NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Mechanical Engineering

AIRPLANE DESIGN ANALYSIS

Graduation Project
ME- 400

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From childhood I was very much fond of airplanes as this machine fascinated me. I always dreamed of doing something related to it. I am very thankful to my Head of Department Prof. Dr. Kasif ONARAN who made my dreams come true by giving me this project. It was a really an honour and a challenge for me.

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ABSTRACT

Airplane is basically an engine-driven vehicle that can fly through the air supported by the action of air against its wings. Once an airplane is in the air there are four forces acting on it, Lift, Drag, Thrust and Weight. The design analysis of an airplane when flying mainly depends on the control of lift and drag. The resultant aerodynamic efficiency of an airplane is measured in terms of lift/drag.

The aim of this project is once an aircraft of a given size is specified and design point settled there arises the particular problem of determining the optimum shape of an airplane, The optimum shape of an airplane has three aspects, the shape in its basic form, changes made in the basic shape of an aircraft and modifications to the basic shape. The three aspects of shape must be balanced according to the role requirement, which are mostly discussed in this project.

Chapter 1 basically gives a brief introduction of how an airplane flies and the design analysis needed to be made for subsonic, supersonic and transonic flights. Chapter 2, explains the calculations for the design of optimum lift/drag when range flying. In this search, effect of aspect ratios and wetted areas are analyzed. The aspect ratio ranges from 10 – 2, depending on the shape of an airplane. The wetted area is calculated by using an equation $(L / D)_{max} = (\sqrt{\pi}) / 2 \sqrt{(\{ b^2 / A_w \} 1 / (K C_{D fric}))}$. Chapter 3 gives a theoretical knowledge, which is useful to know much of the art of aircraft design lies in the creation of economical airframe structures. Airframes must be strong and stiff, in that the weight of structural materials must be no more than is absolutely necessary otherwise the payload and fuel load will be reduced. The mechanical properties of greatest importance are a high strength/weight, particularly at high temperatures, and high specific stiffness. Chapter 4, explains the types of airplanes such as land planes, seaplanes, amphibians, and airplanes that can leave the ground using the jet thrust of their engines or rotors (rotating wings) and then switch to wing-borne flight. A discussion is made on two modern aircrafts with state of the art technology. Namely, Lockheed F117-A stealth fighter and F-22 Advanced tactical fighter to satisfy aerodynamic performance requirements but stealth requirements as well.

NOMENCLATURE

A	aerodynamic aspect ratio (b^2/S)
A	cross-sectional area of a cylinder of air
A_w	total wetted area of airframe
a	acceleration along flight path
a	velocity of sound
b	wing span
bhp	brake horsepower
C	total fuel consumption
c	chord
C_D	coefficient of drag ($D = C_D qS$)
C_{DF}	zero lift drag coefficient
C_{DL}	lift dependent drag coefficient
$C_{D\ fric}$	frictional drag coefficient
$C_{D\ min}$	minimum drag coefficient
C_L	lift coefficient of complete airplane ($L = C_L qS$)
$C_{L\ max}$	maximum lift coefficient
d	diameter
D	total drag of airplane
D_F	zero lift drag
D_L	lift dependent drag
D_{fric}	total frictional drag
f	equivalent parasite area of airplane
f( )	some unspecified function
g	gravitational acceleration
h	height above mean sea level
K	factor of planform efficiency
L	total lift
L_F	part of total lift supporting weight of fuselage
(L/D)	lift/drag, the measure of aerodynamic efficiency
$(L/D)_{max}$	maximum lift/drag
$(L/D)_R$	optimum range lift/drag (about 0.94 $(L/D)_{max}$)

l	aerofoil section lift
l	overall length of airplane
M	mach number
M_{crit}	critical mach number
$M_{crit\ D}$	critical mach number where wave drag becomes measurable
M	bending and fixing moment
N	number of alternating load cycles per second
N_e	number of engines
N_P	number of passengers
n ml	nautical miles, (1 n ml = 6,080 ft)
p	static pressure
Q	Applied shear force
Q	dynamic pressure ($1/2\rho V^2$, $0.7pM^2$)
R_N	Reynold number (Vc/v)
S	wing area
T	torque
(t/c)	thickness ratio of airfoil section
V	relative velocity of airfoil
v	component of root mean square velocity
W	instantaneous weight
W	specific load
x	distance measured in direction (O-X axis)
X	structural length
y	distance measured in direction (O-Y axis)
Z	structural depth
z	distance measured in direction (O-Z axis)
α	angle of attack

CONVERSION FACTORS

SI SYSTEM		
Multiply	By	To Get
Pounds (lb)	4.448	Newtons (N)
Feet (ft)	0.3048	Meters (m)
Slugs	14.59	Kilograms (kg)
Slugs per cubic foot ($slugs/ft^3$)	515.4	Kilogram per cubic meter (kg/m^3)
Horsepower (hp)	0.7457	Kilowatts (kW)
Pounds per square inch (psi)	6895.0	Pascals (Pa)
Pounds per square foot (psf)	47.88	Pascals (Pa)
Miles per hour (mph)	0.4471	Meters per second (m/s)
Knots (kt)	0.5151	Meters per second (m/s)
Nautical miles (n ml)	1853.184	Meters
* 1 n ml = 6,080 ft		

CHAPTER 1

INTRODUCTION

Once an aircraft of a given size is specified, and the design point settled, there arises the particular problem of determining the optimum shape of the airplane. The optimum shape is not the pure basic shape to satisfy conditions at the design point, for aircraft must be flexible enough to operate safely and with reasonably economy off-design.

- The basic shape in its purest form, satisfying the conditions at the design point alone
- Changes of the basic shape in flight to improve off-design performance
- Fixed modifications of the basic shape to improve local airflows

1.1 HISTORICAL BACKGROUND

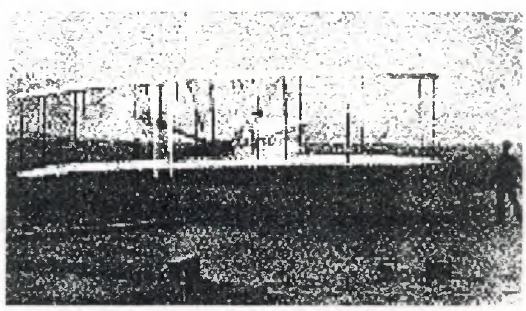


Figure 1.1 The Wright brother's biplane lifting off the ground at the hills of Kitty Hawk in 1903

In 1903, at Kitty Hawk, in North Carolina, Wright brother's made their first successful flight in a full-sized airplane. The machine was a biplane; shown in Figure 1.1. On that first day, The Wrights made four successful flights the longest being about 59 seconds in duration at a speed of 30 miles per hour. By October 1905, after solving many problems with their aircraft, Wilbur Wright was making flights that covered a distance of 24 miles that lasted 38 minutes. After their machine was proved satisfactory, the Wrights had to find a market for their invention, unfortunately their airplane was not fully appreciated in the United States until after they had succeeded abroad.

The year 1913 became known as the glorious year of flying. Aerobatics, or acrobatic flying, was introduced, and upside-down flying, loops, and other stunts proved the maneuverability of airplanes. Long-distance flights made in 1913 included a 4,000-km flight from France to Egypt, with many stops, and the first nonstop flight across the Mediterranean Sea, from France to Tunisia. In Britain, a modified Farnborough BE2 proved itself to be the first naturally stable airplane in the world. The BE2c version of this airplane was so successful that nearly 2,000 were subsequently built.

During World War I, the development of the airplane accelerated dramatically. European designers such as Louis Blériot and Dutch-American engineer Anthony Herman Fokker exploited basic concepts created by the Wrights and developed ever faster, more capable, and deadlier combat airplanes. The concentrated research and development made necessary by wartime pressures produced great progress in airplane design and construction. During World War I, outstanding early British fighters included the Stopwith Pup (1916) and the Stopwith Camel (1917), which flew as high as 5,800 m and had a top speed of 190 km/h (120 mph). Notable French fighters included the Spad (1916) and the Nieuport 28 (1918). By the end of World War I in 1918, both warring sides had fighters that could fly at altitudes of 7,600 m and speeds up to 250 km/h.

Introduced in 1933, Boeing's Model 247 was considered the first truly modern airliner. It was an all-metal, low-wing monoplane, with retractable landing gear, an insulated cabin, and room for ten passengers. An order from United Air Lines for 60 planes of this type tied up Boeing's production line and led indirectly to the development of perhaps the most successful propeller airliner in history, the Douglas DC-3. Trans World Airlines, not willing to wait for Boeing to finish the order from United, approached airplane manufacturer Donald Douglas in Long Beach, California, for an alternative, which became, in quick succession, the DC-1, the DC-2, and the DC-3. The DC-3 carried 21 passengers, used powerful, 1,000-horsepower engines, and could travel across the country in less than

24 hours of travel time, although it had to stop many times for fuel. The DC-3 quickly came to dominate commercial aviation in the late 1930s, and some DC-3s are still in service today. Boeing provided the next major breakthrough with its Model 307 Stratoliner, a pressurized derivative of the famous B-17 bomber, entering service in 1940. With its regulated cabin air pressure, the Stratoliner could carry 33 passengers at altitudes up to 6,100 m and at speeds of 322 km/h.

The next frontier, pioneered in the late 1960s, was the age of the jumbo jet. Boeing, McDonnell Douglas, and Lockheed all produced wide-body airliners, sometimes called jumbo jets. McDonnell Douglas built a somewhat smaller, three-engine jet called the DC-10, produced later in an updated version known as the MD-11. Lockheed built the L-1011 Tristar, a trijet that competed with the DC-10. The L-1011 is no longer in production, and Lockheed-Martin does not build commercial airliners anymore. In the 1980s McDonnell Douglas introduced the twin-engine MD-80 family, and Boeing brought online the narrow-body 757 model and wide-body 767model twin jets. Airbus Industrie had developed the A300 wide-body twin during the 1970s. During the 1980s and 1990s Airbus expanded its family of aircraft by introducing the slightly smaller A310 twin jet and the narrow-body A320 twin, a unique, so-called fly-by-wire aircraft with sidestick controllers for the pilots rather than conventional control columns and wheels. Airbus also introduced the larger A330 twin and the A340, a four-engine airplane for longer routes, on which passenger loads are somewhat lighter. In the mid-1990s the company announced plans to develop a super jumbo class of airliners capable of carrying 550 or more passengers. Boeing introduced the model 777, a wide-body jumbo jet that can hold up to 400 passengers, in 1995. In 1997 Boeing acquired longtime rival McDonnell Douglas, and a year the company later announced its intention to halt production of the passenger workhorses MD-11, MD-80, and MD-90. The company entered the super jumbo jet market in 1999 when it announced plans to expand the seating capacity of the model 747 to accommodate up to 524 passengers, making it the world's largest passenger airliner.

1.2 BASIC THEORY OF FLIGHT

One of the hardest concepts to understand is the theory of what makes and airplane fly, or what even got it up into the air in the first place. The first thing that we must understand is what makes the airplane have the ability to fly.

