12	6
APU	14	145	432	0	-12
Empty Weight		13002	294.4	-0.4	-2.6
Pilot	1	225	121	0	6
Co-Pilot	5	225	181	0	18
Trapped Fuel	10	45	300	0	24
Operating Empty Wt.		13497	289.6	-0.4	-2.0
Fuel, Air-Superiority		4500	300	0	24
Fuel, Ground Superiority		4500	300	0	24
Ammunition		170	252	12	6
3 Mk 82 (Right)		1515	303	84	0
3 Mk 82 (Left)		1515	303	-84	0
Aim-9L (Right Tip)		191	414	186	-6
Aim-9L (Right)		191	303	84	0
Aim-9L (Left Tip)		191	414	-186	-6
Aim-9L (Left)		191	303	-84	0
Maximum Takeoff Wt.		21579	295.6	-0.2	3.7

4.4 Center of Gravity Determination

Determining the center of gravity (c.g.) location of the Gremlin required an analysis of the c.g. location of the individual components (see Table 4.2.2). Each component was positioned in the plane to reduce distances to the areas where they will be used and to keep the overall c.g. location within the distance between the two nozzles. Table 4.3.2 shows the weight and c.g. location of the components analyzed with respect to three axis. The first is the fuselage station. This axis represents the c.g. location with respect to the front of the fuselage to the tail. This direction can be observed from the top views. The next location is the center line station. This axis can be viewed from the Gremlin top view. The c.g. locations that are off line of an imaginary center line drawn down the fuselage of the plane. The next location is the waterline station. This axis can be viewed from a side view. The center line station has a direction positive from the nose tip to the positive z-direction. The c.g. location is negative if below the center line. Figure 4.3.1 shows the location of the components with respect to the fuselage and waterline locations.

5. Geometry

5.1 Wing Geometry

The design of the wing for the Gremlin is a 31 foot span with a leading edge angle of 50 degrees. The wing has a reference area of 360 square feet. This was determined from wing loading requirements and comparisons with historical data. The root to tip ratio is 7 to 1. The trailing edge has an angle of 8.74 degrees (see Figure 5.1.1).

To determine the mean aerodynamic chord, a method that involves geometry was used. A line equal in length to the root was added to the tip while a line equal in length to the tip was added to the root thus creating a box. From this, two lines were drawn connecting opposite corners of the box. The point where the two lines intersected labeled the mean aerodynamic chord. The chord length was determined to be 11.5 feet. At half of the mean aerodynamic chord length, a line was drawn perpendicular towards the center line. This point represents the c.g. location of the wing.

Another aspect of the wing determined was the location of the aerodynamic center for both subsonic and supersonic flight regimes. The subsonic aerodynamic aerodynamic center was determined to be 25 percent of the mean chord and the supersonic aerodynamic center is located at 40-percent of the mean chord.

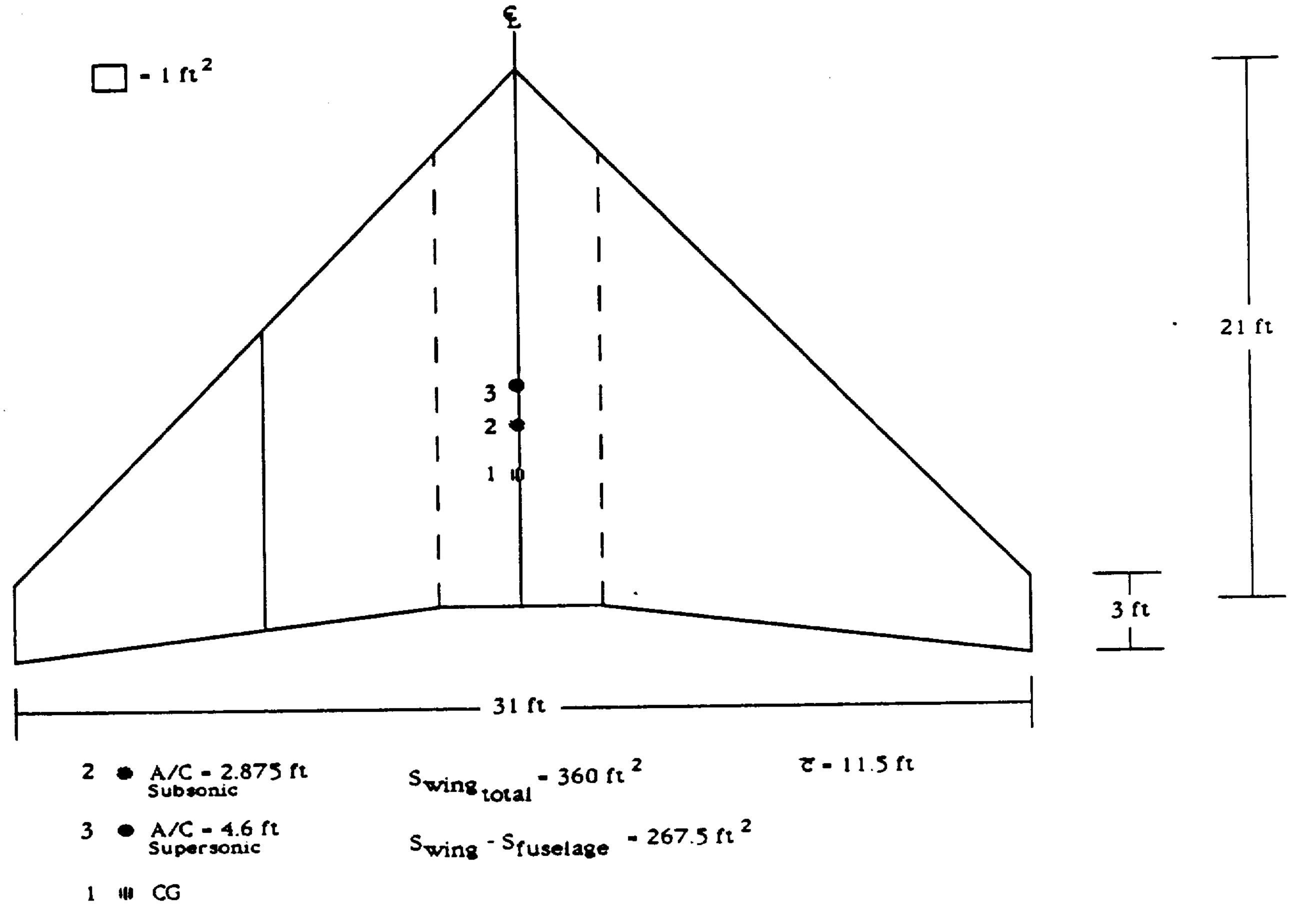
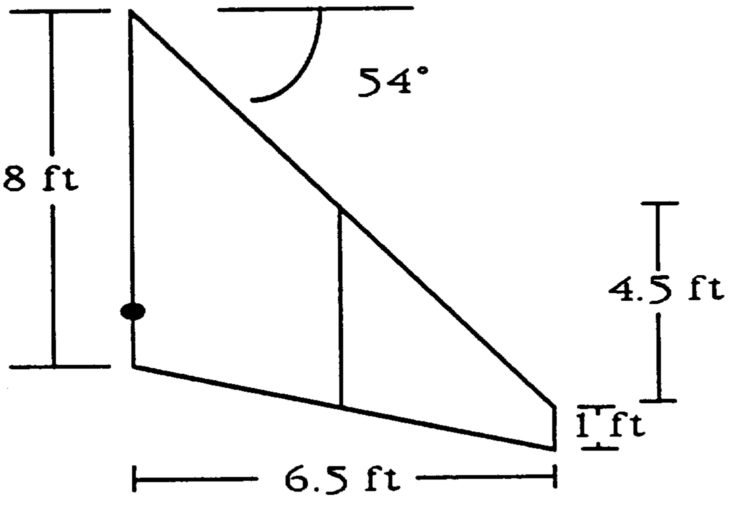


Figure 5.1.1 Wing Geometry

5.2 Horizontal Tail Geometry

The horizontal tail was designed with a reference area of 30.88 square feet. The root length is 8 feet and the tip length is one foot. The sweep angle of the leading edge is 54 degrees. The c.g. was determined using the same method as the wing (see Figure 5.2.1). The area of the tail was determined through comparison with the area of the wing and corrolation with comparable aircraft designs. The sweep angle of the tail is greater than the wing in order to delay the onset of shocks on the tail thus improving maneuverability in the transonic regime.

Determing the mean aerodynamic chord of the horizontal tail was accomplished using geometry as done for the wing. The chord length was determined to be 4.5 feet.



● C.G S_{Wet} - 61.85 $S_{Wet_{tot}}$ - 123.71

S_{Ref} - 30.88 $S_{Ref_{tot}}$ - 61.76

Figure 5.2.1 Horizontal Tail Geometry

5.3 Vertical Tail Geometry

The vertical tail was designed with a height of 7.5 feet, a root length of 9.25 feet and a tip length of 2.25 feet. The leading edge angle is 50 degrees. The vertical tail has a reference area of 40.36 square feet (see Figure 5.3.1).

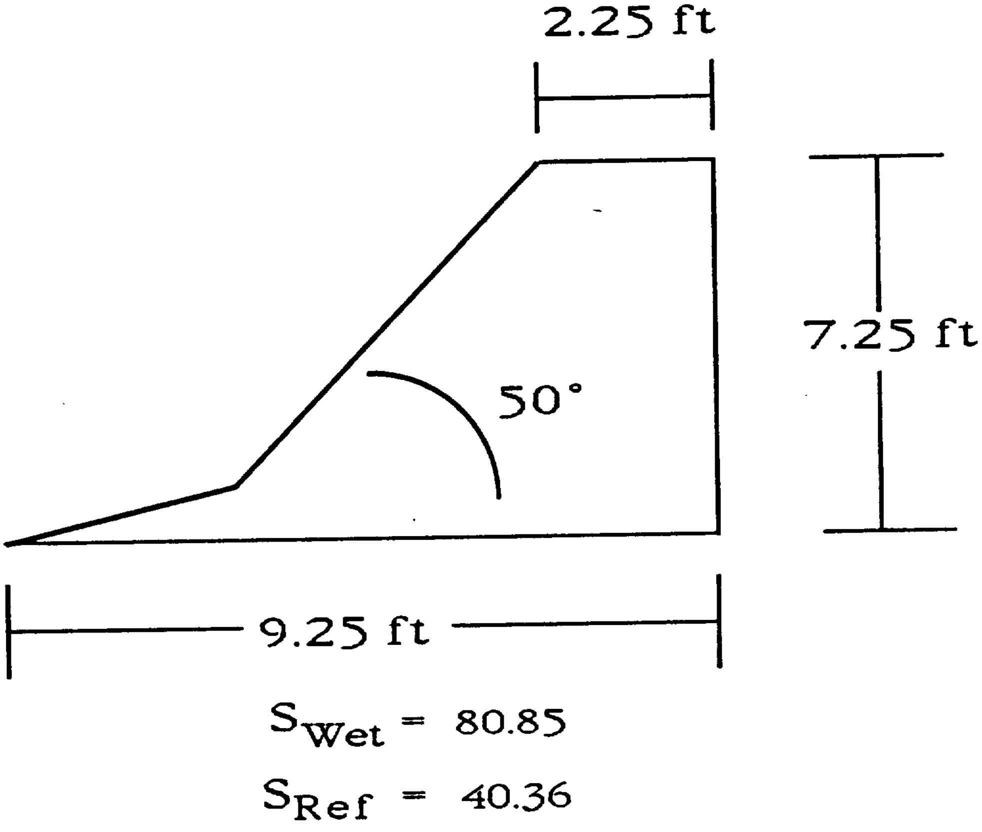


Figure 5.3.1 Vertical Tail Geometry

5.4 Control Surface Sizing

Control surfaces are very critical to an aircraft's performance. The three primary control surfaces vital to an aircraft are the aileron to control roll, the elevator to control pitch, and the rudder to control yaw. The final sizes depend on dynamic analysis for control effectiveness. But, for initial sizing, historical data can be used. The ailerons typically extend from about 50 to 90 percent of the wetted span of one wing. But, because of the Gremlin's wing fold location, the ailerons had to be placed 62 to 100 percent of the wetted wing span of one wing (see Figure 5.4.1).

A major drawback to ailerons on high speed aircraft is the phenomenon called "aileron reversal". This is when forces produced by the air flow twists the wing. At a certain velocity, the wing could possibly twist so much that a rolling moment that occurs from the twisted wing can be much greater than the rolling moment that the aileron generates. This tends to have an adverse effect on the aircraft, making it roll in the opposite direction. To combat this effect, many aircraft use inboard ailerons. But, due to the nature of vectored thrust, inboard ailerons do not have to be used.

For most aircraft, the elevators and rudder start from the fuselage to 90% of the span. This is the specification used in the Gremlin's control surface sizing in the tail (see Figures 5.4.2 and 5.4.3).