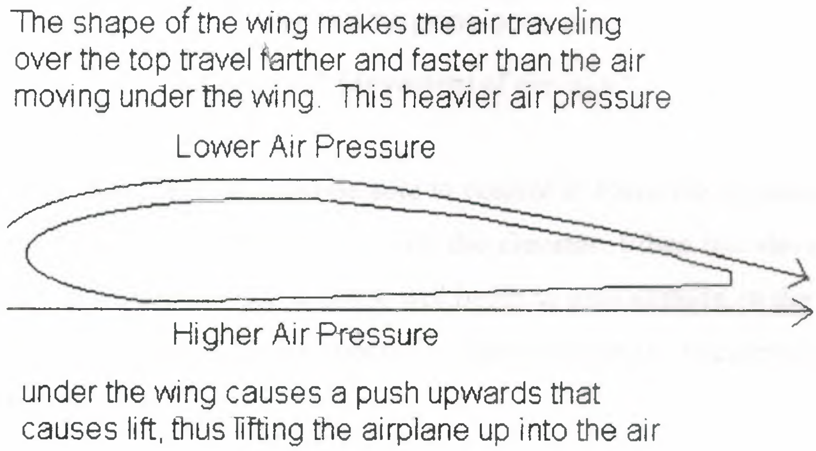


Figure 1.2 Air pressures under the wing

Lift to the airplane is provided from the wing traveling through the air. In order to accomplish forward motion there must be some force or thrust to cause the airplane to move. An engine can provide thrust, which as it causes the plane to move forward must be able to provide enough power to overcome the drag on the airplane. As the airplane moves thru the air, air begins to travel over and under the wing; as shown in Figure 1.2 and as this happens, the air going over the wing travels farther and faster than the air going under the wing. The slower air under the wing causes high pressure to form and pushes up on the bottom of the wing.

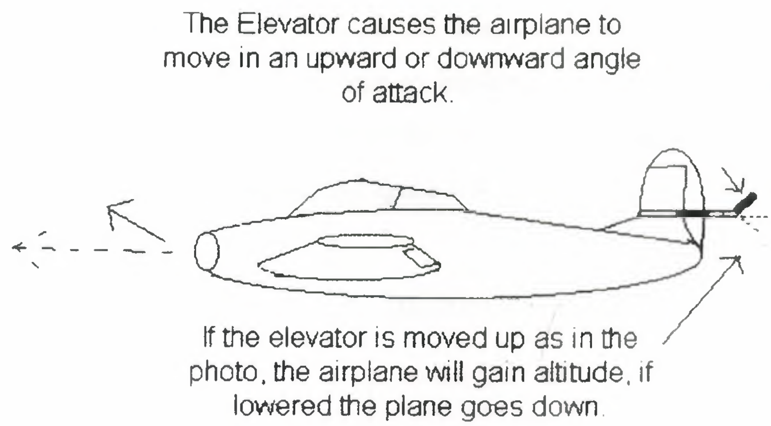


Figure 1.3 Movement of elevator

Lift is a wonderful thing, but we must be able to control it. Once the airplane is in the air, we control our ability to go up and down with the elevator. When the elevator is moved upward as shown in Figure 1.3, the airplane will begin to gain altitude, in the same respect when forward pressure is applied to the controls of the airplane and the elevator goes down, we will lose altitude.

1.3 WHAT MAKES AN AIRPLANE TURN?

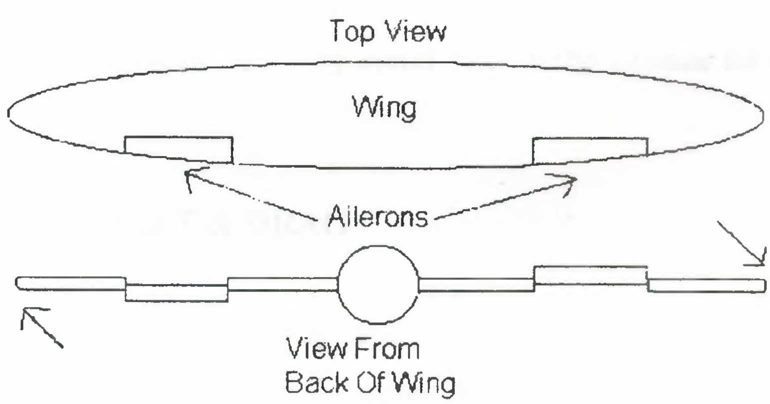


Figure 1.4 Wing view

The next thing to consider about an airplane is: what makes it have the ability to make a controlled turn in the air without going out of control. This is accomplished by controls on the wings called ailerons, and by the rudder, which is on the tail of the airplane. The first controls we will discuss concerning turn are the ailerons. Each wing on an airplane has some form of an aileron to aid the airplane in banking turns when combined with the elevator. The ailerons each move in an opposite direction from each other, and by doing this causes the airplane to roll, as shown in Figure 1.4.

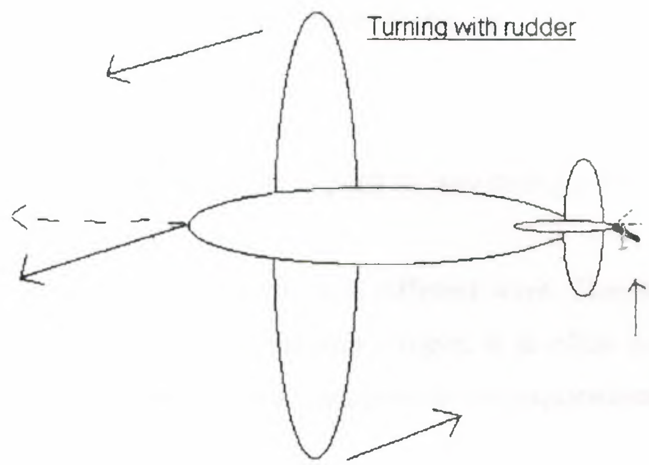


Figure 1.5 Movement of rudder

The last device on the airplane associated with turn is the rudder. When the rudder is turned one way or the other, side pressure is applied to the rear of the airplane thus causing a change in heading, the rudder is a very useful tool on the airplane for lining up for a landing.

1.4 CONCEPT OF LIFT & DRAG

Think of an airplane sitting on the ground. The plane and the earth are pulling on each other because of the force called gravity. However, we would like to be able to raise the plane up into the air and it is called lift. Also, unless you push really hard on it, the plane is sitting still on the ground because of the friction between the wheels and the ground. When the plane starts rolling there will be friction between the air and the plane and we call that drag. When the plane starts flying there will still be drag.

To make the airplane fly somewhere, we have to do at least two things.

- Lift the plane in the air
- Push the plane through the air

The best components that engineers have come up with so far to satisfy the two requirements above are;

- To have wings to provide lift.
- To have big engines to have the plane push its way through the air

Airplanes and birds both fly, but they do it in different ways. They have different forms (or structures) to accomplish the same function - flight. It is often useful for engineers and other types of designers to think of the functions or the requirements of something before thinking of the form.

1.4.1 LIFT

Lift is the component of the resultant aerodynamic forces on an airplane normal to the airplane's velocity vector. Mostly, the lift is directed vertically upward and sustains the weight of the airplane.

The component that is a major lift producer on an airplane is the wing. Depending on the airplane's geometry, other components can contribute to or significantly affect the lift including the fuselage, engine nacelles, and horizontal tail.

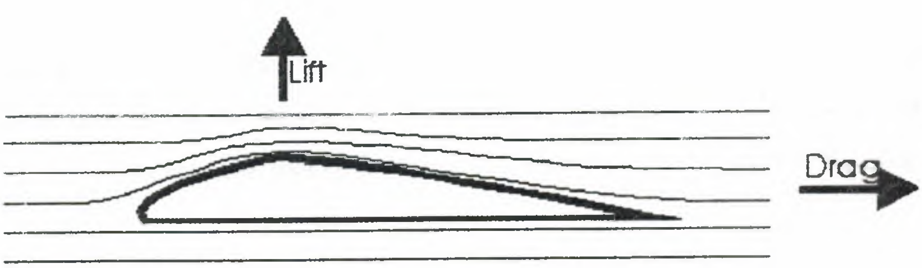


Figure 1.7 Action of lift and drag on an airfoil

1.4.2 DRAG

It takes power to move a vehicle through the air. This power is required to overcome the aerodynamic force on the vehicle opposite to its velocity vector. Any reduction of this force, known as the drag, represents either a direct saving in fuel or an increase in performance.

The estimation of the drag of a complete airplane is a difficult and challenging task, even for the simplest configurations. A list of various types of drag is given as follows;

- Induced Drag
- Parasite Drag
- Skin Friction Drag
- Form Drag
- Interference Drag
- Trim Drag
- Profile Drag
- Cooling Drag
- Base Drag
- Wave Drag

1.5 THE BASIC AERODYNAMIC SHAPE

We know that the shape of an aeroplane varies with role and flight regime, for this has been shown in the figure. In considering the aerodynamic reason we shall simplify the problem by only thinking of the wing plus body combination: the stabilizing surfaces belong to a further problem, that of keeping the aero plane flying at the required attitude to the air.

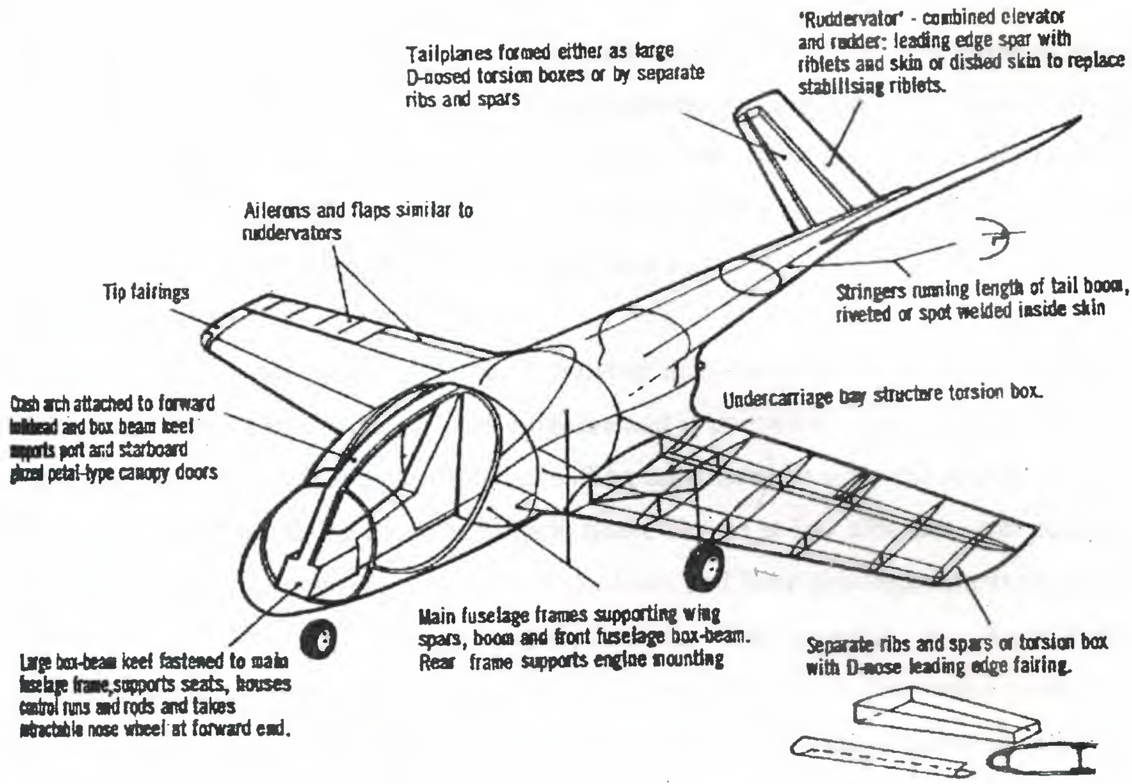


FIGURE 1.8 Sketch of main details of aeroplane structure

Generally there are three types of flights;

- Supersonic flight
- Subsonic flight
- Transonic flight

Speeds are measured in units called Mach number. Which represents the ratio of the speed of an airplane to the speed of the sound as it moves air? An airplane traveling below the speed of sound ($M < 1$) is subsonic. An airplane traveling at the speed of sound ($M = 1$) is transonic. An airplane traveling twice the speed of sound ($M > 2$) is supersonic. If $M > 5$ then it is referred to as hypersonic.

SUPERSONIC FLIGHTS

Supersonic flight is defined as flight at a speed greater than that of the local speed of sound. At sea level, sound travels through air at approximately 1,220 km/h (760 mph). At high altitudes, sound travels more slowly because the air is less dense. At the speed of sound, a shock wave consisting of highly compressed air forms at the nose of the plane. This shock wave moves back at a sharp angle as the speed increases.

The shock wave created by an airplane moving at supersonic and hypersonic speeds represents a rather abrupt change in air pressure and is perceived on the ground as a sonic boom, the exact nature of which varies depending upon how far away the aircraft is and the distance of the observer from the flight path. Sonic booms at low altitudes over populated areas are generally considered a significant problem and have prevented most supersonic airplanes from efficiently utilizing overland routes. For example, the Anglo-French Concorde, a commercial supersonic aircraft, is generally limited to over-water routes, or to those over sparsely populated regions of the world. Designers today believe they can help lessen the impact of sonic booms created by supersonic airliners but probably cannot eliminate them.

One of the most difficult practical barriers to supersonic flight is the fact that high-speed flight produces heat through friction. At such high speeds, enormous temperatures are reached at the surface of the craft. In fact, today's Concorde must fly a flight profile dictated by temperature requirements; if the aircraft moves too fast, then the temperature rises above safe limits for the aluminum structure of the airplane. Titanium and other relatively exotic, and expensive, metals are more heat-resistant, but harder to manufacture and maintain. Airplane designers have concluded that a speed of Mach 2.7 is about the limit for conventional, relatively inexpensive materials and fuels. Above that speed, an airplane would need to be constructed of more temperature-resistant materials, and would most likely have to find a way to cool its fuel.

SUBSONIC FLIGHTS

Subsonic flights are those flights, which travel slower than 1,220 kmph, the speed at which sound travels in air flying at speeds slower than the speed of sound, especially not designed to fly above the speed of sound.

TRANSONIC FLIGHTS

Those flights which operate on Mach No. = 1. The development of slats, slotted flaps, and other sophisticated high-lift devices for landing and takeoff enabled designers to use smaller wings, which in turn allowed them to achieve higher speeds. Turbojets became more powerful, and, in the late 1950s, afterburning, or reheat, was introduced; this permitted large temporary thrust increases by the spraying of fuel into hot exhaust gases in the tailpipe. As these developments took hold, a second generation of fighters appeared that were capable of operating in the transonic regime. These aircraft had thinner lifting and control surfaces than first-generation jets, and most had swept-back wings. Aerodynamic refinements and more powerful, quicker-accelerating engines gave them better flight characteristics, particularly at high altitudes, and some could exceed the Mach in a shallow dive.

1.5.1 DESIGN FOR SUBSONIC FLIGHT

The principal aerodynamic features of subsonic aeroplanes are the lack of wing sweep and the presence of a fuselage that is discrete from the wing in every respect. The shape of the fuselage usually resembles a streamlines cylinder that may also be considered as a very low aspect ratio aerofoil. The profile thickness distribution is similar to that of the aerofoil sections used in the particular flight regime, as may be seen in the figure below. In which a low-subsonic fuselage is compared with a supersonic fuselage of the same minimum cross-section, as determined by the height of a man. It should be borne in mind that the supersonic fuselage shown carries about double the payload of the subsonic version. The existence of a discrete fuselage, as well as any other discrete body, alters the wetted area of the aero plane and, hence, the skin-friction drag in the proportion shown in the Figure 1.9. The proportion apply equal well to all flight regimes.

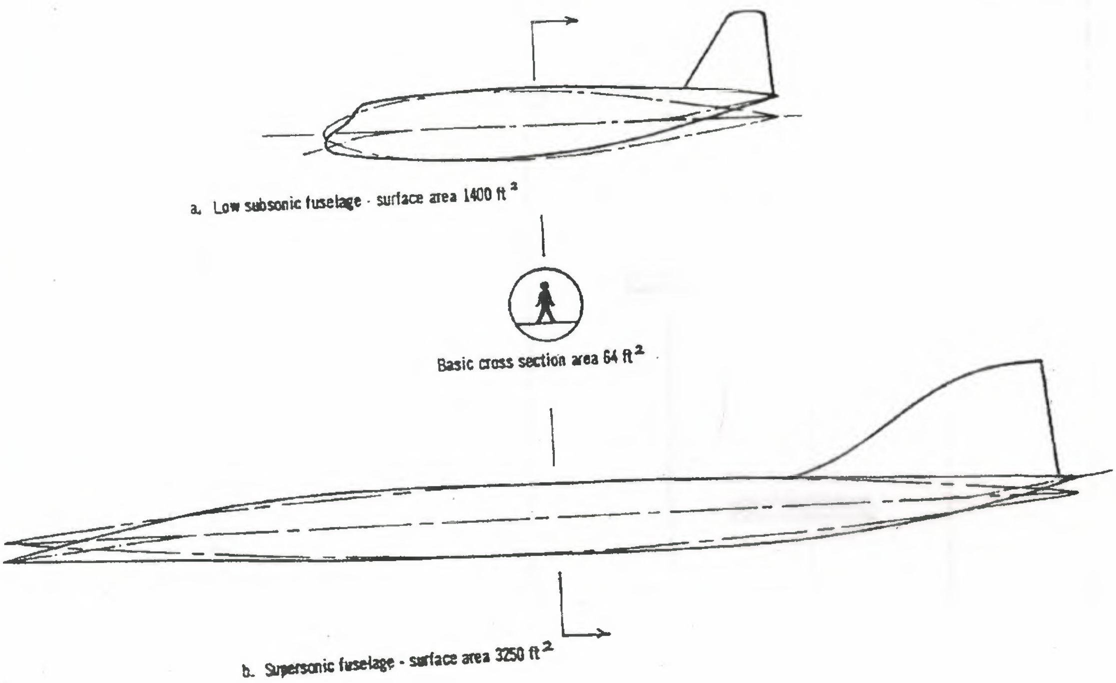


FIGURE 1.9 Comparison of typical low and high speed transport fuselages. Approximately equivalent aerofoil thickness distribution shown

The sweep of a wing requires some definition, for some subsonic airplanes appear to feature swept wings but the reason is different from that for aircraft designed for higher speeds. A wing is said to be unswept if it has zero sweep to any span wise line between 25 and 70 % of the chord. Swept wings have appeared on low-subsonic aero planes as aids to stability: either as a way of arranging the center of gravity and aerodynamic center in the correct relationship, or as a mean of increasing the moment arm of control surface in a tailless design. On subsonic aircraft design for higher speeds we shall say more in a moment.

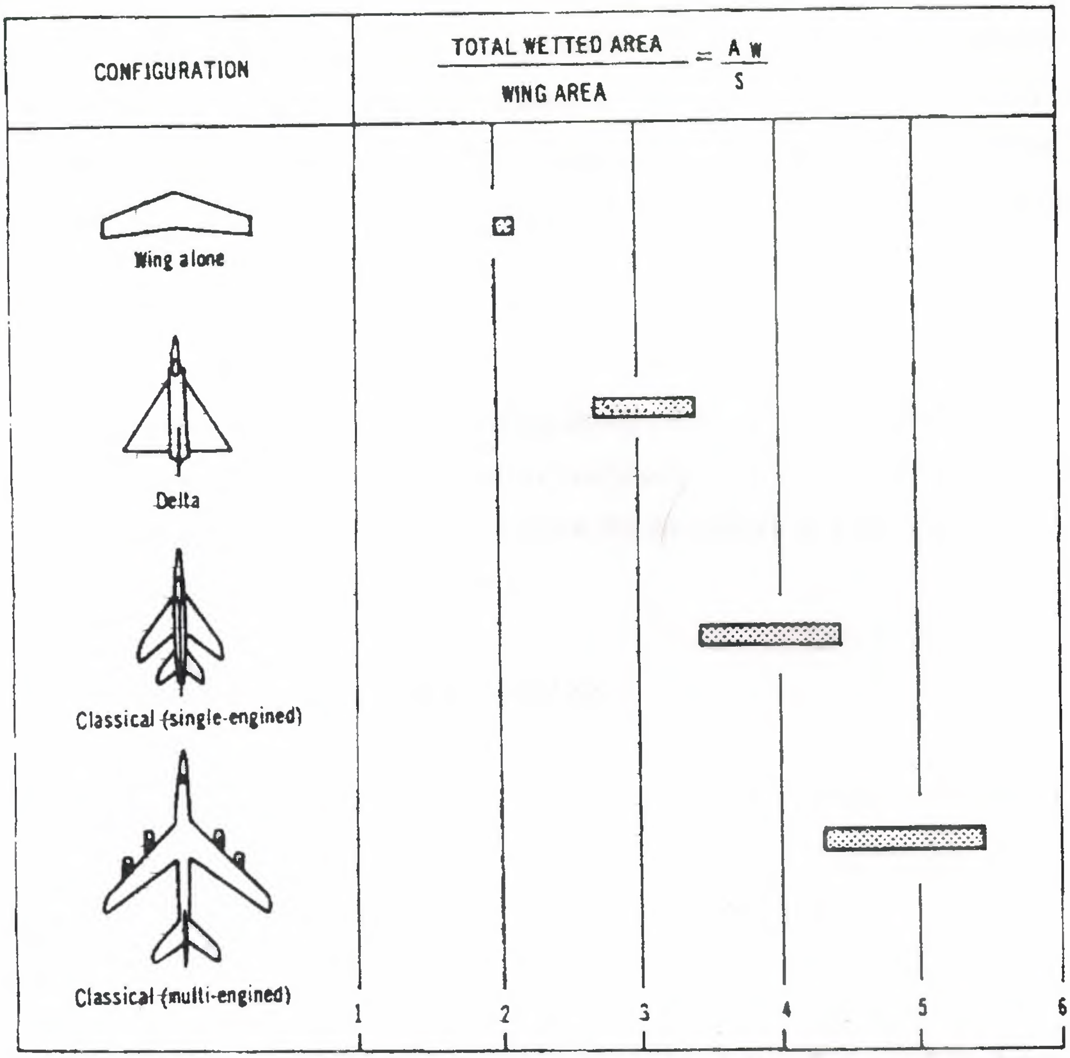


FIGURE 1.10 Wetted area of airframe in terms of wing area for different configurations

Wing section thickness ratios are of the order of the 12%, While the point of maximum camber lies well forward, making sections humped-looking, with well-rounded leading edges. Aspect ratios are higher, being around 10, with lift/drag ratios of 15 to 20. Invariably the stabilizing surfaces appear at the tail in the form of tail-plane and elevator, fin and rudder.