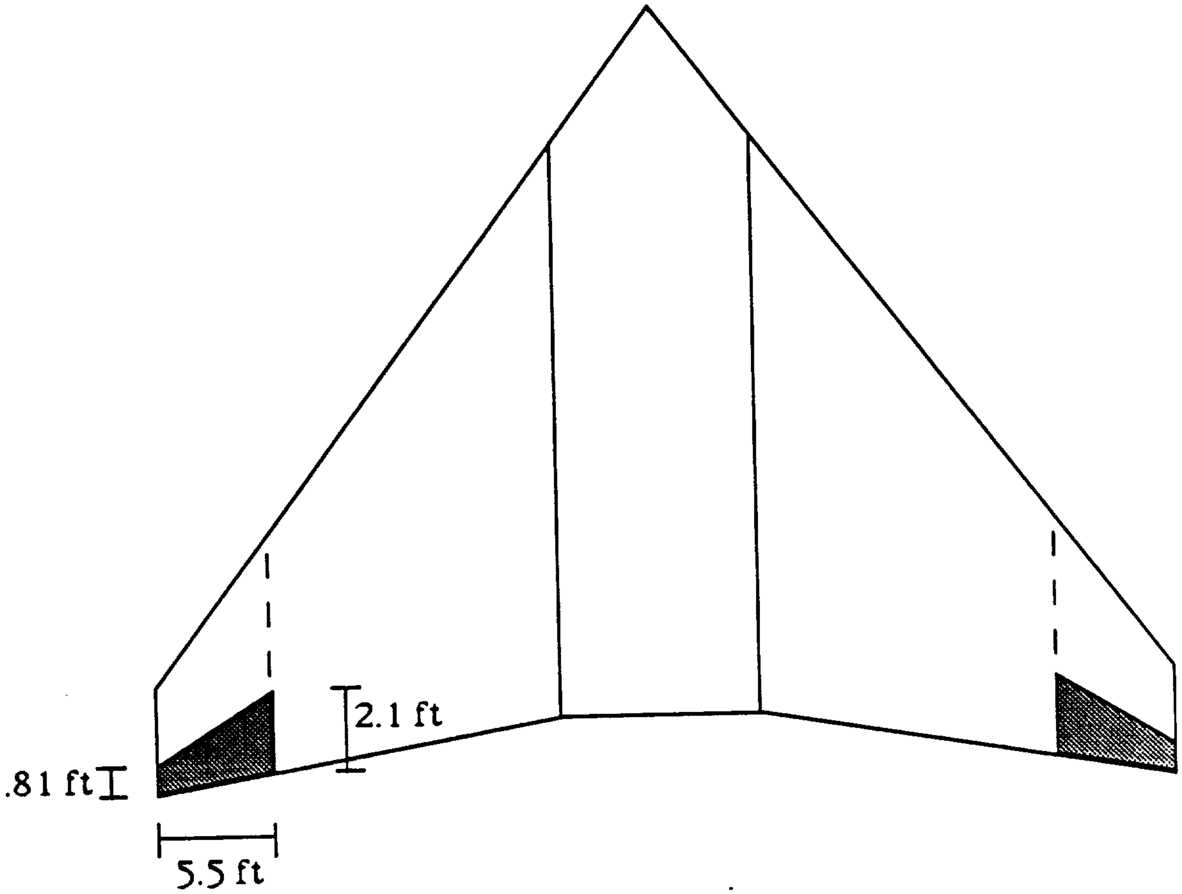


Figure 5.4.1 Ailerons

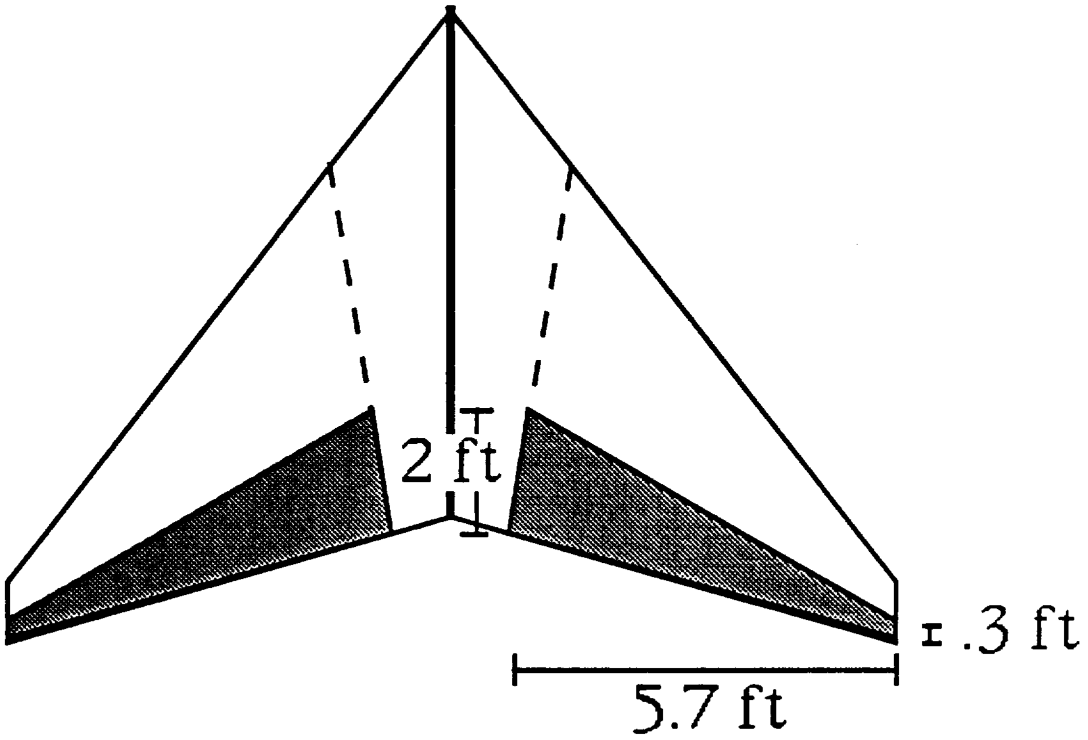


Figure 5.4.2 Elevators

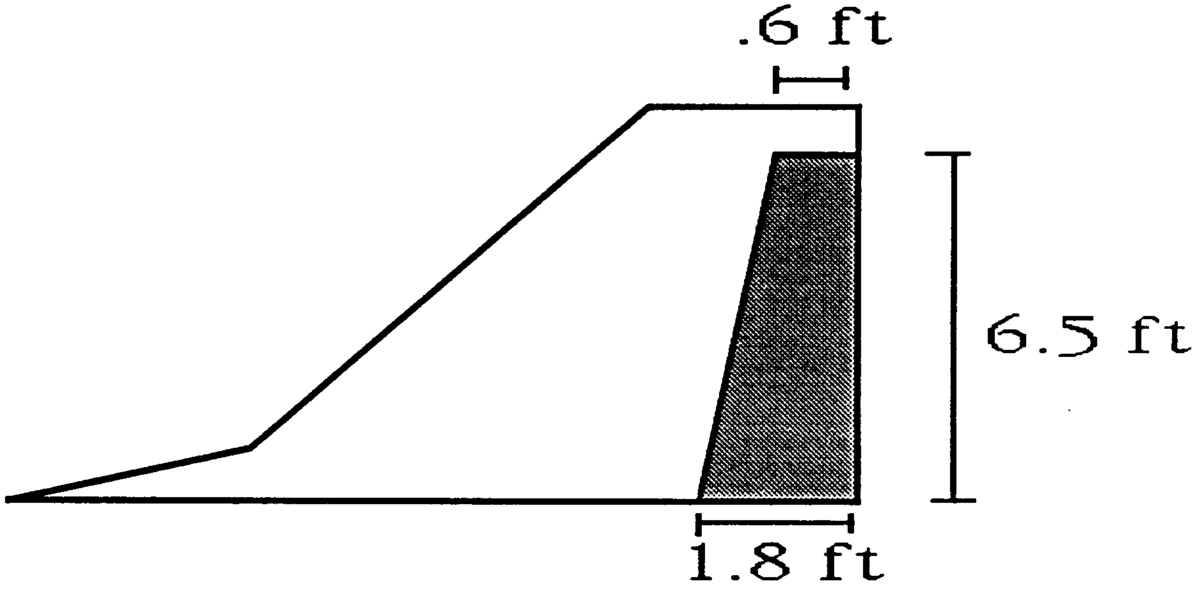


Figure 5.4.3 Rudder

6. Rubber Engine

Due to a lack of information and data on production and future engines, the Gremlin has been fitted with a rubber engine. Using experimentally derived equations, an engine may be created to fit the needs of a particular airplane. This is known as a rubber engine. The advanced, supersonic Pegasus 11-61 was the desired engine to power the Gremlin, but very few actual parameters were available. Without these parameters, the Gremlin could not have been designed. The Pegasus is classified through the British government and Rolls Royce possesses proprietorship of all Pegasus data. Neither the British government nor Rolls Royce would voluntarily release any specific information on the Pegasus. Also, two engines were provided as part of the design contest options. Neither of these engines met the needs of the Gremlin.

One of the engines provided was a Rolls Royce direct lift engine. Since two engines are required when a direct lift engine is utilized, the weight of the airplane is much greater than with only one engine. Also, during horizontal flight, the direct lift engine is dead weight since it contributes no thrust. The need to stock two engines and spare parts is another drawback. Since the Gremlin will take advantage of vectoring thrust during flight, the direct lift engine could not be used since it does not possess this capability.

The other engine provided is a purely conceptual engine in terms of today's technology and will not be in production for about two decades. This engine does not fit the requirements of the Gremlin since it is a three poster instead of four poster engine and did not produce enough thrust. The number of posters of an engine refers to the number of nozzles providing thrust.

Since a rubber engine was ultimately the only possible engine to use, the parameters were calculated for the needs of the Gremlin. Equations obtained from the Raymer reference provided an accurate estimation method for the specific rubber engine performance aspects. Using the weight, thrust, bypass ratio, and maximum Mach number, the rubber engine parameters are given in Table 6.1.

Table 6.1 Engine Parameters

Weight	1919.830 lb
Length	150.008 in
Diameter	46.068 in
Specific Fuel Consumption for Maximum Thrust	1.526 lb(fuel)/hr lb(thrust)
Specific Fuel Consumption for Cruise	0.717 lb(fuel)/hr lb(thrust)

7. Landing Gear

When considering an aircraft design, weight must be minimized and space is at a premium. The design of the STOVL Gremlin aircraft is no exception. Since the rotatable nozzles project from the side of the mid-fuselage area, landing gear must be placed elsewhere. Given the classically thin supersonic airfoil of this aircraft, gear storage inside the wing structure is considered impractical.

Because of the similarities between the Gremlin and the AV-8B Harrier, the solution for the Gremlin landing gear design is seen as a modified bicycle landing gear approach similar to the AV-8B Harrier as shown in Figure 7.1. This type of design consists of two main gear in tandem along the main fuselage. The main gear are located approximately at the rear third of the fuselage. The main gear support approximately 75 percent of the weight of the aircraft in a static situation. The remaining 25 percent of the weight of the aircraft is carried by the outboard "outrigger" gear which are attached to the wing at 9 feet from the center line. These outriggers serve a dual purpose. Besides reducing the load on the main gear, the outboard gear balance the aircraft and provide a very wide wheelbase for vertical flight takeoff/landing operations. Rough field operations considerations are the main advantages of this landing gear configuration. During flight operations from unimproved fields, larger stresses and loads are placed upon the landing gear and aircraft structure. A significant portion of these stresses can be relieved through the effective use of shock absorbers. However, the remaining stresses on the landing gear must be relieved by way of the aircraft structure. Since the fuselage is the sturdiest portion of the aircraft structure, and since the wing is already highly loaded due to fuel and ordnances, the main portion of the weight of the aircraft is relieved to the fuselage structure.

The outboard landing gear will fold rearward during storage and will be surrounded by streamlined nacelles to minimize the resulting drag increase due to the outboard configuration.

Since the Gremlin is designed to operate in rough field conditions, oversized tires will be used on the main gear. The gear structure itself will be constructed almost entirely from T steel. This alloy is a common type used in landing gear structures.

Landing gear design is almost a complete engineering discipline within itself. Therefore, the Gremlin's landing gear system will be subcontracted to a firm with suitable experience in gear design. Because of the large amount of experience with this type of landing gear on existing aircraft (i.e. Harrier), the expected development time and associated cost should be minimized.