As shown in Figure 1.10, Configurations of different types of airplanes can be calculated by using the relation wetted area of airframe in terms of wing area. The subsonic airplane represents 'Classical' layout in what is probably its most efficient form. The classical layout had been used successfully for so long that it was adapted and modified as much as possible in the year following the appearance of the turbojet. It is only recently that technology has advanced for enough for lift/drag is lower than subsonic, and the sfc (specific fuel consumption) of supersonic engines in a high, speeds can be calculated as;

$$(V/c').\ (L/D)$$

Falls with in a range of 'good' values for range flying efficiency. Until the truly supersonic aero plane appeared high speed aircraft where really only transonic, in the sense that their shapes were designed in such a way as to make the air behave in a subsonic fashion, as though nothing unusual was happening to it.

1.5.2 TRANSONIC DESIGN FEATURES

The outstanding feature of the transonic airplane is the swept wing in its different guises. The use of wing sweep to delay the onset of compressibility was suggested by A. Betz in 1939, after Busemann had drawn attention to such advantages of the swept wing at supersonic speeds at the Volta Congress in Rome in 1935.

To understand the effect of sweep, It is seen that as particles of air are forced over the surfaces of an aerofoil they are impelled to move relative to their undisturbed positions; to circulate. The magnitude of such movement depends upon the thickness-distribution of the aerofoil section and the camber, which together determine the slope of the surface impelling the air to move. If an aerofoil is swept forwards or backwards through an angle, then the geometrical effect is to decrease the thickness-distribution of the section. In the Figure 1.11 a parallel chord aerofoil is shown, in which case the thickness ratio decreases in proportion to cos θ. Clearly then, the air is displaced by the finer section in a longer time, so that the air has more time in which to adjust itself to the disturbance. Since drag-rise is roughly proportional to the square of the maximum thickness/chord, the aerodynamic advantage of thin sections is obvious but thin section raise many structural strength problems.

If lines are drawn joining all points of equal pressure over an aerofoil surface they form a family of isobars as shown in the figure. There are two important features to be noted about isobars, both of which determine the pressure gradient across a surface, they are;

- The intensity of pressure that each represents
- Their spacing.

If the change of pressure is intense, then the pressure gradient is steep and it is likely that the ultimate readjustment of the air to its undisturbed conditions will be violent, with undesirable characteristics.

It follows that the critical conditions governing the behavior of the air on a surface are to be found on a line along which the gradient is measured, lying normal to the isobars through the region in question. We may now apply a mathematical artifice and postulate that the critical pressure gradient is a function of the component of velocity normal to the isobars-for practical purposes the component across the geometric chord, normal to the quarter-chord axis of the airfoil.

If an aerofoil is yawed, then the critical velocity component is reduced. In the case of a theoretical infinite aerofoil of a parallel chord, the isobars lie parallel to the leading and trailing edge. The presence of both fuselage and wing tips alter the isobars pattern and, thus the effect of sweep along the span.

In Figure 1.11c the aircraft is assumed to be flying at M = 0.7 or thereabout, but the wing root and tip are nearer to their critical Mach numbers for compressibility effects. For this reason we find unusual changes of camber in the vicinity of root and tips of transonic airplanes; wing roots with additional sweep, giving the wing a crescent shape and tips with increasing curvature from leading to trailing edge that, in effect progressively increase sweep outboard, these are called stream wise tips. All of such can be seen in Figure 2.5.

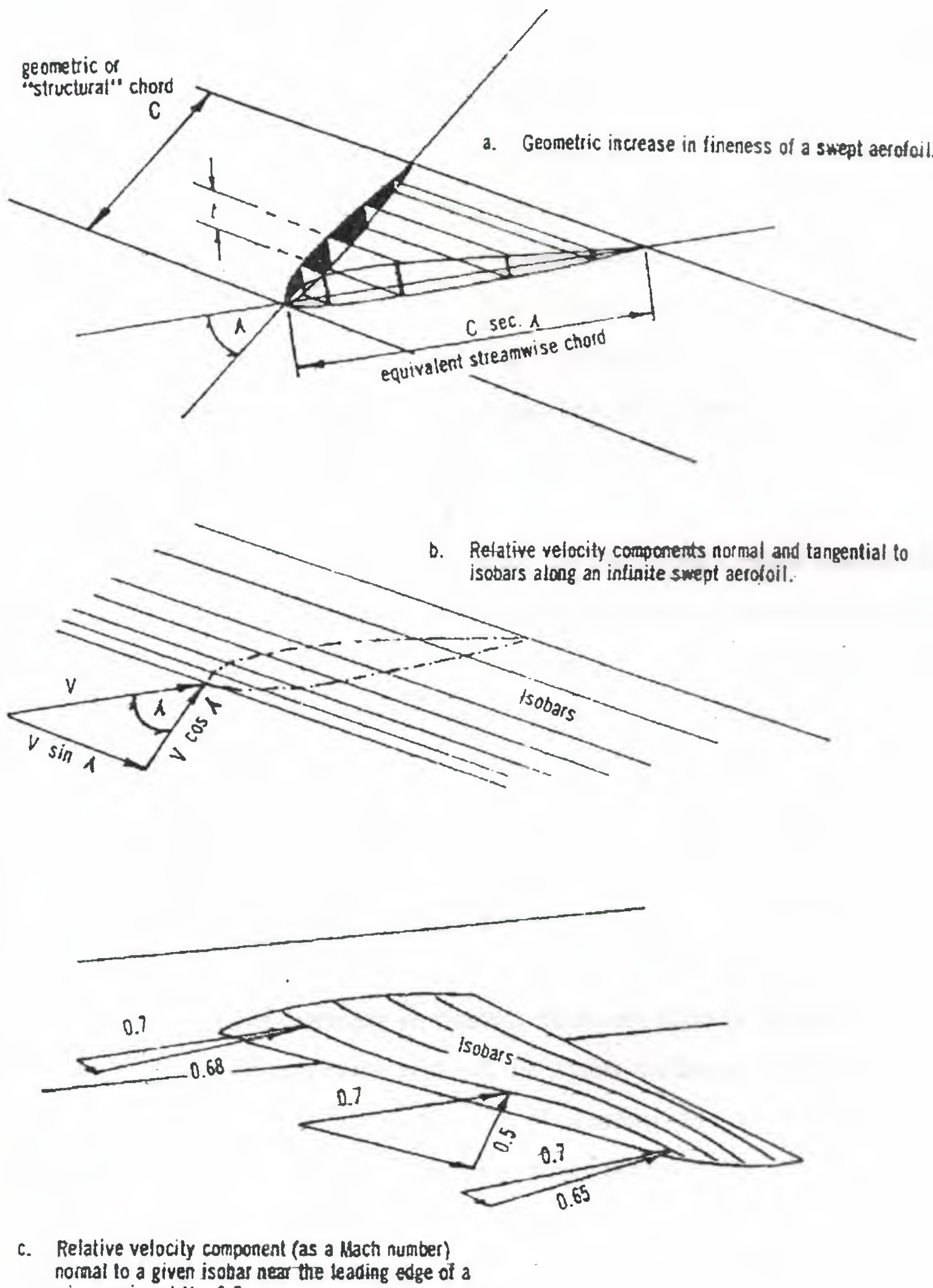


FIGURE 1.11 The theory of sweep

The unpleasant effects of compressibility are rapid drag-rise, loss of lift, breakdown of local airflows (shock stalling) and buffeting that may be damaging to the airframe and destabilizing from its effect upon control and tail surfaces. The air reaching supersonic speeds at some point on the surface of an aerofoil causes these. The deceleration back again to subsonic conditions takes place in a very short distance, through a shock wave (measured in parts of one thousandth of an inch), so called because of the violent increase in static pressure. The increase in static pressure is high enough to cause boundary layer separation, with effects similar to the low-speed stall. Fig 1.12a shows the general effect of sweepback on the drag of an aerofoil at transonic Mach numbers, the relative airflow is still subsonic at some point on the surface of the airframe.

The flight Mach number-in wind tunnel terms the free-stream Mach number at which the relative airflow reaches the speed of sound at some point on the airframe is called M_{crit}. Below M_{crit} the condition of the relative airflow is said to be sub critical, above M_{crit}, supercritical. The situation is hard to determine because one can never be sure of the state of the flow everywhere at once. A more precise value, $M_{crit\ D}$, is used corresponding with an arbitrary increase in the subsonic drag coefficient of 0.002 or thereabouts, at constant angle of attack. It will be seen that $M_{crit\ D}$ (which almost corresponds with the steep rise of drag coefficient in Figure 1.12a.) is increased by sweep.

The general relationship between equivalent thickness ratio is shown in Fig. 1.12b. The thinner and more highly swept the aerofoil, the higher the $M_{crit\ D}$. The second, more recent, feature of transonic airplanes is the use of wasting and area distribution, grouped collectively under area ruling. Area rulling is shown dotted in Fig. 1.13a. Fig.1.13b and Fig. 1.13c, in a slightly different way, how the waisted fuselage generates expansions and compressions that cancel the effects of the wing compressions and expansions. It will be remembered that shock waves and similar compression phenomena are caused when the air is squeezed into a smaller volume. Conversely, expansion waves are the result of the air being free to expand into a large volume.