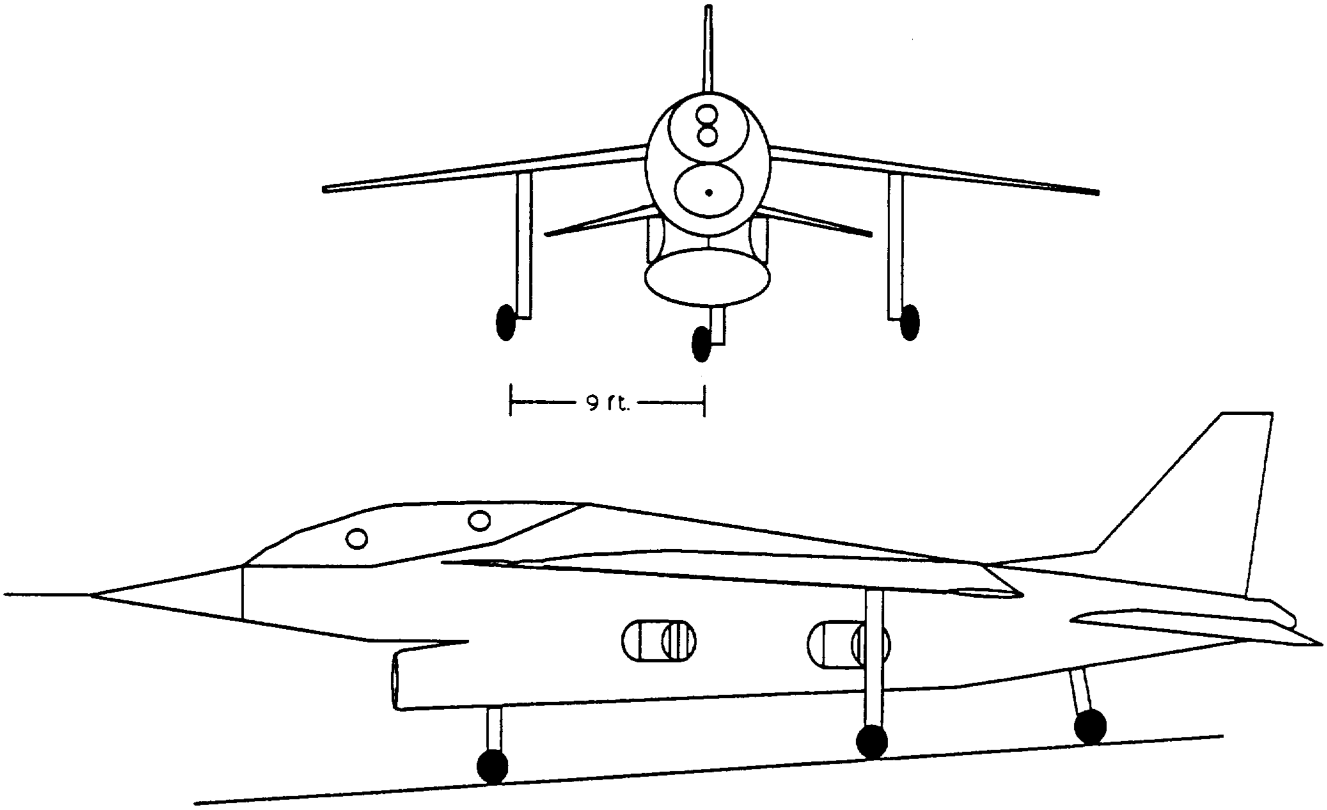


Figure 7.1 Gremlin Landing Gear

8. Weapons System

The gun has been the main weapon of fighter engagements since the dawn of air combat during WWI. Even though the use of air-to-air missiles have limited the use of the gun, it is still an invaluable weapon system.

The standard U.S. gun installed in all fighters is the M61A1 "Vulcan" six-barrel Gatling gun (Figure 8.1). In order to maintain compatibility with U.S. forces, this is the choice for the Gremlin aircraft.

An ammunition container is attached to the gun for easy reloading and ammunition handling. The Vulcan can produce up to two tons of recoil force, therefore, it is prudent to place the gun near the center line of the aircraft to prevent a sudden yawing moment.

When fired, the Vulcan produces a bright flash and a cloud of smoke. The gun muzzle was positioned where the muzzle flash is not harmful to the pilot's vision. The gun was also placed where gases from the smoke cannot cause a jet engine to stall if it is ingested into the inlet.

The purpose of most military aircraft is to act as a platform to transport weapons to destroy targets. Weapons can consist of missiles, bombs, and guns.

Missiles can be launched from aircraft by two methods. The AIM-9 Sidewinder that the Gremlin is designed to carry is rail launched. A rail-launcher is attached to either the wing-tips or underwing pylons. The missile has several mounting lugs, which slide onto the launcher. When launched, the propulsive force from the missile moves it along the rail and slides free of the aircraft. The Gremlin will employ wing tip mounted launchers as well as pylon launchers for sidewinders.

Ejection-launch is mainly used for large missiles. The missile is attached to the aircraft by hooks powered by explosive charges which can release very quickly. The explosive also powers two pistons, which push the missile away from the body of the aircraft. Bombs can also be released in this manner or they can be released in free fall. This method is considered undesirable for the Gremlin.

Because of the size limitations inherent to all fighter aircraft, the capability to have the weapons stored inside a weapons bay is not possible. The only option left for the Gremlin is the placement of weapons externally. This type of carriage calls for hardpoints under the wing and fuselage to which weapon pylons are attached. These pylons are dropable for maximum dog fighting capability. The Gremlin can also carry external fuel tanks on the pylons. These fuel tanks are jettisoned during air-to-air combat.

A major drawback to externally carried weapons is the extremely high drag that the weapons produce. When an aircraft approaches Mach one with an external load of weapons, the weapons can produce more drag than the aircraft generates.

The location of missiles and bombs relative to other aircraft components and the ground was considered. A minimum clearance of three inches above the ground was required when designing the Gremlin. This requirement is for the scenario that one tire and shock strut goes flat and the aircraft has a five degree roll. When weapons are placed near each other there is a minimum of three inches clearance between them.

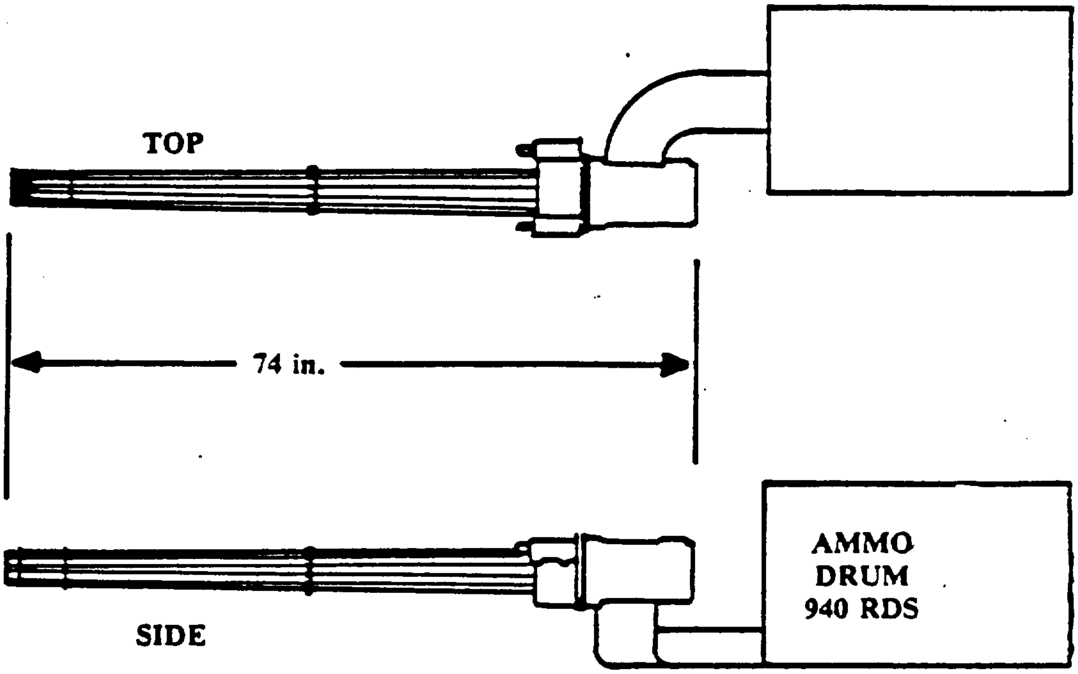


Figure 8.1 M61 Vulcan Gun

9. Special Considerations

9.1 Hydraulics

The hydraulic system in an aircraft pressurizes hydraulic fluid by a pump and stores it in an accumulator. When a valve is opened by a control stick, the pressurized hydraulic fluid flows to an actuator to move a piston that moves the control surfaces. The hydraulic fluid is then returned to the pump by a return line. In more recent aircraft designs, a fly-by-wire approach is used instead of the hydraulic system. A fly-by-wire system transforms the pilot's inputs into electrical impulses and sends them as values to the actuator.

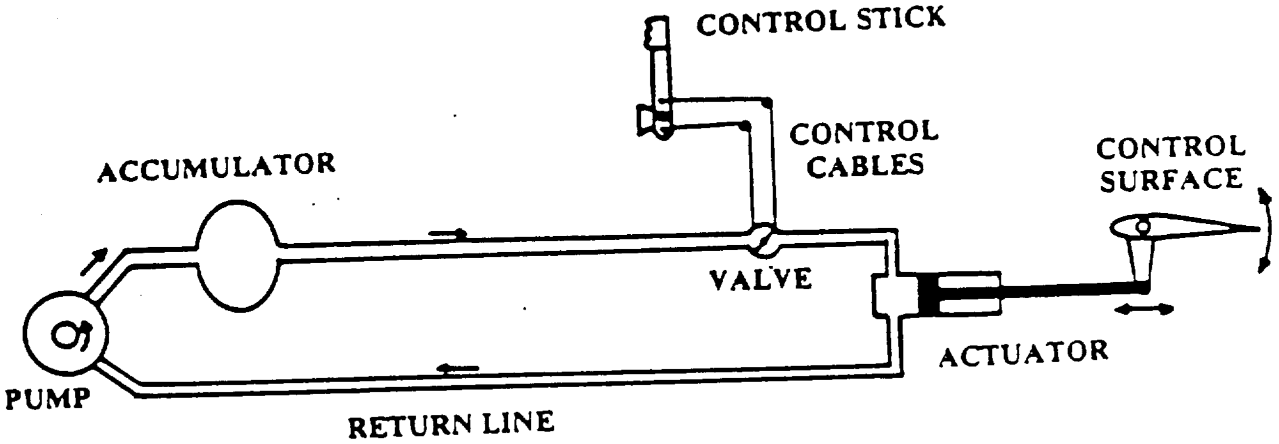


Figure 9.1.1 Simplified Hydraulic System

9.2 Avionics

In today's increasingly complex air combat arena, the avionics of a fighter/attack aircraft is as important as the quality of the pilot in insuring aircraft survivability. Avionics typically include radios for communication, navigational instruments, flight control computers for stability, radar for obtaining contacts, and other types of sensors to identify and classify types of contacts. Avionics occupy a large volume of the aircraft structure, which complicates the placement of the equipment. Also, the nose of the aircraft must be designed to hold a radar system. The avionics and integration system is shown in Figure 9.2.1. This system is based upon the F/A-18 Hornet. Because of the similar mission profiles and advanced avionics package of the Hornet, as well as the low cost of installing a developed system, this system was chosen as the avionics package for the Gremlin.

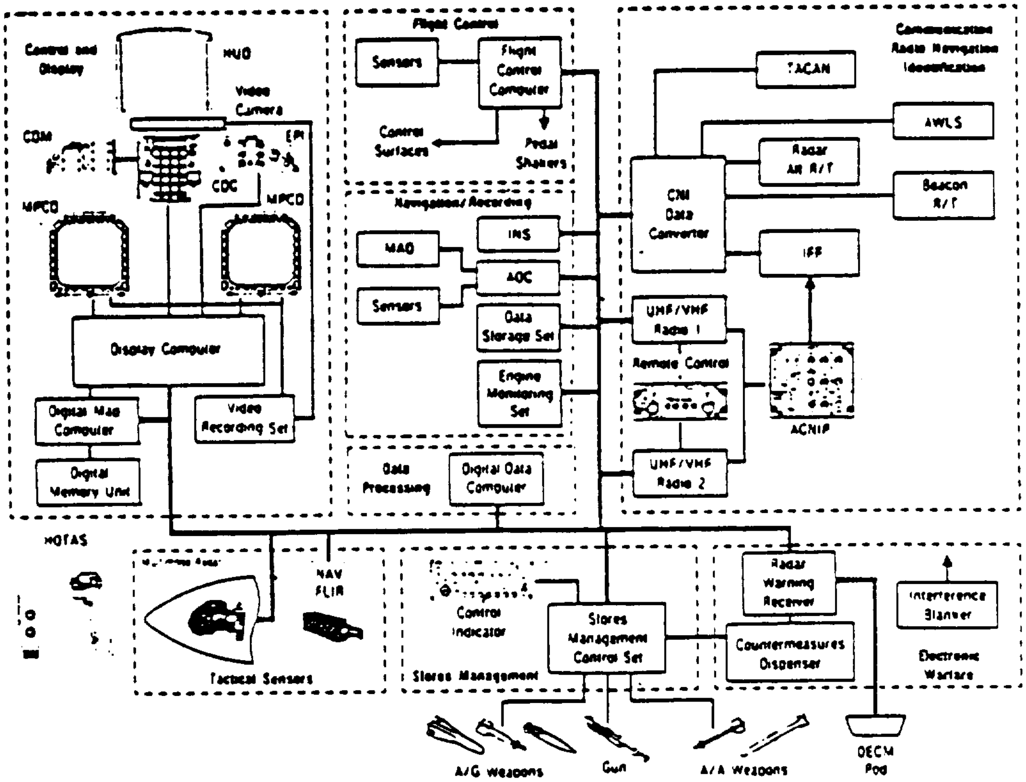


Figure 9.2.1 Avionics Block Diagram (reference: McDonnell Douglas, The Harrier II Plus-Report MDC)

9.3 Crew Station

The crew station of an aircraft must be designed primarily for the pilot to have unobstructed outside visibility and efficient access to all instruments. Generally, crew stations are designed to accomodate the average pilot size in which 95% of all pilots fall.

The crew station has two main reference points that determine its dimensions. The point on the seat where the pilot's back meets the bench is the point of reference for the floor height and the leg room. The point where the pilot's eyes are located is the second reference point. This reference point is the base where the overnose angle, transparency grazing angle, and pilot's head clearance are found (Figure 9.3.1).

The Gremlin's crew station layout uses a 17 degree seat tilt-back angle. This reduces the visibility somewhat from the standard 13 degrees, but it enhances the pilot's ability to withstand high-g turns and can also lead to reduced drag because the canopy can be made smaller.

Overnose vision is very important, especially in the landing stage and in air-to-air combat. Military specifications require an 11-15 degree overnose angle for fighter and attack aircraft. The Gremlin achieves an 11.5 degree angle as seen in Figure 9.3.1.

Typically, fighters and attack aircraft have a 40 degree over-the-side angle. The Gremlin achieves a 43 degree over-the-side angle.

The pilot control panel integrates the F/A-18 Hornet's and AV-8B Harrier's systems. From Figures 9.3.3 and 9.3.4, the displays and controls can be seen. These systems are taken mostly from the Hornet. Using the Hornet's displays and controls allows the manufacturer to keep costs down by using already existing systems. A major modification to the aircraft's design is that the throttle is removed and a Harrier throttle and nozzle control are installed. This allows for the vectoring of the nozzles as well as thrust control (Figure 9.3.5).

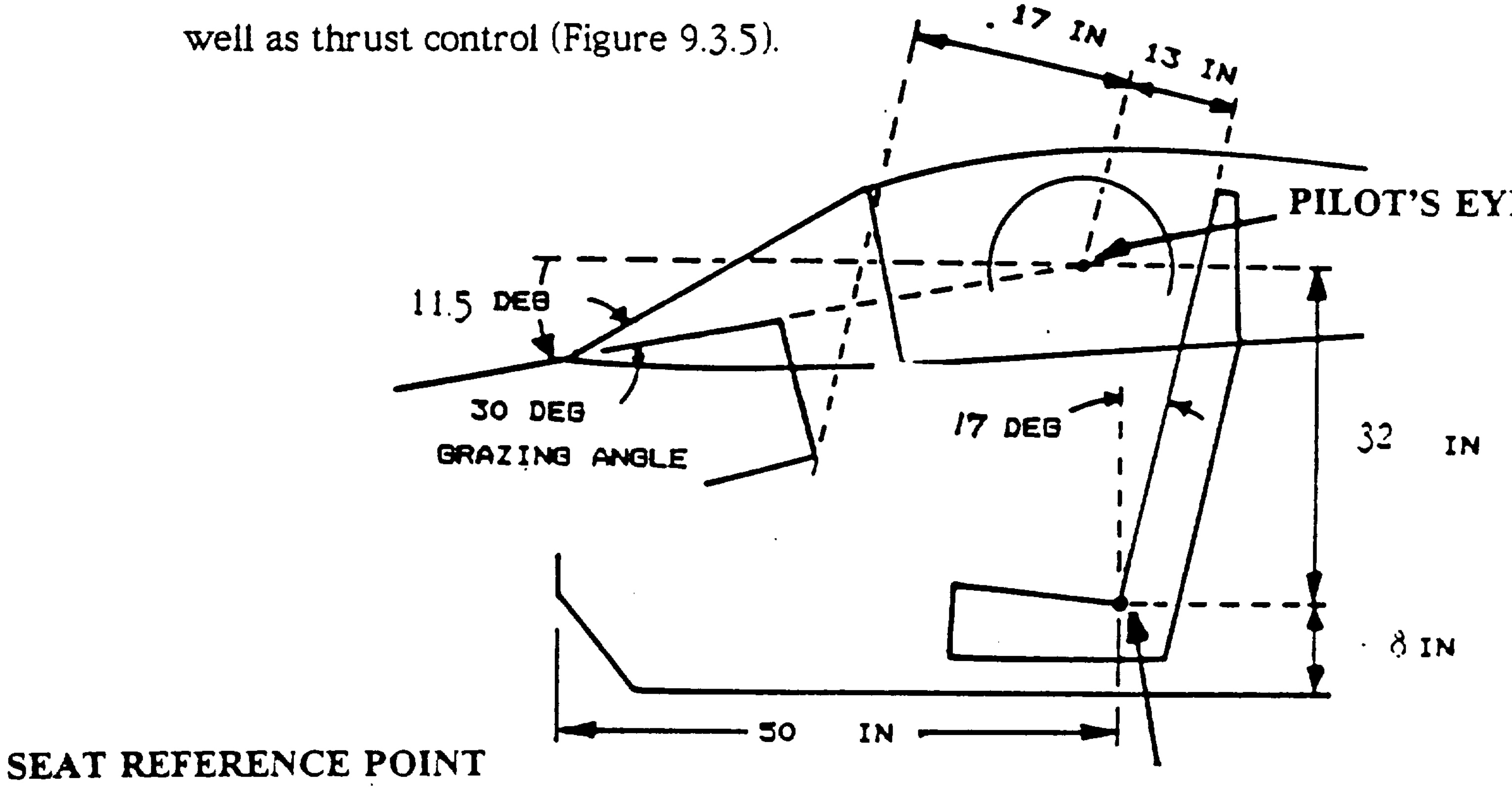


Figure 9.3.1 Crew Station Geometry

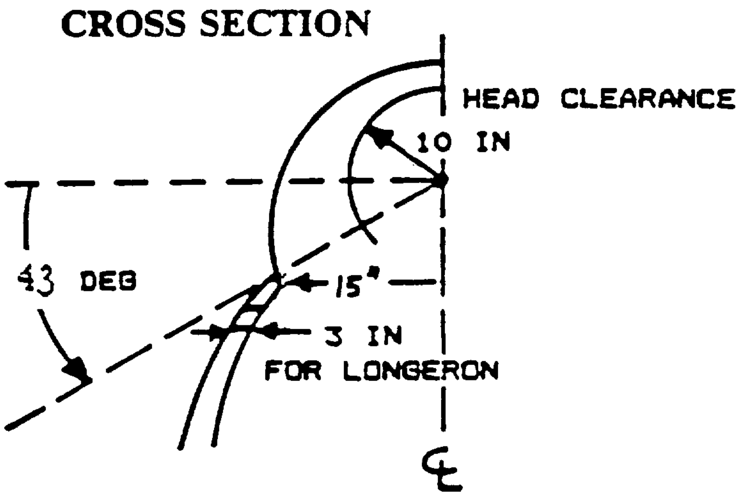


Figure 9.3.2 Pilot Visibility

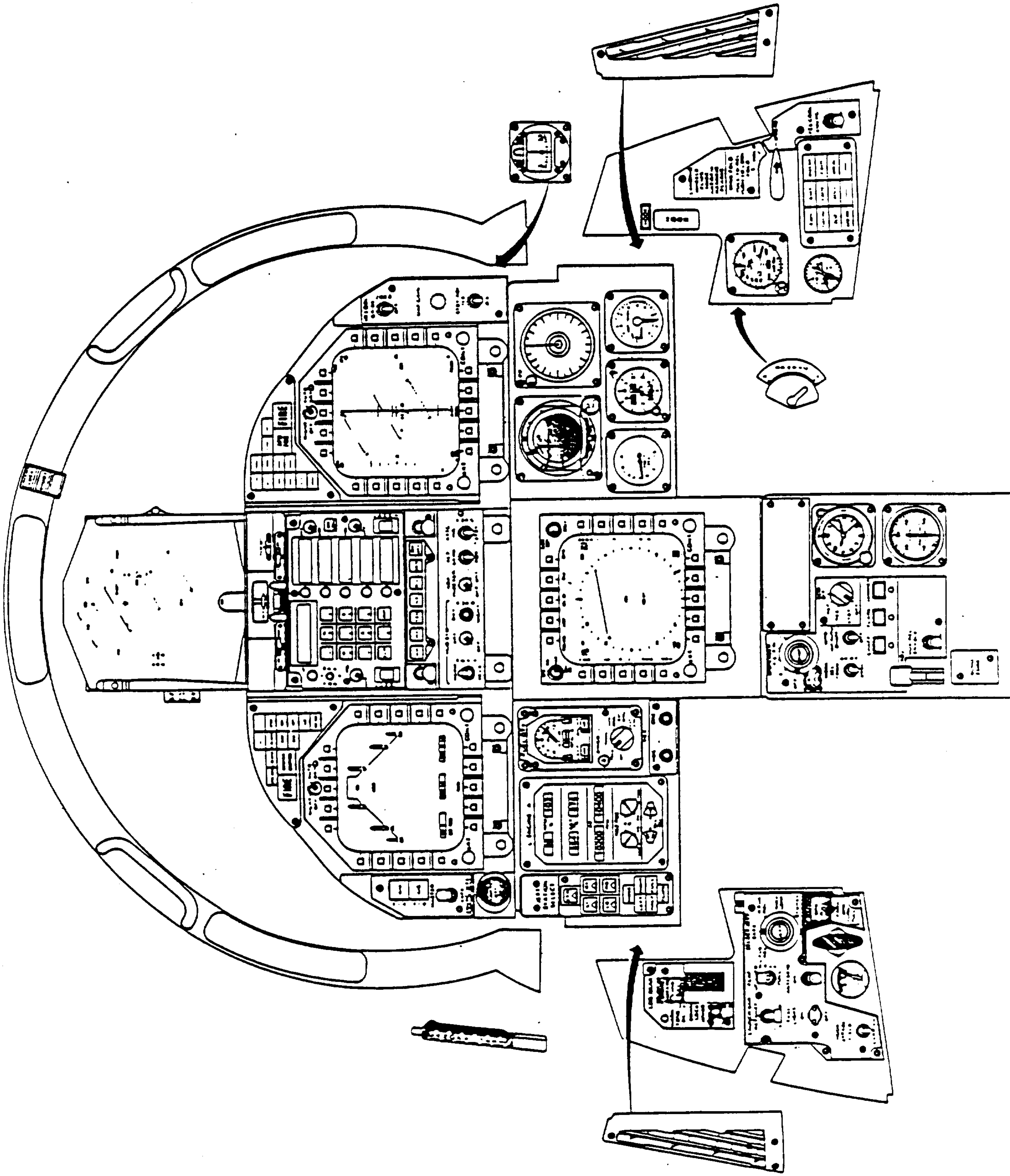
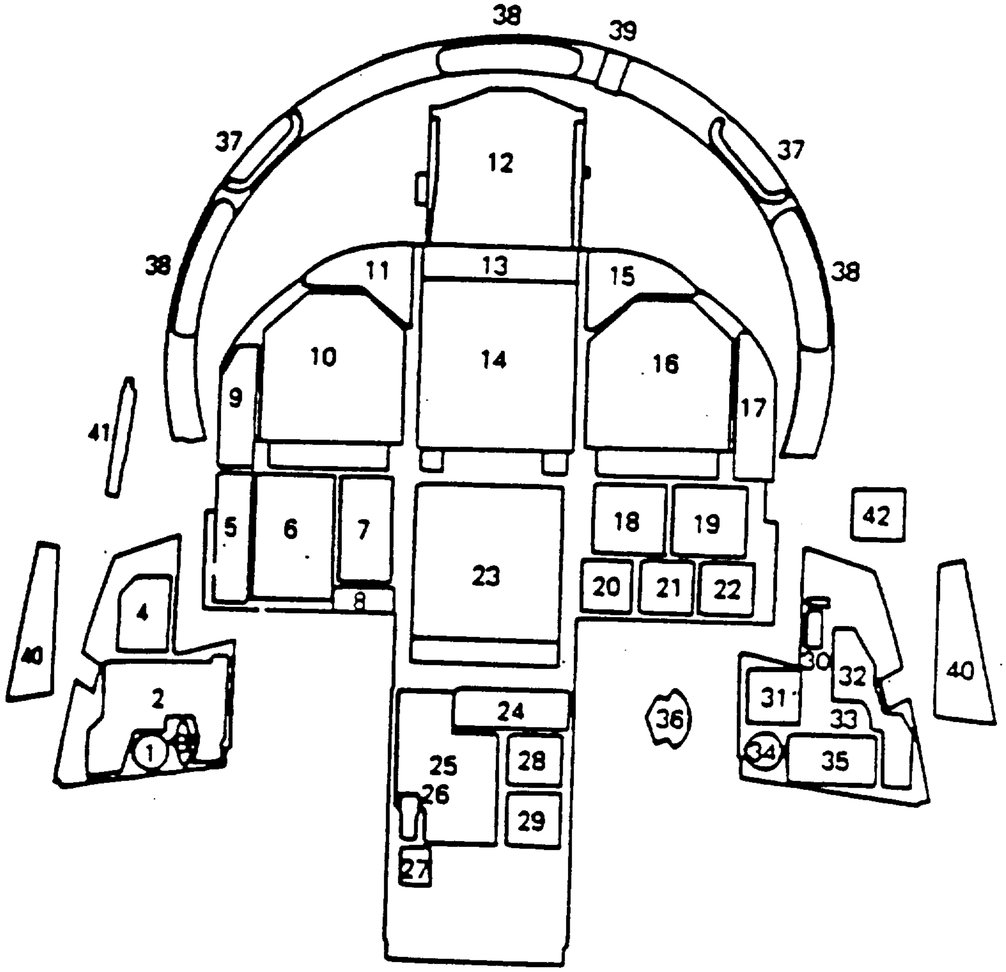


Figure 9.3.3 Pilot's View of Control Panel



1 Brake pressure indicator
2 Landing hook bypass, launch bar and stores jettison selectors
3 Emergency/parking brake handle
4 Landing gear controls
5 Stores jettison indicators
6 Digital engine monitor display
7 Fuel quantity indicator
8 Course and heading lightplate
9 Master armament panel
10 Master monitor display
11 Left warning panel
12 Head-up display
13 Head-up display camera
14 Up-front control panel
15 Right warning panel
16 Multi-function display
17 IR cooling, map gain and ILS/Deck landing switches
18 Attitude reference indicator
19 Radar warning display
20 Standby airspeed indicator
21 Standby altimeter
22 Vertical speed indicator
23 Horizontal situation display
24 ECM growth space
25 ECM control panel
26 Rudder pedal adjustment
27 Aircraft build-number plate
28 Clock
29 Cabin pressure altimeter
30 Arrester hook control
31 Altitude indicator
32 Landing lightplate
33 Wing fold control
34 Hydraulic pressure indicator
35 Caution light panel
36 Static-pressure source selector
37 Canopy frame handle
38 Mirror
39 Lock/shoot indicator
40 Environmental control system louvre
41 Canopy jettison lever
42 Standby magnetic compass