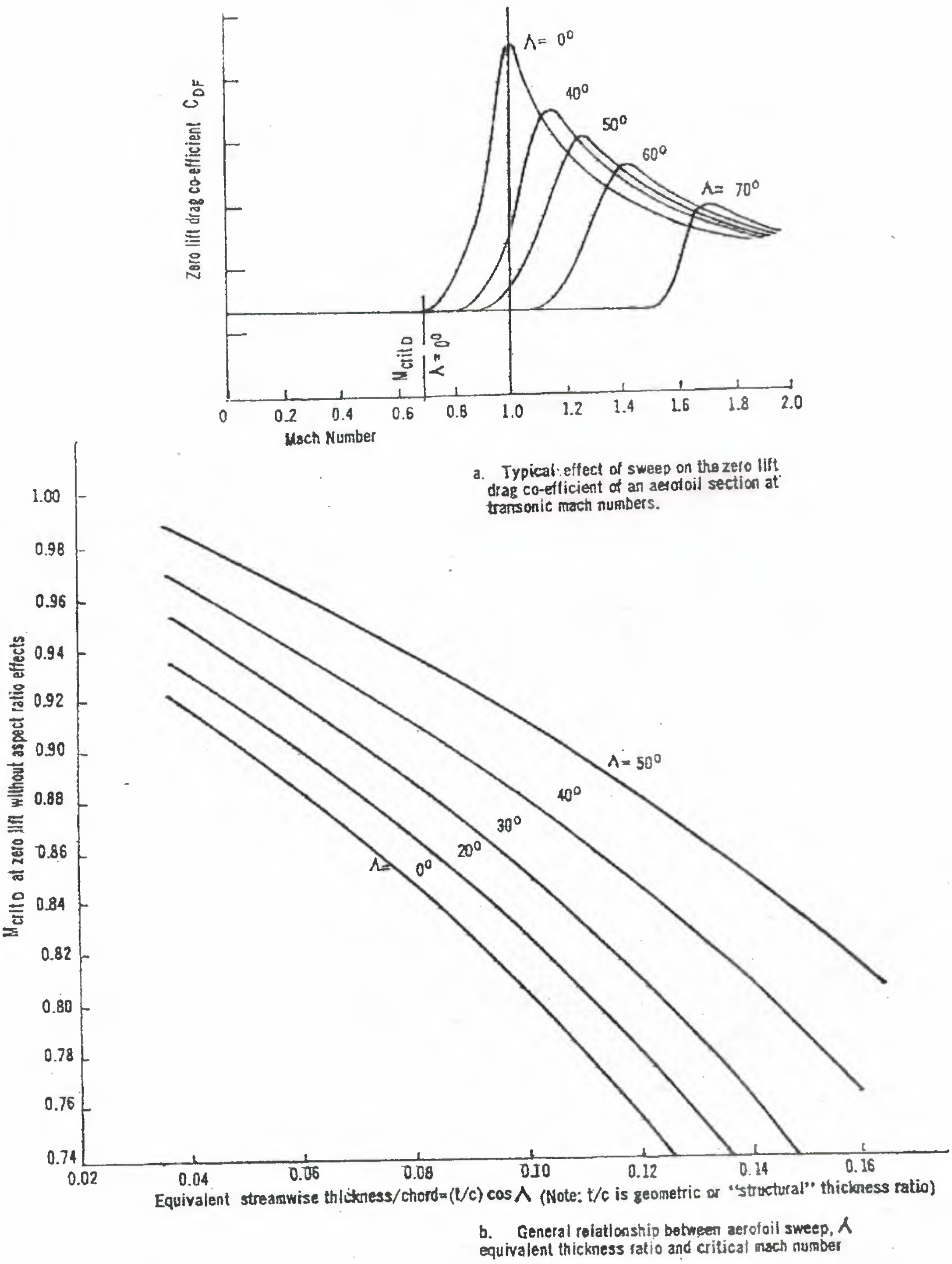
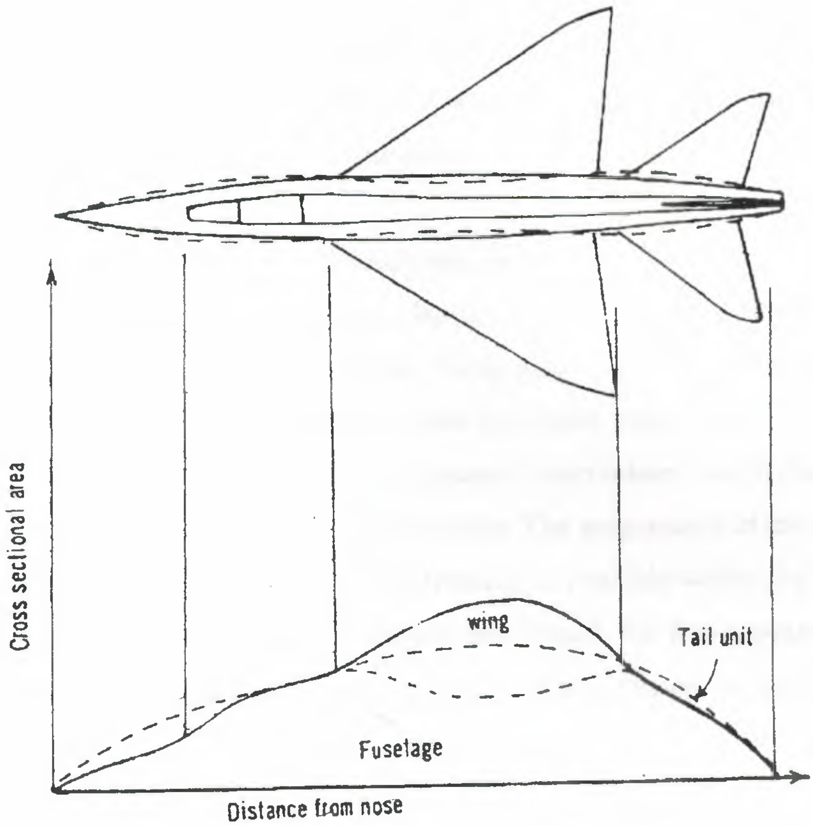
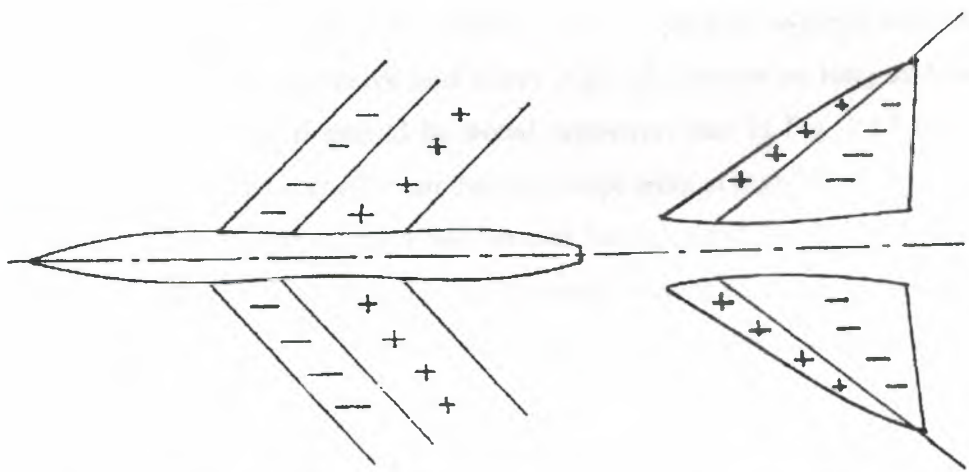


FIGURE 1.12 The effect of aerofoil sweep and thickness on compressibility drag rise



a. Area distribution with modification (dotted) to reduce wing-fuselage interference.



b. Waist generating expansion and compression waves

c. Wings alone.

FIGURE 1.13 Area rulling as a mean of obtaining favorable wing fuselage interference

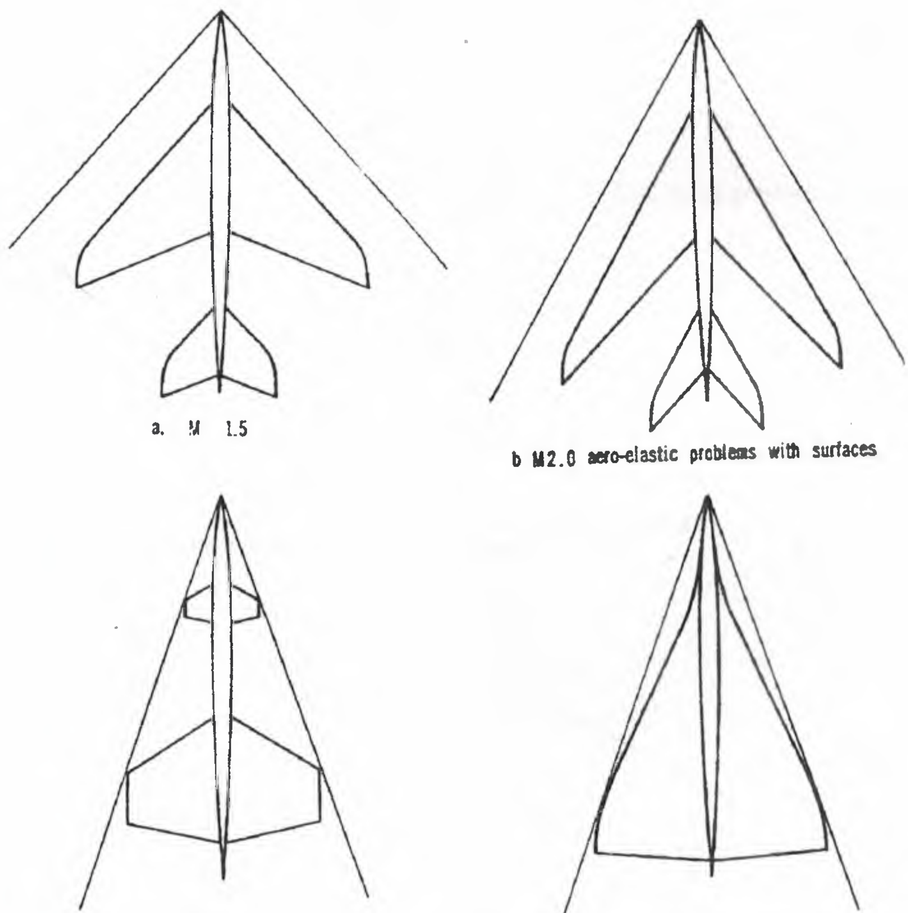
1.5.3 DESIGN FOR SUPERSONIC FLIGHT

The design of a supersonic airplanes is simplified by the flow being of one type only: by the time an airplane has reached M = 1.5 or 1.6 it is unlikely that any significant transonic region will be found over the surface of the airframe.

Design for minimum wave drag is of paramount importance. Wings are thin, around 3 or 5 percent thickness ratio, fuselage are long and slender, and may feature camber to achieve more favorable lift/drag interference with the lifting surfaces. Wingspans are short to reduce wave drag by confining the surfaces within the Mach cone; Fig. 1.14 and aspect ratios are low, so low in fact that span wise pressure distribution approximates to that around a pair of wing tips joined together in the middle. The proportions of the airplane are determined by the need to keep as much of the airframe as possible within the Mach cone shed from the nose, Fig. 1.14, which illustrates the reason for the appearance of the integrated slender-delta configuration as a more efficient alternatives to the classical for economic operations.

The slender-delta has more wing area than a 'straight-winged' classical airplane and, therefore, a lower wing loading. The additional area is needed to compensate for the lower lift coefficient. It follows that such an airplane should be able to achieve lower landing speeds without recourse to expensive and heavy high lift devices as long as low speed instability can be overcome. It should be noted, however, that in Fig. 1.12 the straight (classical) wing has lower drag coefficient that the swept wing at high Mach numbers. That is one reason why supersonic fighters and aircraft have tended to classical rather than integrated layouts. When flying off-design the classical straight wing generates the highest drag in the region of mixed sub and supersonic flows. Of the two layouts the one using acute sweep is theoretically preferable.

Another significant feature of the supersonic classical configuration is that the wing tail tips only affect the span wise pressure distribution within a region bounded by Mach cones shed from the tip of each leading edge. At subsonic speeds it will be remembered that the tips influence the whole span. The inefficient portion of the wing or tail tip is therefore cropped away at the semi angle of the Mach cone, thus saving some weight. This feature tends to appear on missile and aircraft intended for continuous flight at one design point, for example, bomber, reconnaissance and supersonic transport aircraft. Cropped surfaces are shown in Fig. 18. It will be seen that the distribution zone caused by the Mach cone shed from the kinked leading edge of the wing above is removed by the presence of a favorably shaped body.