Figure 9.3.4 Explanation of Control Panel

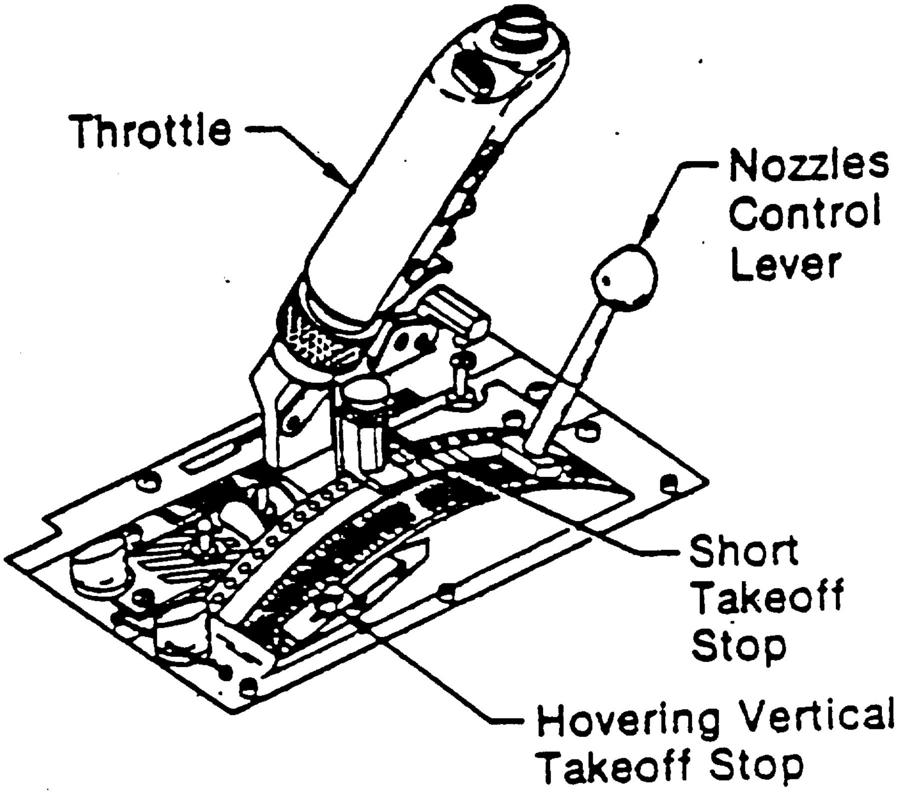


Figure 9.3.5 Nozzle Vector Control and Throttle

9.5 Materials

The trade-offs of both weight and cost were considered in the selection of materials used in the Gremlin. Composite materials were used in many parts of the Gremlin to minimize weight, thus increasing the fighter's thrust-to-weight ratio. However, use of composites was limited due to their high cost.

In order to become familiar with the fabrication and distributing processes of composites, our design group visited the Sikorski/Dow Composite Plant in Tallassee, Alabama. This plant is mainly responsible for the fabrication of composite materials on the UH-60 Blackhawk helicopter but also produces composite parts for aircraft on a small scale. After our visit to the composite plant, this design group decided what materials would be used on every part of the Gremlin. The Gremlin was estimated to be 70 percent aluminum and 30 percent other materials by weight. The fuselage and airframe of the Gremlin are made of an aluminum alloy. Aluminum is a lightweight, high strength, low cost material. It is also easily formed and has proven to be very efficient as an aircraft material.

The vertical and horizontal tails of the Gremlin are made of a composite material called graphite-epoxy. This material is widely used as a substitute for aluminum because it provides a weight savings of up to 25 percent over aluminum. The shapes of the Gremlin's tails are simplistic, therefore, not difficult to reproduce from composites, reducing their cost.

The Gremlin's wings are made of graphite-epoxy also, but special consideration has been given to the high heat areas on the wings due to supersonic flight. For example, on the leading edges of the wings, a special composite strip of polymide is placed to withstand the intense heat. Polymide is a composite which will withstand temperatures up to 600 degrees Fahrenheit, but is difficult to process, thus is very expensive to use in large quantities.

The radome of the fighter is made of a composite called airamid. This material provides easy visibility for the radar. The fighter's canopy is made of a single piece of stretched acrylic. This material has high strength as well as provides good pilot visibility.

The engine nozzles and landing gear are made of a steel alloy (4130). This material is a steel alloy of chromium and molybendum composition and is notable for its high strength as well as good fatigue resistance. Steel is relatively easy to fabricate and is relatively inexpensive.

The "hot spots" around the engine are made of titanium. Titanium has a better strength-to-weight ratio than aluminum and is capable of withstanding extremely high temperatures. However, titanium is extremely expensive so it was not used extensively in the Gremlin. The engine inlet is made of a composite capable of withstanding high temperatures.

9.5 On Board Oxygen Generating System (OBOGS)

At high altitudes, the pilot of a fighter needs an oxygen supply because of the low air density associated with higher altitudes. There are basically two ways to provide this oxygen supply. One option is the outfitting of aircraft with liquids or compressed oxygen. This method was used in almost all fighters, but proved quite dangerous in case the liquid or compressed oxygen cannisters were to rupture.

OBOGS provides oxygen to the pilot from air bleed off from the engine compressor that is run through a processing unit. The OBOGS method was determined to be the most suitable option of providing oxygen to the pilot in a forward based area where oxygen cannisters may not be readily handy. This system is currently in operation in fighters like the General Dynamics F-16C.

10. Survivability/Vulnerability

In order for an aircraft to survive air combat, it must have several features. Among the most important are speed, maneuverability, and still the most important of all, a competent pilot.

The most useful method to reduce air combat vulnerability is the use of redundant systems. By duplicating the major systems of an aircraft, survivability is enhanced considerably. The main redundant systems on an aircraft include redundant fuel lines, hydraulic lines and electrical cables.

Although most combat aircraft designs incorporate redundant systems to reduce vulnerability, oftentimes these systems are not positioned effectively. The dual lines are sometimes designed to be run parallel to each other with very little space between them. In this case, a single projectile could disable both the primary and secondary systems thus completely disabling the aircraft. This may seem fairly obvious as a design consideration but two notable aircraft, the F-105 and F-111, did not take this aspect of vulnerability into account and had many combat losses due to this oversight. (reference: Richardson, Steve)

Redundant systems are not always a sign of increased survivability. A notable example of this case is multi-engine aircraft. A multi-engine aircraft would seem to be less vulnerable than a single engine aircraft because of the redundant engine(s). However, this is not always the case. If an aircraft has multi-engines, this means its weight and performance was designed around this factor. If one of these engines fails, steady flight is not insured. Usually the increased yaw and reduced handling due to the lost engine dictates a very quick landing. This landing is not always a safe one. There is a statistic which best illustrates the misconception that two engines equals survivability. During the Vietman War two engine fighters had a significantly higher rate of combat losses than single engine fighters. (reference: Richardson, Steve)

Fire onboard an aircraft is the worst fear of a pilot. This almost certainly spells disaster. In order to reduce the chance of ignition as well as propagation of flame onboard an aircraft, several options can be incorporated into a design. Most important is the use of firewalls to prevent the spread of fire from one compartment to another.

Conventional wisdom dictates that in order to minimize the possibility of fire onboard an aircraft, it is necessary to keep the fuel as far away from the engine as possible. This is suggested in order to keep fuel from coming in contact with the hot engine. However, in the Gremlin STOVL configuration the fuel and engine must be placed together. This is necessary for two reasons. In order to have vertical flight the vectored thrust must be balanced around the center of gravity (c.g.). Therefore, the engine must be placed at the aircraft's c.g. Also, in order to minimize c.g. shift during a long flight, the main fuel tanks must be placed about the c.g.

A way to prevent fires from starting in a fuel cavity is by filling all empty spaces with an inert gas such as nitrogen. The Gremlin's onboard oxygen system (OBOGS) separates the oxygen and nitrogen from the air. The oxygen is obviously used for the crew. However, the inert nitrogen could be pumped into the voids of fuel tanks and other areas where spark propagation and static charges as well as combat danger could cause a fire or explosion. The inert gas, in conjunction with self sealing fuel tanks, is a design safety measure which cannot be ignored.

Visual detectability is also a consideration for combat survivability. In modern air combat, with long range radar and night vision sensors, it seems archaic to be concerned with camouflage. However, visual sighting is the most important factor in a close dog fight situation. By painting an aircraft a color of grey which blends in with both sea and sky, a few vital seconds may be gained before an opponent has a chance to react. Since most air combat kills occur on the first surprise pass, visual indetectability is a cheap method of helping to insure the success of an aircraft in combat.

In a worst case scenario, an aircraft is damaged to the point where it is uncontrollable. In this case, a pilot must eject from the aircraft. Since the pilot is the most important system in an aircraft, it is extremely important to insure his survival.

Many modern ejection seats use the term "zero-zero" to describe their performance. A "zero-zero" ejection seat is expected to eject a pilot safely and have the parachute fully deploy before reaching the ground in a situation where the aircraft is at zero altitude and zero airspeed. Advanced ejection seats are being developed which should be able to safely eject a pilot from a inverted flight condition. The aircraft also experiences some significant sink rate. While this development will be a welcome advance for pilots, it awaits experimental validation before installation in production aircraft.

Because of the importance of having the most advanced escape system available, a "zero-zero" ejection seat system designed and constructed by the Martin-Baker Company was selected for installation in the Gremlin aircraft. In the reasonable event that a more advanced ejection system becomes available before production of this aircraft occurs, the new seat could be installed with only a small amount of engineering work necessary.

In conventional vertical flight aircraft, a cockpit canopy is designed to open from the front. This feature is designed to take advantage of the force of the wind during ejection from an aircraft. When a canopy of this type is opened only a small amount during forward motion, the wind blast rips the canopy away from the aircraft almost immediately. This situation frees the only major obstruction from the path of an ejecting pilot.

However, in a STOVL aircraft such as the Gremlin, a crucial portion of a flight occurs in vertical flight operations when there is an insignificant airflow across the canopy. To prevent significant injury to the pilot/ copilot, the canopy shell will be removed by the use of explosive cord embedded in the acrylic shell of the canopy. This is common practice and can be seen in several production aircraft such as the AV-8B and T-45.

11. Performance

11.1 Airfoil

To begin analyzing the performance of an aircraft, a brief review of drag and lift needs to be mentioned. For an airplane in normal level steady-state flight, there are two components of aerodynamic force, lift and drag. Drag has components of induced drag, parasite drag, and compressible drag. At subsonic velocities, an aircraft is concerned with induced drag and parasite drag. Compressible drag becomes a factor around Mach number of 0.8 and continues into the supersonic regime. To reduce the effects of drag, an airfoil was selected with a small thickness ratio (t/c). The NACA airfoil 64-006 has a t/c of .06. This airfoil has good lift and drag characteristics up to Mach 1.5. This airfoil also exhibits good behavior during the transonic regime where compressible drag is significant.

The airflow over the surface of the aircraft is usually mixed laminar and turbulent flow. For the analysis of the Gremlin, turbulent flow was assumed to encompass the entire aircraft. From historical data, most aircraft experience 70 per cent or greater turbulent flow therefore supporting the assumption of turbulent flow.

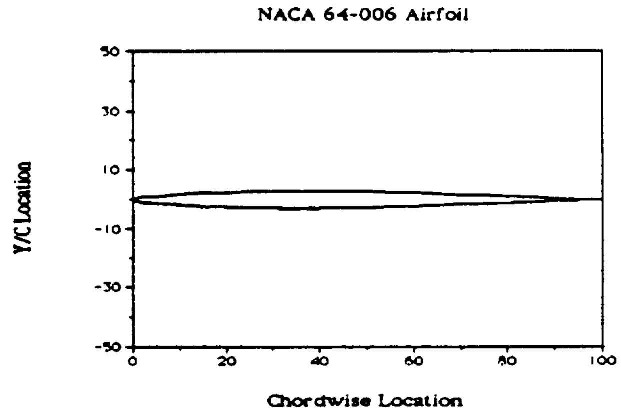


Figure 11.1.1 NACA 64-006 Airfoil Selection

11.2 Drag Polar

The first step in analyzing the Gremlin was to create a CD versus CL plot, Figure11.2.1. These plots were created from M=.1 to M=1.5 with each plot containing data from sea level to 35000 feet. Plots were generated for mission configuration containing missiles and subsonic configurations with Mk-82s. From the drag polars, we are able to create plots of Drag versus Mach number and CD versus Mach number. From these plots it will be necessary to reuse data from the drag polars. The following sections will provide more detail on the analysis.

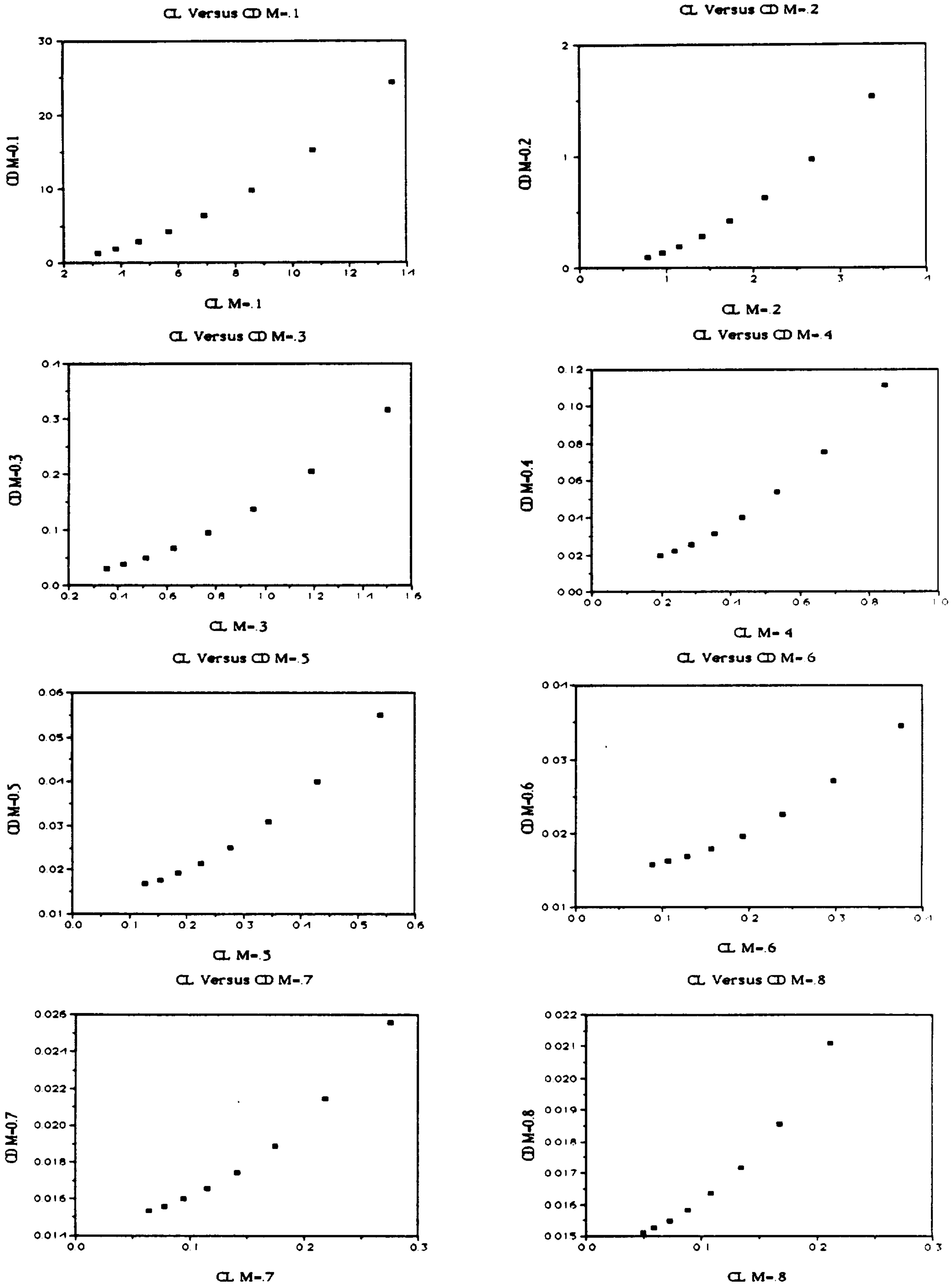


Figure 11.2.1A C_D versus C_L for Mach Number of 0.1 to 0.8

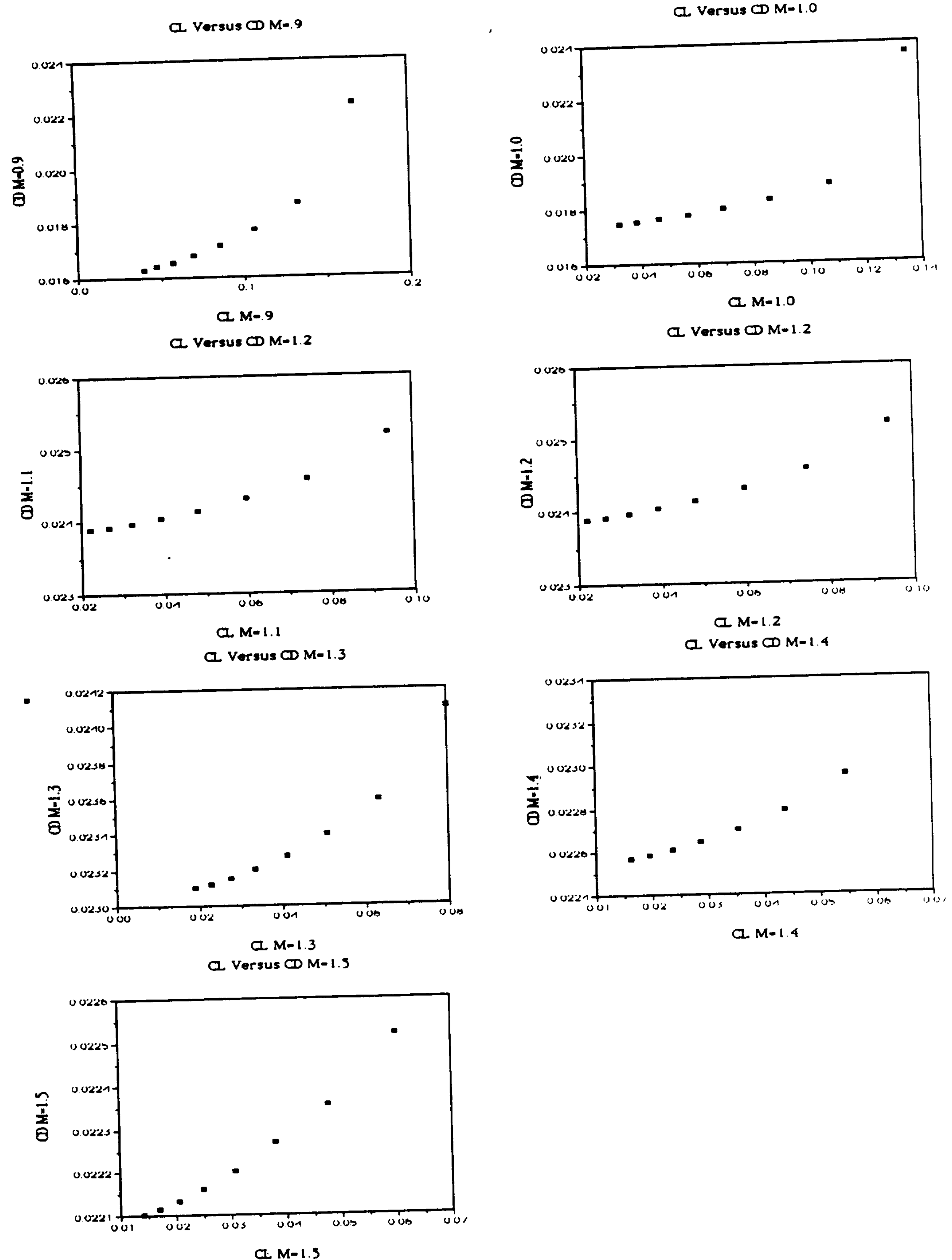


Figure 11.2.1B C_D versus CL for Mach Numbers 0.9 to 1.5

11.3 Drag versus Mach Number

Converting the CD coefficient to Drag was done for M=.1 to M=1.5 at all altitudes. Figure 11.3.1 shows the results obtained from graphing Drag versus Mach number. From this graph, the drag generated at all altitudes and velocities can be determined. For example, at 35000 feet there is approximately 5500 pounds of drag generated, which is less than the thrust generated proving that M=1.5 at 35000 feet is possible. Also from the graph, at sea level, M=1.5 there is 27000 pounds of drag. This is 1.2 times the amount of thrust capable of being generated. Therefore M=1.5 at sea level conditions cannot be accomplished.

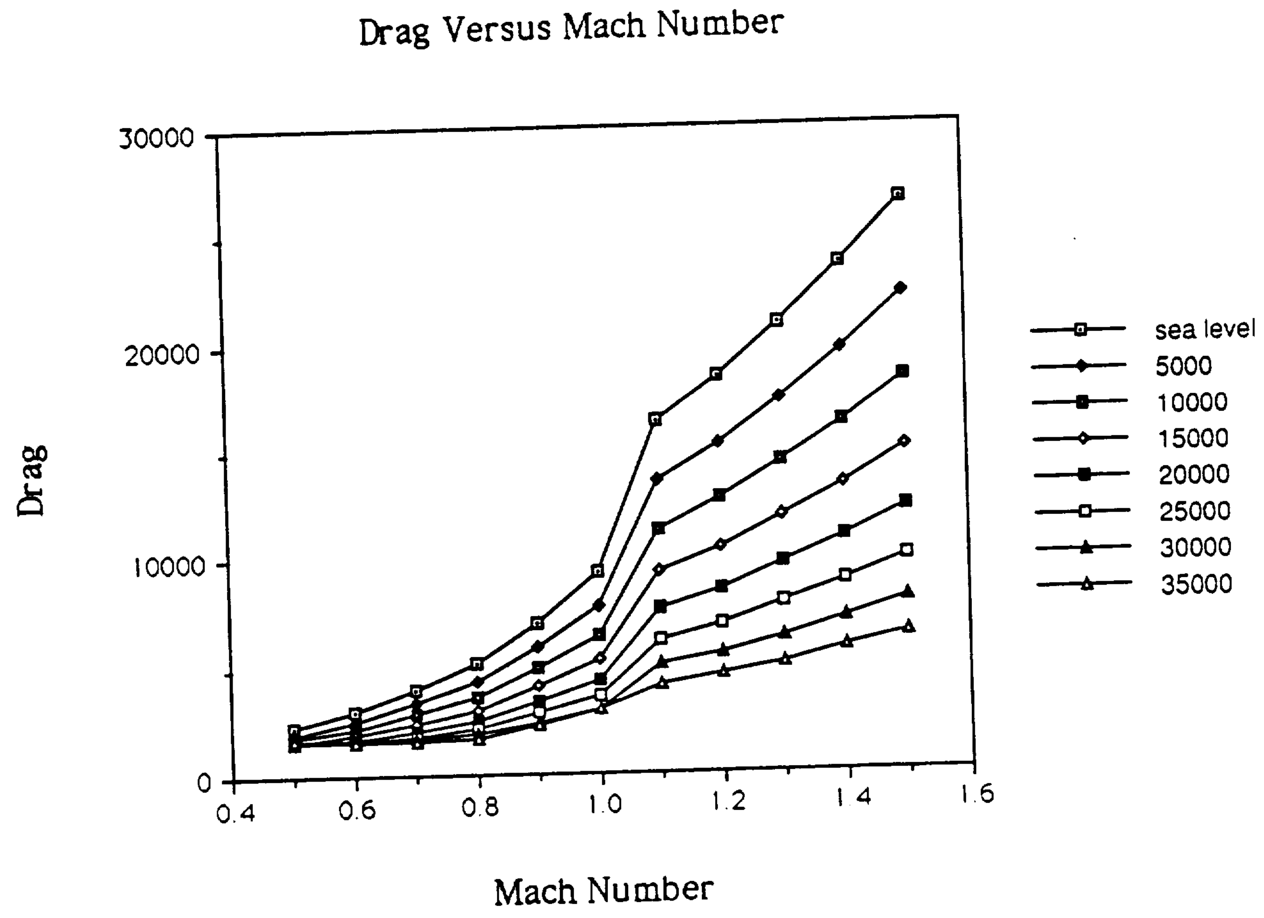


Figure 11.3.1 Drag Versus Mach Number

11.4 CD versus Mach Number

In order to determine the best cruise Mach number and altitude, it is necessary to generate a CD versus Mach number graph, Figure 11.4.1. From the graph, the best cruise Mach number was determined to be M=.89. After determining this value, a line was drawn tangent from the origin to the CL versus CD plot for the drag polar graph at M=.9. An iteration revealed the best cruise altitude to be at 30000 feet.