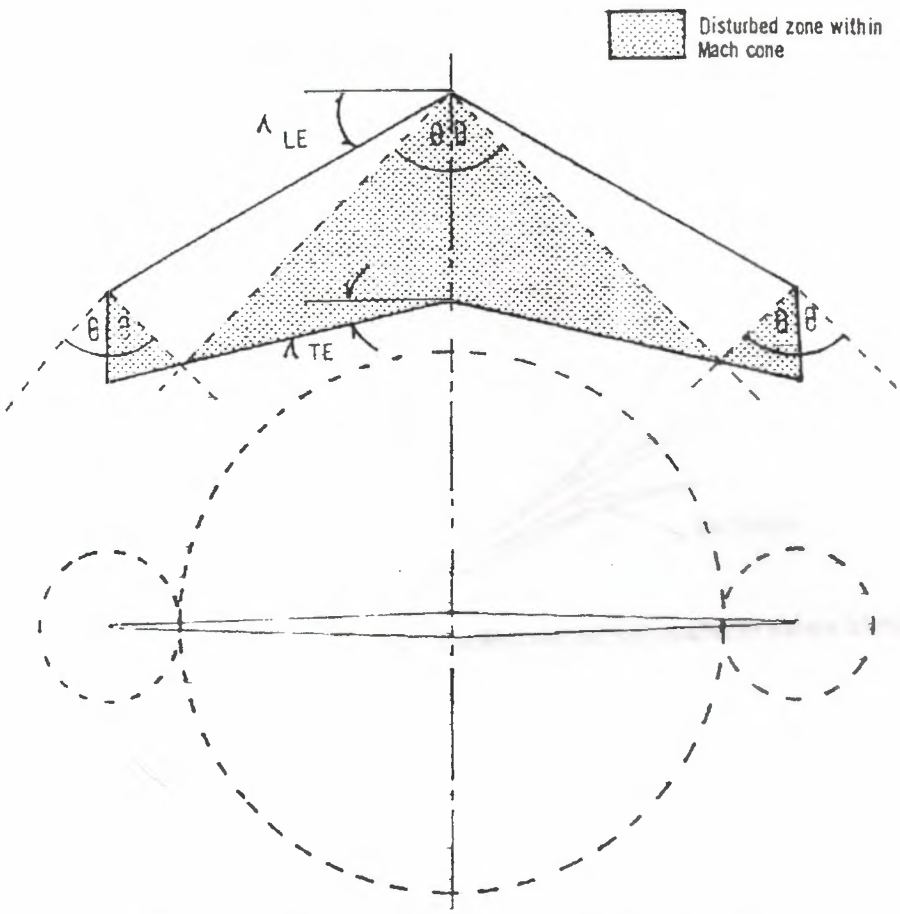
a. M 1.5

b M2.0 aero-elastic problems with surfaces

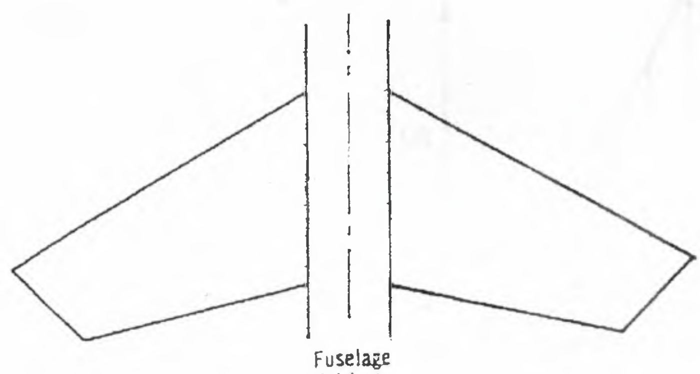
c. M 3.0, canard ahead of wing for trim.

d. M 3.0, slender delta provides working-volume and lift further forward.

FIGURE 1.14 Enforced slenderness and decreased aspect ratio for low wave-drag in supersonic regime



a. Wing alone in supersonic flow showing disturbed zones within Mach cones shed from tips and wing junction leading-edge.



b. Cropped wing, centre section disturbed zone eliminated by favourable body.

FIGURE 1.15 Wing with inefficient portions of surface removed by cropping and fairing

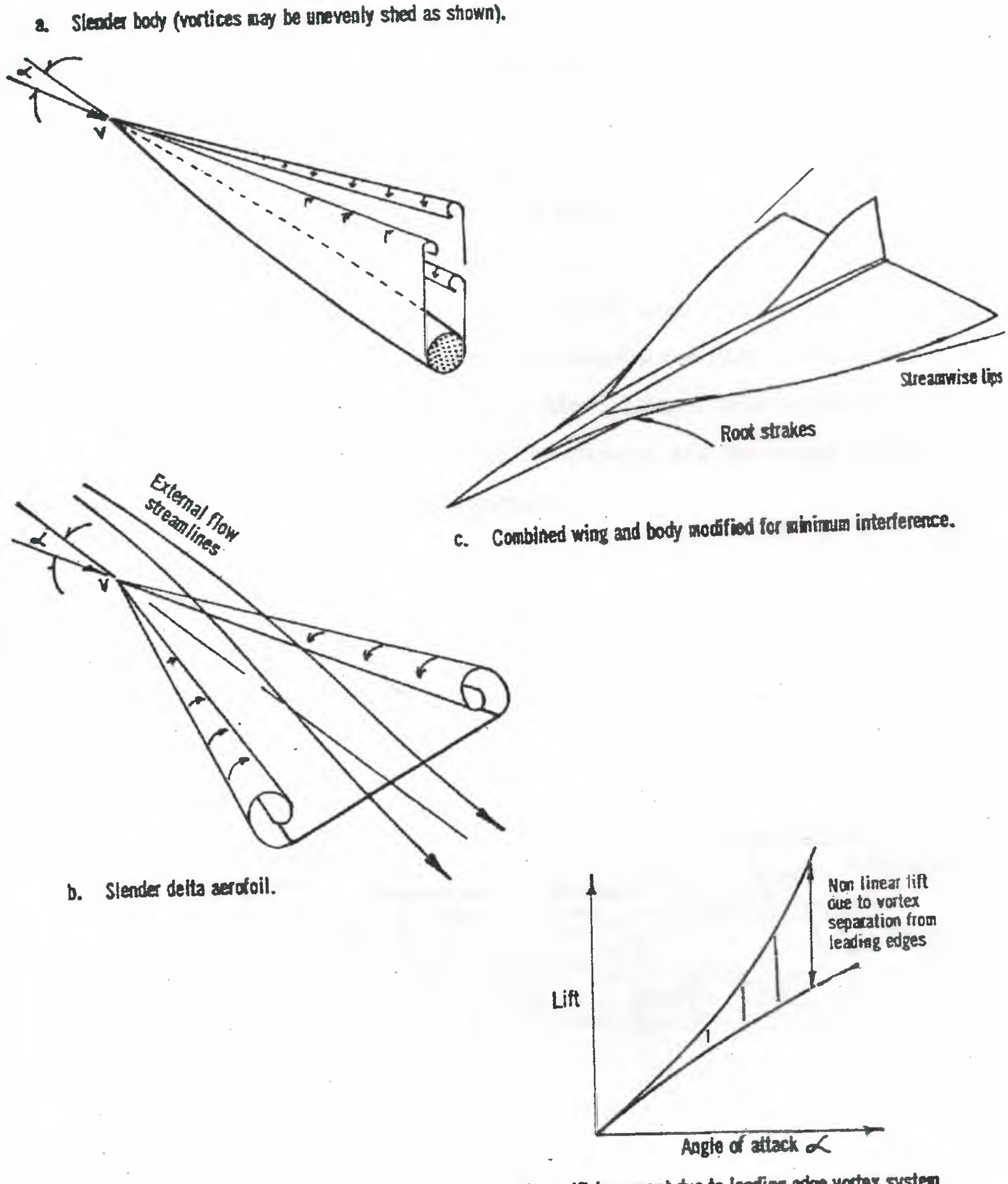


FIGURE 1.16 Lifting vortices generated by a separated flow at low speed

1.5.4 COMPRESSION LIFT

Beyond M = 3 the shape of the airplane is dictated by the need to make use of grossly unfavorable features of the violently distributed airflow. Shock waves are the predominant feature of the relative airflow and, as they cannot be avoided, they may be used to generate compression-lift and thrust producing regions when combined with surface burning of fuel. Fuel is burnt in the air stream over a rearward facing surface and the resulting increase in local pressure produces thrust. The shapes of such aircraft are determined by the need to produce favorable interactions between the relatively high-pressure regions behind shock waves and the adjacent airframe surfaces. The simplest example is shown in Fig. 1.18, in which an ogive, shedding a complete ogival Mach cone, is split longitudinally and fitted with wings. The semi-ogive sheds a semi-Mach-cone and the wings trap the pressure between the body and their sonic leading edges.

The American B-70, which first flew in May 1964, was designed to generate compression lift. Fig. 1.18 c shows a typical curve of compression lift/drag compared with the lift/drag of a conventional design. The salient features of the B-70 are shown in Fig. 1.19. The engine box beneath the delta wing performs a similar function in compressing the airflow to the semi-ogive shown in Fig. 1.18b.

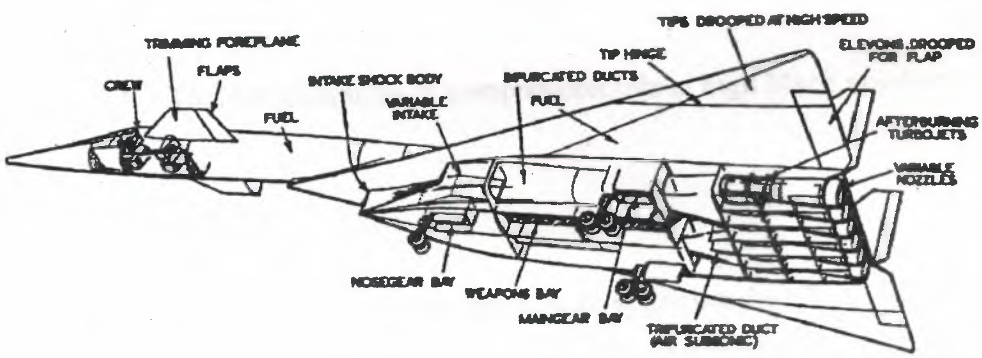


FIGURE 21: - The North American B-70 showing salient features that are typical of current aeronautical practice. Compare the shape of engine box and wing combination with Figure 1.18