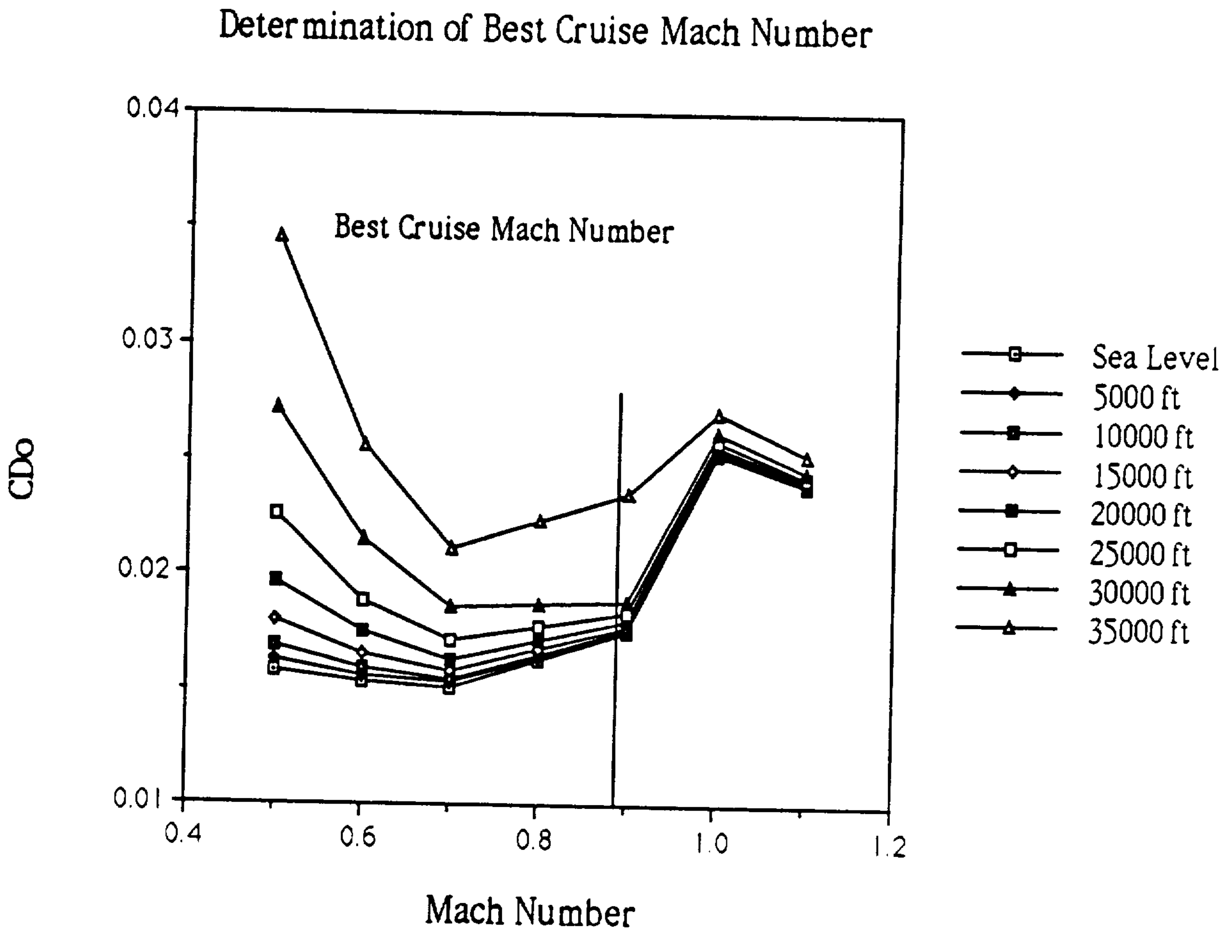


Figure 11.4.1 Determination of Best Cruise Mach Number

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Philip N. French
PHILIP N. FRENCH
Document Evaluator

13. Discussion

When designing an aircraft there are many design options that an engineering team explores. In many ways, an aircraft that has a defined mission profile can design itself. However, many times there are conflicting expectations outlined in requests for proposals (RFP) which can complicate design efforts. The AIAA RFP outlines the mission requirements for the STOVL aircraft design. In this RFP, the (expensive) supersonic dual role (fighter/attack) nature of the aircraft is discussed. The expected use of (expensive) advanced materials and avionics is outlined in relative detail. However, the RFP also expects this aircraft to be "low cost" as to be suitable for export. This conflict was intentionally produced in order to challenge this design team to conceive unique solutions to the never ending challenge to restrict the cost of an aircraft program.

Aircraft design is a science. However, it is far from being an exact science. A preliminary design is based on both mission requirements and experience of the group designing the aircraft. The aerodynamic configuration of an aircraft is determined through numerical aerodynamic analysis as well as through observation of historical trends concerning similarly performing aircraft. However, because of the complex aerodynamic nature of today's aircraft, much predicted aerodynamic performance is inaccurate and can only be verified through wind tunnel testing or perhaps advanced CFD techniques. These aspects of aircraft aerodynamic performance analysis are outside the scope of this paper.

Aircraft design is also an iterative process. Many tradeoffs had to be made in order to reduce aircraft cost with only a minimal reduction in performance. Since development costs are a major percentage of an aircraft program's total cost the reliance on developed systems is a valuable tool to minimize cost. However, since this aircraft is not expected to fly before the year 2005, several of the developed systems used in the Gremlin may then be obsolete.

A major example of this expected obsolescence is the Gremlin's avionics package. Aircraft avionics is very fast paced. Although there are several trends in avionics development, it would be foolish to try and predict the cost, capability, and types of avionics available 15 years into the future.

There have been announcements of programs to develop helmet mounted heads up displays (HUD's) giving a pilot a "good eye view" of the air combat area as well as "look and shoot" capability. Voice responsive avionics have also been discussed for development. However, unknown performance, weight, as well as acquisition and maintenance costs preclude this proposal from considering such conceptual systems for its design.

Low observable (LO) technology was also suggested as a design option in the RFP. Low observable technology includes both reducing the effective radar cross section of an aircraft as well as reducing infrared (IR) emissions. This is an extreme advantage in air combat as the two main detection and targeting techniques use microwave and IR radiation receivers in both an active and passive mode.

The only two known production aircraft to make full use of LO technology are the B-2 and F-117A. Since the technology and research used to produce these aircraft is extremely sensitive (and therefore classified), very little data is available to evaluate LO technology for use in this project. However, the cost of these aircraft have been published and it seems evident that LO technology is inherently expensive to develop and produce. Because of the cost considerations, LO technology was considered incompatible with the "low cost" aspect of this aircraft's RFP guidelines.

Another challenge to this design group is the large amount of research and data which is unavailable. The Gremlin aircraft is in no way a duplication of the VTOL Harrier aircraft. However, since the Harrier is the only operation VTOL aircraft in the western military inventory at this time, much could be learned from the development efforts of McDonnell Douglas and British Aerospace. Because of national security and proprietorship concerns in both the United States and Great Britain, much of the STOVL Research and experimental data generated from the AV-8B Harrier development is unaccessible.

This is not to say that there is an absence of information available about STOVL aircraft design and development. The detail and quality of the published reports that are available is occasionally disheartening.

A solution to the problem of research was to visit and consult with the engineers responsible for the development of the Harrier II at McDonnell Douglas in St. Louis, Missouri. The experiences of this design group at McDonnell Douglas added immeasurably to the quality and scope of this project. By consulting with the Harrier design engineers, there is a much clearer understanding of how engineering decisions are formulated. Not only did the McDonnell Douglas engineers respect the questions of this group, but they also added their own professional input and voiced their own problems concerning development of a supersonic STOVL aircraft.

14. Conclusions

The main objective of this design group was to design a fighter that was mathematically feasible as well as capable of meeting its mission requirements. This group accomplished both objectives. All performance calculations done by this design group on the Gremlin either meet or exceeded the AIAA's set requirements for a STOVL aircraft design. The Gremlin is a supersonic STOVL aircraft that can sustain a 6.5g turn during a flight speed of Mach .8 flight. The fighter can also meet the range and payload requirements.

The mathematical feasibility of our aircraft design was proven by various plots done on Excel. After creating plots of the drag polar, it could be observed that for every altitude that the drag polar was calculated, all curves approximated a textbook drag polar with a slight error due to assumptions of data in the transonic regime. A graph of CD versus Mach number for various altitudes matched expected curves and clearly showed a distinction between different drag components during the flight regime.

The final plot of drag versus Mach number at different altitudes gave the expected trends of change in drag due to a change in Mach number. Also, unfeasible Mach numbers at certain altitudes could clearly be seen from this graph.

This project and the design work involved has greatly enhanced our overall understanding of various aeronautical engineering topics and their interrelationships.

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Appendix A

Trip to St. Louis

Trip to St. Louis

The first quarter of AE447 required a significant amount of research in order for the design team to become familiar with the many aspects of their design project. It was assumed at the outset that there would be little problem finding the quality sources needed to gain a working knowledge of STOVL aircraft performance and design. However, aside from a few trade journals, such as Aviation Week, there were few credible or technical sources available. Since STOVL aircraft design is a relatively unique area in aircraft engineering, traditional methods of analysis did not always apply.

A solution to this problem was to communicate personally with engineers at McDonnell Douglas responsible for development of the AV-8B Harrier II. The AV-8B is the only STOVL aircraft in western military inventories at this time. Therefore, it would be a windfall for this project if a professional relationship could be cultivated between McDonnell Douglas engineers and the Auburn University STOVL project design team.

Through phone conversations and correspondence, the Auburn STOVL team discussed aspects of the project which were causing concern. However, because of proprietary and other concerns, these engineers were very hesitant to discuss specifics when communicating over the phone. Since this arrangement was awkward for both parties, an invitation was extended to the Auburn STOVL group to visit McDonnell Douglas in St. Louis.

By consulting with the design advisor, Dr. J.O. Nichols, funds were secured for the transportation aspect of this trip. By contacting USRA headquarters in Houston, Texas, the use of design funds were approved.

Upon reaching McDonnell Douglas headquarters in St. Louis, Missouri, it was discussed that an extensive itinerary was arranged for us by our hosts. After an initial briefing by our guide concerning the operational setup of McDonnell Douglas, a plant tour was conducted.

To say that this tour was extensive would be an understatement. The entire production facilities of McDonnell Douglas were explained in detail. Production was followed from design layout and tool fabrication through to final assembly and test evaluation. The aircraft types seen being produced included the F-15, F-18, C-17, T-45, as well as the AV-8B Harrier.

After returning from lunch, the Auburn STOVL team was scheduled to meet with the design engineers responsible for the development of a next generation STOVL aircraft. In the next three hours, the amount of knowledge gained by the Auburn team was immeasurable. After detailed discussions with the design engineers, the preliminary STOVL design was reevaluated and modified to reflect a more accurate and realistic approach to aircraft design. The questions of the Auburn STOVL team were received by the McDonnell Douglas STOVL group with genuine interest and respect. The answers in response to questions posed by the Auburn STOVL group were in no way less technical than that expected.

Appendix B

Calculations

Mission Weight Calculations

I Warmup and Takeoff

$W_e/W_o = A{*}W_o^c{*}K_{vs}{*}(0.85)$

W_o=takeoff gross weight

W_e=empty weight

K_{vs}=variable sweep constant=1

A=constant=2.34

C=constant=-0.13

0.85 fudge factor due to replacing aluminum with composites

II Mission Profile for Ground Superiority

(The ground superiority mission was used since it requires a larger weight than the air superiority mission.)

Position during mission (see Figure)

0=ground
1=takeoff
2=after climb to cruise altitude
3=after 150 n.mi. cruise
4=after 50 n.mi cruise at 250 ft. altitude
5=after dropping bombs
6=after making 3, 6.5 g turns
7=after 50 n.mi cruise at 250 ft. altitude egress
8=after 150 n.mi. egress at altitude
9=land

W1/W0 = 0.970

W2/W1 = 0.985

W9/W8 = 0.995

(from Table 3.2, p. 16, reference)

$W(i+1)/Wi = e^{-R*C/((V*L)/D)}$

W3/W2=0.979

R=range=150 n.mi.

C=specific fuel consumption=0.8 $lb_f/hr/lb_{thrust}$

V=velocity

L/D=lift to drag ratio

Determining L/D:

AR_{wetted}=1.1 (from Figure 3.5, p. 21, reference: Raymer, Daniel P.)

$(L/D)_{max}$=14.0 (from Figure 3.6, p. 22, reference: Raymer, Daniel P.)

$(L/D)_{cruise}=0.866(L/D)_{max} = 12.124$

Determining Velocity:

V=M*a=800 ft./sec.

M=Mach number=0.8

a=speed of sound at approximately 29,000 ft.=1000 ft./sec.

W4/W3=0.994

R=50 n.mi.

C=0.8

V at 250 ft.=893 ft./sec.

L/D=12.123

W5/W4=0.8344

W5=W4-3000 lb.

(W5/W4 was a variable in the initial weight iteration)

$W6/W5=1-C^*(T/W)^*d=0.982$

T/W=thrust to weight ratio=1.0 (assumed)

Determining d:

d=time duration at maximum power=$(2^*pi^*V_x)/(g^*(n^2-1))$

n=load factor=6.5

x=number of turns=3

V=Velocity=893 ft./sec.

g=gravity=32.2 ft./sec^2

$W7/W6=W4/W3=0.994$

$W8/W7=W3/W2=0.979$

III Takeoff Gross Weight

$W9/W_o=(W9/W8)^*(W8/W7)^*(W7/W6)^*(W6/W5)^*(W5/W4)$
$^*(W4/W3)^*(W3/W2)^*(W2/W1)^*(W1/W0)=0.74292$

Fuel Fraction Estimation: $W_f/W_o=1.05^*(1-W9/W_o)$

W_f=fuel weight

Payload=2 pilots+2 sidewinder missiles+1 machine gun+6 bombs
=2*(225 lb.)+2*(200 lb.)+450 lb.+3000 lb.=4300 lb.

$W_o=W_f+W_e+W_p$

W_p=Payload Weight

Dividing by W_o: $1=W_f/W_o+W_e/W_o+W_p/W_o=1.05^*(1-W9/W_o)+$
$1.989^*W_o^{-0.13}+4300/W_o$

$W_o=4300/(1-W9/W_o-(1.989^*W_o^{-0.13}))$

Iterating, W_o=24,111 lb.

IV Fuel Weight

$W_f=W_o-W_9-W_{bombs}$

$W_f=24111-17545.5-3000=3565.5\ lb_f$

Component Weight Calculations

I Wing

$W_{wing}=0.0103*K_{dw}*K_{vs}*(W_{dg}*N_z)^{0.5}*S_w^{0.622}*A^{0.785}*(t/c)_{root}^{-0.4}$
$*(1+\lambda)^{0.05}*(\cos(\Lambda))-1.0*S_{csw}^{0.04}$

K_{dw}=constant=1.0 for non-delta wing

K_{vs}=constant=1.0 for non-delta wing

W_{dg}=design gross weight=24111 lb.

N_z=ultimate load factor=1.5*limit load factor=1.5*6.50=9.75

S_w=trapezoidal wing area=190 ft.^{2}

A=aspect ratio=2.7

$(t/c)_{root}$=thickness ratio at root=0.06

λ=tip to root ratio=0.23

Λ=wing sweep at 25% MAC=44 degrees

S_{csw}=control surface (wing mounted)=25 ft.^{2}

W_{wing}=757.6 lb_f.