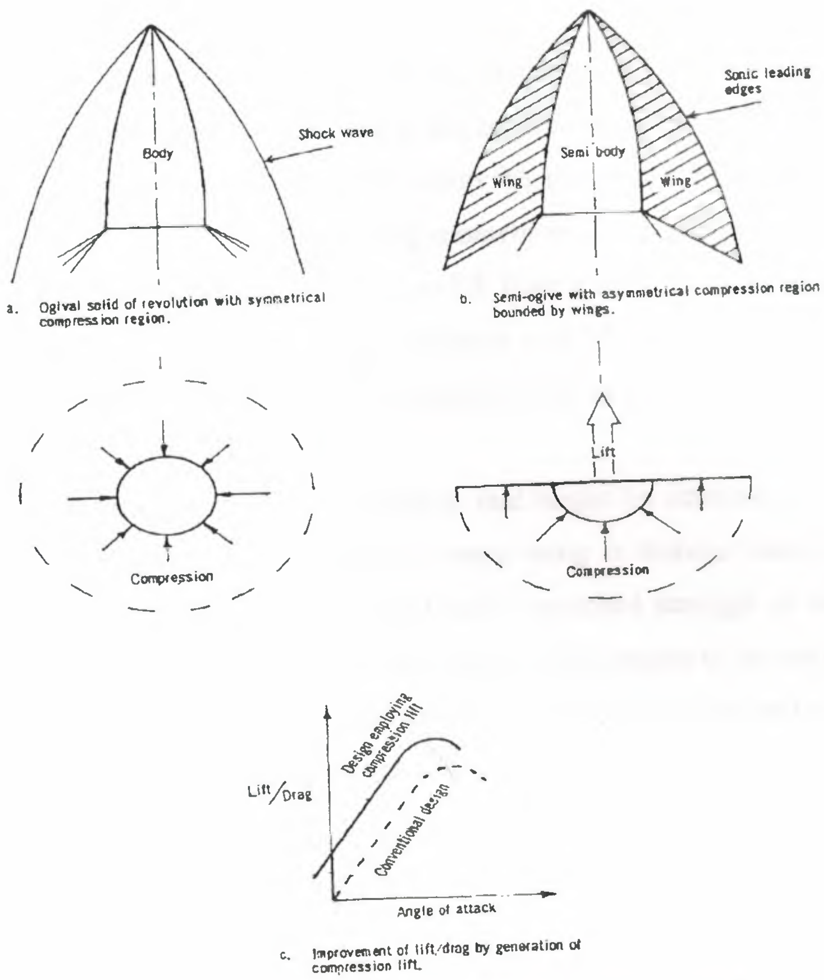


FIGURE 1.18 The generation of compression lifts at high Mach numbers

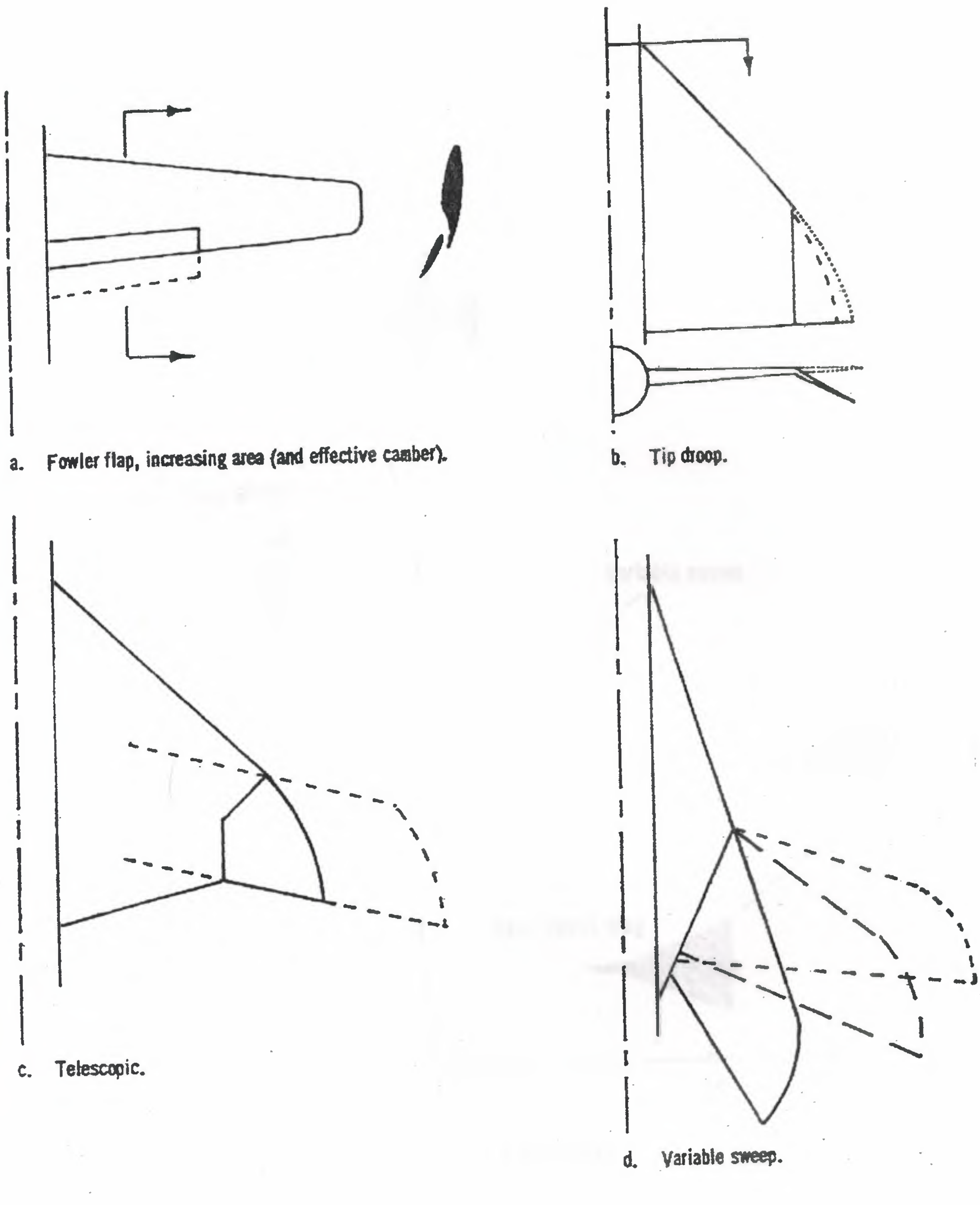
1.6 Variable Geometry

Variable geometry is, in various ways, the means of so changing the effective configuration of the lifting surfaces in flight, that the aerodynamic efficiency of the aeroplane is improved in extreme off-design conditions. Variable geometry appears in two forms: polymorphism, in which the planform and, hence, the aspect ratio of a wing is altered; and variable camber, in which for example flaps are lowered to increase lift at low speeds. Certain aircraft, notably those for naval operations, may feature variable incidence wings: a way of altering the angle of attack without altering the fuselage attitude to the flight path.

1.6.1 THE POLYMORPH

A truly polymorphous wing can take many forms, as shown in Fig. 1.19. The Fowler flap, which increases the area of the wing as well as the camber increases the lift and reduces the landing speed. Tip droop, used on the B-70, moves the aerodynamic center forward at high speeds and decreases the nose-down pitching moment and trim drag: it also increases the effective fin-area and increases the compression lift. Both a telescopic and a variable sweep wing reduce the wave drag at high speed and achieve high lift! Drag ratios at low EAS. The improved cruising efficiency resulting from variable sweep is shown in Fig. 1.20.

Table 1.1 is given to show the typical benefits that might be obtained from the use of variable sweep for a specific. The variable sweep wing is heavier than a fixed wing, because of the weight of moving parts and locally increased strength of members. The reduced drag, however, enables a less powerful and lighter engine to be used. Less fuel is therefore needed, because the engine is less thirsty and, the fuel system can be made lighter. The payload is constant, but this appears as a different percentage of the all-up weight of each airplane. It can be seen from Table 1.1 the airplane with the variable sweep wing will be the lighter and, hence, the cheaper of the two.



a. Fowler flap, increasing area (and effective camber).

b. Tip droop.

c. Telescopic.

d. Variable sweep.

FIGURE 1.19 Polymorphous variable geometry

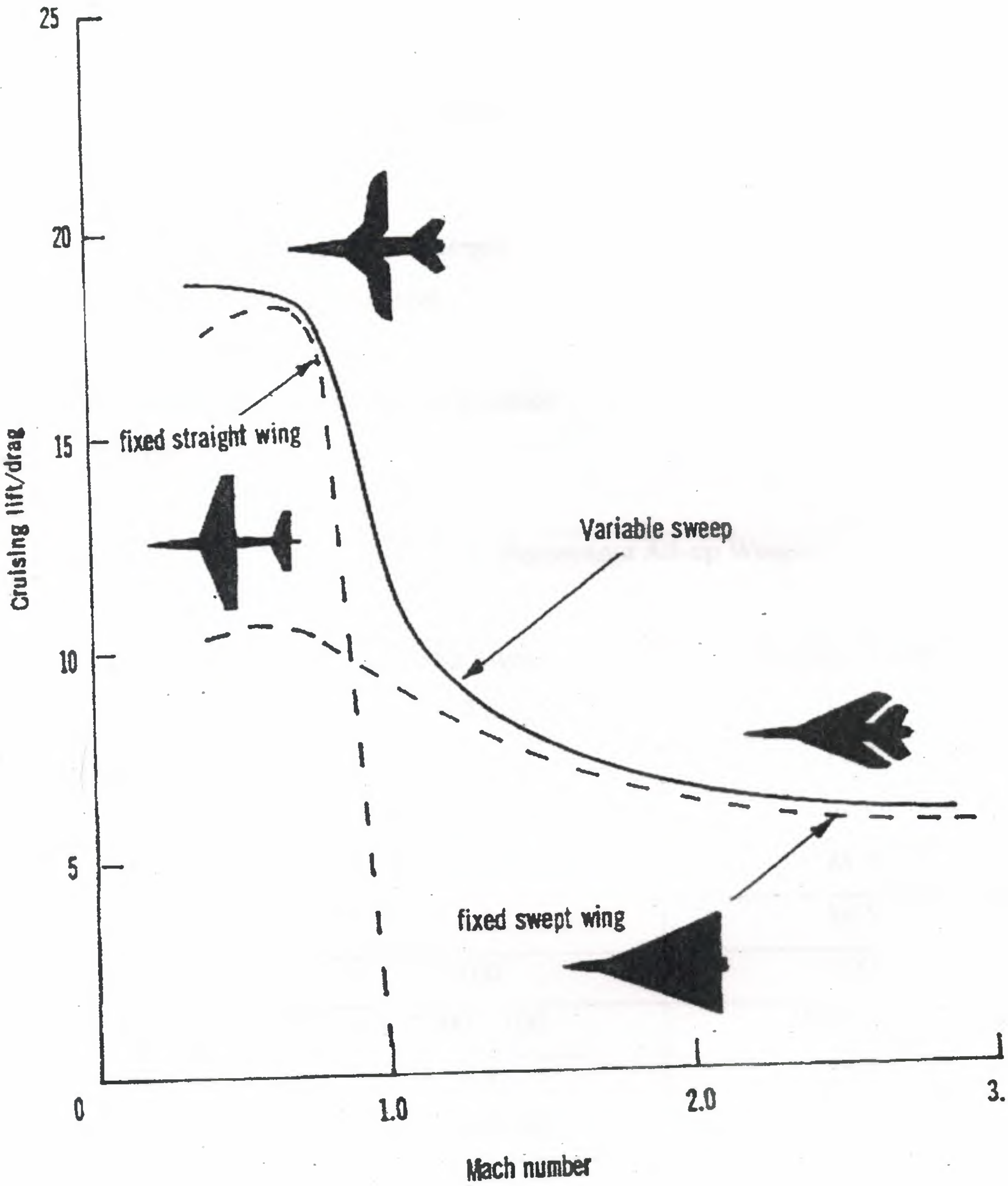


FIGURE 1.20 Variable sweep as a means of improving theoretical cruising lift/drag and, therefore, reducing the fuel required for range

TABLE 1.1

Specification		
Range : 1,600 nm at range speed and height : 200 nm at M = 0.9 at sea level Endurance : loiter for 4 hours : Supersonic dash to M = 2 for 5 minutes Payload: : 7,500 lb		
Item	Percentage All-up Weight	
	Fixed Sweep	Variable Sweep
Structure	30.2	33.2
Power Plant	13.8	12.2
Services (hydraulic etc.)	7.4	8.0
Fuel	37.9	28.5
Payload	8.9	16.5
Total	100	100
Take-off (all up weight) $\frac{(7500 \times 100)}{\text{Payload \% weight}}$	$\frac{7500 \times 100}{8.9}$ = 84000 lb	$\frac{7500 \times 100}{16.5}$ = 45500 lb

But broadly speaking variable sweep offers its main advantages over fixed sweep when the required performance involves the need to fly efficiently over a large part of the flight envelope. For example; combining supersonic dash with STOL and subsonic loiter.

1.6.2 DEVICES THAT CHANGE THE EFFECTIVE CAMBER OF SECTIONS

The camber of an aerofoil section alters the curvature over the upper and lower surfaces and, therefore, the displacement of the air being affected. Positive camber increases the curvature of the upper surface and decreases that of the lower, so that there is a net increase in the lifting circulation imparted to the air. It follows that the greater the positive camber the greater the nose-down pitching moment, and *vice versa*.