II Horizontal Tail

$W_{horiz\ tail}=3.316*(1+F_w/B_h)^{-2.0}*((W_{dg}*N_z)/1000)^{0.260}*S_{ht}^{0.806}$

F_w=fuselage width at horizontal tail intersection=2 ft.

B_h=horizontal tail span=13 ft.

S_{ht}=horizontal tail area=65 ft.^{2}

$W_{horiz\ tail}$=297.882 lb_f.

III Vertical Tail

$W_{vert\ tail}=0.452*K_{rht}*(1+H_t/H_v)^{0.5}*(W_{dg}*N_z)^{0.488}*S_{vt}^{0.718}*M^{0.341}*L_t^{-1.0}*$
$(1+S_r/S_{vt})^{0.348}*A_{vt}^{0.223}*(1+\lambda)^{0.25}*(\cos(\Lambda_{vt}))^{-0.323}$

K_{rht}=constant=1.0

H_t/H_v=0.0 for conventional tail

M=Mach number=0.8

L_t=tail length=22.8 in.

S_r=rudder area=7.83 $in.^2$

S_{vt}=vertical tail area=33.6 $in.^2$

A_{vt}=vertical tail area=1.0 $in.^2$

λ=tip to root ratio=0.23

Λ_{vt}=vertical tail sweep=50 deg.

$W_{vert\ tail}$=101.32 lb_f.

IV Fuselage

$W_{fuselage}=0.499*K_{dwf}*W_{dg}^{0.35}*N_z^{0.25}*L^{0.5}*D^{0.849}*W^{0.685}$

K_{dwf}=constant=1.0 for non-delta wing aircraft

L=fuselage structural length=45 ft.

D=fuselage structural depth=5 ft.

W=fuselage structural width=5 ft.

Wfuselage=1351 lb_f.

V Main Landing Gear

$W_{main\ landing}=K_{cb}*K_{tpg}*(W_l*N_l)^{0.25}*L_m^{0.973}$

K_{cb}=constant=1.0 for non-cross-beam gear

K_{tpg}=constant=1.0

W_l=landing design gross weight=17890 lbf.

N_l=ultimate landing load factor=5.5

L_m=length of main landing gear=48 in.

$W_{main\ landing}$=765.75 lb_f.

VI Nose Landing Gear

$W_{\text{nose gear}}=(W_l*N_l)^{0.290}*L_n^{0.5}*N_{nw}^{0.525}$

L_n=nose gear length=54 in.

N_{nw}=number of nose wheels=1

$W_{\text{nose gear}}$=206.1 lb_f.

VII Engine Mounts

$N_{\text{eng mounts}}=0.013*N_{en}^{0.795}*T^{0.579}*N_z$

N_{en}=number of engines=1

T=total engine thrust=24000 lb.

$N_{\text{eng mounts}}$=41.17 lb_f.

VIII Firewall

$W_{\text{firewall}}=1.13*S_{fw}$

S_{fw}=firewall surface area=25 ft.^2

W_{firewall}=28.25 lb_f.

IX Engine Section

$W_{\text{eng section}}=0.01*W_{en}^{0.717}*N_{en}*N_z$

W_{en}=engine weight=1919.830 lb_f.

$We_{\text{ng section}}$=20.33 lb_f.

X Air Induction System

$W_{\text{air induct}}=13.29*K_{vg}*L_d^{0.643}*K_d^{0.182}*N_{en}^{1.498}*(L_s/L_d)^{-0.373}*De$

K_{vg}=constant=1.0

L_d=duct length=10 ft.

K_d=2.6

L_s=3 ft.

D_e=engine diameter=46.068 in.

$W_{air\ induct}$=418.12 lb_f.

XI Engine Cooling

$W_{eng\ cooling}=4.55*D_e*L_{sh}*N_{en}$

L_{sh}=length of engine shroud=12.5 ft.

$W_{eng\ cooling}$=255.9 lb_f

XII Oil Cooling

$W_{oil\ cool}=37.82*N_{en}^{1.023}$

$W_{oil\ cool}$=37.82 lb_f.

XIII Engine Controls

$W_{eng\ cont}=10.5*N_{en}^{1.008}*L_{ec}^{0.222}$

L_{ec}=length from engine front to cockpit=150.008 ft.

$W_{eng\ cont}$=3.04 lb_f

XIV Starter (Pneumatic)

$W_{starter}=0.025*T_e^{0.760}*N_{en}^{0.72}$

T_e=thrust per engine=24000 lb.

$W_{starter}$=53.32 lb_f.

XV Fuel System and Tanks

$$W_{fuel\ sys}=7.45*V_t^{0.47}*(1+(V_i/V_t))^{-0.095}*(1+(V_p/V_t))*N_t^{0.066}*N_{en}^{0.052}$$
$$*((T*SFC)/1000)^{0.249}$$

V_t=total fuel volume=524.34 gallon

V_i/V_t=integral tanks volume/total fuel volume=1

V_p/V_t=self-sealing "protected" tanks volume/total fuel volume=1

N_t=number of fuel tanks=3

SFC=engine specific fuel consumption=1.526

$W_{fuel\ sys}$=697.71 lb_f.

XVI Flight Controls

$$W_{flight\ cont}=36.28*M^{0.003}*S_{cs}^{0.489}*N_s^{0.484}*N_c^{0.127}$$

M=Mach number=1.5

S_{cs}=total area of control surfaces=50 ft.^{2}

N_s=number of flight control systems=2

N_c=number of crew=2

$W_{flight\ cont}$=375.77 lb_f.

XVII Instruments

$$W_{instr}=8.0+36.37*N_{en}^{0.676}*N_t^{0.237}+26.4*(1+N_{ci})^{1.356}$$

N_{ci}=1.2 for pilot and backseater

W_{instr}=132.09 lb_f.

XVIII Hydraulics

$$W_{hyd}=37.23*K_{vsh}*N_u^{0.664}$$

K_{vsh}=1.0 for non-variable sweep wings

N_u=number of hydraulic utility functions

W_{hyd}=171.75 lb_f.

XIX Electrical

$W_{electrical}=172.2*K_{mc}*R_{kva}^{0.152}*N_c^{0.10}*L_a^{0.10}*N_{gen}^{0.091}$

$K_{mc}=1.45$ since mission completion required after failure

R_{kva}=system electrical rating=50 kv*A

L_a=electrical routing distance=30 ft.

N_{gen}=number of generators=1

$W_{electrical}=681.49\ lb_f$.

XX Avionics

$W_{avionics}=2.117*W_{uav}^{0.9933}$

W_{uav}=uninstalled avionics weight=1100 lb_f.

$W_{avionics}=1456.6\ lb_f$.

XXI Furnishings

$W_{furn}=217.6*N_c$

$W_{furn}=435.2\ lb_f$.

XXII Air Conditioning and Anti-Ice

$W_{ac}=201.6*((W_{uav}+200*N_c)/1000)^{0.735}$

$W_{ac}=302.4\ lb_f$.

XXIII Handling Gear

$W_{hand\ gear}=3.2\text{x}10^{-4}*W_{dg}$

$W_{hand\ gear}=7.716\ lb_f$.

Rubber Engine Calculations

W=weight of engine
T=takeoff thrust=24000 lb.
BPR=bypass ratio=0.8
M=max Mach number=1.5
Cruise is at 36,000 ft. and 0.9M
SFC=specific fuel consumption

I Weight

$W=0.063*T^{1.1}*M^{0.25}*e^{(-0.81*BPR)}$

$W=0.063*(24000)^{1.1}*(1.5)^{0.25}*e^{(-0.81*0.8)}$

W=2399.788 lb

weight is reduced by 20% due to future improvements in materials and production

W=1919.830 lb

II Length

$L=3.06*T^{0.4}*M^{0.2}$

$L=3.06*(24000)^{0.4}*(1.5)^{0.2}$

L=187.510 in

length is reduced by 20% due to future improvements in materials and production

L=150.008 in.

III Diameter

D=0.288*T0.5*e(0.04*BPR)

D=0.288*(24000)0.5*e(0.04*0.8)

D=46.068 in.

IV Specific Fuel Consumption for Maximum Thrust

$SFC_{maxT}=2.1*e^{(-0.12*BPR)}$

$SFC_{maxT}=2.1*e^{(-0.12*0.8)}$

$SFC_{maxT}=1.908\ lb_{fuel}/hr./lb_{thrust}$

specific fuel consumption for maximum thrust is reduced by 20% due to future improvements in materials and production

$SFC_{maxT}=1.526\ lb_{fuel}/hr./lb_{thrust}$

V Specific Fuel Consumption for Cruise

$SFC_{cruise}=1.04*e^{(-0.186*BPR)}$

$SFC_{cruise}=1.04*e^{(-0.186*0.8)}$

$SFC_{cruise}=0.896$

specific fuel consumption for cruise is reduced by 20% due to future improvements in materials and production

$SFC_{cruise}=0.717\ lb_{fuel}/hr./lb_{thrust}$

VI Thrust for Cruise

$T_{cruise}=1.6*T^{0.74}*e^{(0.023*BPR)}$

$T_{cruise}=1.6*(24000)^{0.74}*e^{(0.023*0.8)}$

$T_{cruise}=2840.974\ lb_f$

Component Sizing

I Fuselage

$L_{fuselage}=A^{*}W_{o}^{c}$

Lfuselage=length of fuselage

A=constant=0.93 for jet fighter

W_o=gross takeoff weight=24111 lb_f.

C=constant=0.39 for jet fighter

$L_{fuselage}=47.5$ ft.

Fineness ratio=$L_{fuselage}/d_{max\ fuselage}$

$d_{max\ fuselage}$=maximum diameter of fuselage=4.9 ft.

Fineness ratio=9.7

II Vertical Tail

$S_{vt}=(C_{vt}{}^{*}b_{w}{}^{*}S_{w})/L_{vt}$

S_{vt}=planform area of vertical tail

C_{vt}=vertical tail volume coefficient=0.07 for jet fighter

b_w=wing span=31.0 ft.

S_w=planform area of wing=353.5 ft.

L_{vt}=length from quarter-chord of wing to quarter-chord of tail =22.8 ft.

$S_{vt}=33.6$ ft.^{2}

III Horizontal Tail

$S_{ht}=(C_{ht}*C_{w}*S_{w})/L_{ht}$

S_{ht}=planform area of horizontal tail

C_{ht}=horizontal tail coefficient=0.40 for jet fighter

C_{w}=wing chord=11.0 ft.

L_{ht}=length from quarter-chord of wing to quarter-chord of tail =22.8 ft.

S_{ht}=68.2 ft.2

horizontal tail area was reduced by 15% due to variable pitch thrust inherent to STOVL aircraft

S_{ht}=57.97 ft.2

Determination of Lift and Drag Coefficients

I $(C_{D0})_{subsonic}$ = sum $((C_{fc}*FF_L*Q_L*S_{wetc})/S_{ref})+C_{Dmisc}+C_{DL}$

C_f=flat plate skin friction

FF=form factor

a=interference factor

S_{wet}=wetted area

S_{ref}=reference area

Subscript c represents individual component, i.e., fuselage, wing, etc.

II $C_f = (0.455/((\log_{10}R)^{2.58}*(1+0.144*M^2)^{0.65})$ - Turbulent

R=Reynolds number=(p*V*l)/u

M=Mach number

III Form Factor

Wing, Pylon, and Strut

$FF = [1+0.6/((x/c)_m)*(t/c)+100*(t/c)^4]*[1.34*M^{0.18}*(\cos(\Lambda)_m)^{0.28}]$

x/c=location of maximum airfoil thickness/chord=0.4

t/c=thickness to chord ratio=0.06

Λ=leading edge sweepback angle

Fuselage and Smooth Canopy

$FF=1+60/f^3+f/400$

$t=l/d=l/((4/\Pi)*A_{max})^{0.5}$

l=component length

d=component diameter

Inlet

$FF=1+(d/l)$

Miscellaneous drags

These values were determined from a graph.

IV Supersonic Drag

$C_D = E_{WD}*[1-0.386*(M-1.2)^{0.57}*(1-((\Pi*\Lambda_{LE}^{0.77})]*(D/q)$

E_{WD}=empirical wave drag=1.0

$D/q=9*\Pi/2*(A_{max}/l)2$

V Total CD

$CD_{Tot} = CD_{induced} + CD_{parasite} + CD_{compressible}$

$CD_{induced} = CL^2/q*S$

$CL=L/q*S$ which was done for M=0.1 to M=1.5 and altitude sea level to 35,000 feet

$q=1/2*p*v^2$

VI Drag

$Drag=C_D*q*S$

Cost Calculations

H_e=engineering hours
H_T=tooling hours
H_M=manufacturing hours
H_Q=quality control

H_e=4.86*(empty weight)0.777*(velocity)0.894*(aircraft quantity)0.163
H_T=5.99*(empty weight)0.777*(velocity)0.696*(quantity)0.263
H_M=7.37*(empty weight)0.82*(velocity)0.484*(quantity)0.641
H_Q=0.133*(manufacturing hours)
Development=C_D=45.42*(empty weight)0.630*(velocity)1.3
Flight test costs=C_F=1243.03*(empty weight)0.325*(velocity)0.822
*(# test vehicles)1.21
Materials cost=C_M=11.0*(empty weight)0.921*(velocity)0.621
*(quantity)0.799

i'=average annual inflation rate
f=market interest rate
i'=(1+i)/(1+f)-1
Cost90=Cost86*(1/1+0.0271)4
Cost90=Cost86*(1.11324)