Thinking in general terms of altering the curvature of a lifting surface to alter the circulation leads to a collection of devices, for controlling lift and drag at low speed. The control of section lift and drag involves control of the boundary layer. Shaping aerofoils by variations of camber, thickness distribution, slots, slats and flaps and, as we shall see, vortex generators, are all ways of inducing the boundary layer to develop and behave in a controlled manner. The term boundary layer control is reserved in practice for mechanical control of the boundary layer by the application of power.

It is seen that for efficiency aerodynamic surfaces must not gather up air any more than is necessary. Intense suction and steep pressure gradients behind suction peaks indicate that the air is being gathered more swiftly than it should be. Slots of various kinds, both fixed and variable, are ways of slackening the pressure gradient. The slot with air blowing from it can be regarded as a means of washing away the air being borne along and tending to cling to the airframe, by the introduction of a sheet of relatively high velocity air tangential to the surface. The slot prolongs the lift curve by increasing the angle of attack at which the stall occurs. A leading edge flap reduces the suction peak just behind the leading edge, produces a thinner boundary layer and increases the stalling angle in a similar way.

The choice between a slat and a flap at the leading edge is usually based upon mechanical and structural convenience rather than aerodynamic merit. Thin high-speed sections with sharp leading edges derive more benefit from nose flaps.

The plain flap is the basis of all conventional control surfaces. When moved downwards lift is increased: upwards, lift is decreased. It is increased in the opposite direction. The advantage of the trailing edge flap over leading edge slats or flaps is that the attitude of the aeroplane on the glide path is more nose-down, with improved vision for the pilot.

1.6.3 MECHANICAL CONTROL OF THE BOUNDARY LAYER

There are three basic ways of controlling the development of the boundary layer and, hence, the lift and drag of a lifting surface by the use of external power:

- Boundary Layer Control proper, in which power is applied to control separation and the stall of the basic surface, while achieving lower drag at higher speeds

- Circulation Control using blowing or suction over flaps and near the trailing edge to increase the circulation and lift at a given angle of attack

- Directed Slipstream from jet or propeller efflux over flap surfaces

BOUNDARY LAYER CONTROL

By the use of suction over a large part of an aerofoil surface has been experimented with for many years as a way of achieving laminar flow. Results suggest that wing zero-lift drag may be reduced to one fifth normal values. A Northrop X-21A is claimed to have flown with suction for four hours on fuel enough for something like two and a half hours in the unsucked condition.

CIRCULATION CONTROL

The use of blowing to generate super circulation is most conveniently achieved by the tapping of air from engine compressors of many high performance jet aeroplanes. This is done with the naval Blackburn Buccaneer, which employs blown flaps, ailerons and tail plane. The use of super-circulation enables smaller lifting surfaces to be used, with a saving in weight that compensates for the increased weight of the power system. The reduction in lifting surface area achieved in a specific case is shown in Fig. 2.1, where an early Blackburn design study leading to the Buccaneer is compared with a later Buccaneer. Generalized lift improvements from flaps, slats and mechanical control of the boundary layer are shown in Fig. 2.2.

1.6.4 AIR BRAKES AND DRAG CHUTES

Drag is controlled crudely but effectively by the use of airbrakes and spoilers. Air brakes are often used at low speed, as well as for deceleration from high speed, to increase the zero lift drag on the approach. By so doing the overall drag is increased, but the speed for minimum drag is decreased, in this way the delta aeroplane, for example, can maintain speed stability at lower approach speeds.

Speed stability is not an entirely satisfactory term to use, but there is no better alternative for describing what should happen when the attitude and hence speed changes transiently at constant power. Beyond the minimum drag speed a decrease of speed is accompanied by a decrease in drag, and vice versa. At constant power a decrease of speed is automatically compensated by acceleration, because thrust is then greater than drag, while a transient increase of speed results in a deceleration, without intercession by the pilot and a decrease of speed is accompanied by increasing drag and further decreasing speed. On the backside of the power curve there is no speed stability.

Many modern airplanes use drag chutes to decrease landing runs and to augment the effectiveness of the wheel brakes. Drag chutes are sometimes used as anti-spin parachutes, to augment the power of the control surfaces and prevent autorotation.

SUMMARY

In this chapter introduction and history of flight is given, when in 1903 Wright Brother's historic flight opened the chapter in the invention of an aircraft and their development. It is important to first develop a concept, what makes an airplane fly? A force must be applied in order to move the airplane forward. This force can be named as thrust, as the airplane moves forward the air travel over and under the wing. However there are other aerodynamic forces which act on the aircraft when it's moving such as lift, drag and weight. In order to understand the idea what makes an airplane turn is accomplished by controls on the wings called ailerons and rudder. Lift and Drag on an airplane is one of the most important concepts in the maneuverability of an aircraft. Lift is the component of the resultant aerodynamic forces on an airplane normal to the airplane's velocity vector. Where as Drag is the resultant aerodynamic forces opposite to the velocity vector,

Once an aircraft of a given size is specified, and the design point settled, there arises the particular problem of determining the optimum shape of an airplane. This shape of an aircraft must satisfy all design conditions and must be flexible enough to operate safely and with reasonable economy off-design. In order to determine the shape of an aircraft we shall simplify by only thinking the wing plus body combination, which will keep the airplane flying at the required altitude to the air. There are three types of flight supersonic, subsonic and transonic. These three types are compared with respect to Mach number. If $M < 1$ then it is a subsonic flight. If $M > 2$ it is supersonic flight and if $M = 1$ then it is transonic flight. However in some cases where $M > 5$ then it is Hypersonic flight. The next aspect for the design of an aircraft when the shape is achieved, The variable geometry in order for changing the effective configuration of the lifting surfaces in flight, that the aerodynamic efficiency of the airplane is improved in extreme off-design conditions. The variable geometry is of two types: polymorphism and variable camber. Generally aircrafts having such characteristics are for naval or low altitude flight operations in which they require variable geometry to overcome the angle of attack without altering the fuselage attitude to the flight. Such features are ways of including the boundary layers to develop and behave in a mechanical controlled manner.

CHAPTER 2

FIXED MODIFIACTION TO IMPROVE LOCAL AIRFLOWS

In this chapter the basic shape of an airplane is combined with variable geometry to maintain high aerodynamic efficiency, there are inevitable local of interference that cause the airflow to break down under certain conditions. Sometimes the effects are small enough to be ignored, or lived with, at other times the effects may be of critical importance. For our purposes we shall divide the fixed modifications to the geometry of the airplane into: palliatives, in the main designed to improve airflow over the lifting surfaces as shown in Figure 2.1; and the design of wing-body junctions. Palliatives, such as vortex generators, may be found extensively around fuselages as well as wings and tails, so one should not think of them as being exclusive to the Lifting surfaces.

2.1 SOME AERODYNAMIC PALLIATIVES

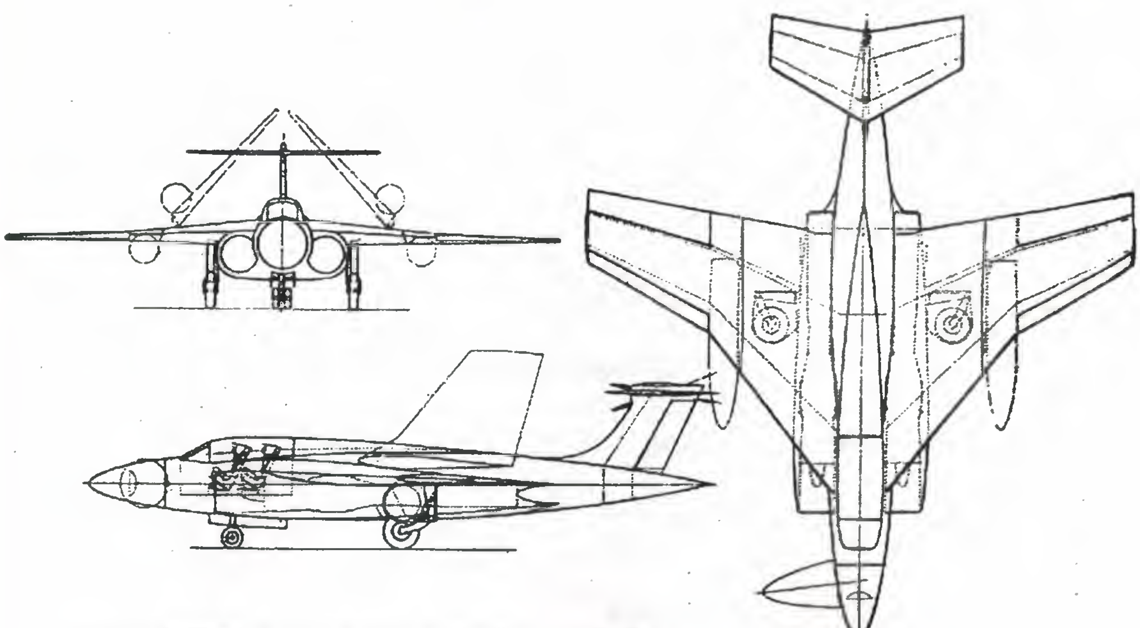
Swept wings are particularly prone to misbehavior of the relative airflow, because of the third component of motion, (see Fig. 1.11b) towards the tips. When shock waves also form severe loss of stability may result from an apparently small disturbance spreading rapidly along a wing. The spanwise component of motion causes a drift of the boundary layer towards the tips with thickening of the layer and proneness to separation, or to at least make separation predictable. Some use a forced vortex to break down an adverse pressure gradient; others employ camber for the same purpose. The vortex generators, fence, and notched leading edge, all induce a chordwise vortex over part of the wing, the flow around the vortex inhibiting the spanwise drift of the boundary layer.

The cambered and dog-toothed leading edges reduce the peak pressure and proneness to separation of the flow from the wing behind. Conic-camber, in which the camber is formed by part of the surface of a cone, has been used to modify some high speed wings for better operation off-design. The notched leading edge is particularly useful on highly swept wings, which shed large leading edge vortices at high angles of attack, for the notch stabilizes the spanwise position of the shed vortex. By preventing the vortex wandering aimlessly up and down the leading edge stability and lateral control can be kept within acceptable limits. Vortex generators are in effect small aerofoils, which, in protruding through the boundary layer, generate relatively powerful vortices from their tips. The flow around each tip vortex draws air from beyond the boundary layer and, by mixing close to the wing surface, increases the relative airflow within the boundary layer. In this way the adverse pressure gradient is reduced and the stagnating boundary layer is washed away into the wake.

Each palliative increases the drag over the theoretical minimum that might ideally be achieved with the basic shape of the airplane, but the increment of drag is less than the drag rise caused in practice without them. Examples, which belong predominantly to the leading edges, are shown in Fig. 2.3, along with a thin section having a slab trailing edge, (g). It will be seen that the slab trailing edge decreases the slope of the aerofoil surfaces behind the point of maximum thickness thus decreasing the adverse pressure gradients. If the surfaces were continued rearwards to meet beyond the trailing edge the resultant section would be much finer aerodynamically than the section used. Apart from local turbulence behind the slab, the air is unable to detect that no surface remains beyond the trailing edge.

2.2 JUNCTIONS

The design of an airplane involves detailed treatment of the aerodynamic and structural properties of the individual parts, in temporary isolation from the rest. Design data sheets enable broad approximations to be made of the lift, drag and pitching moments of items such as mainplanes, tail surfaces, and bodies of various kinds. But the sum total of the individual drags is usually much less than that of the whole, while lift too is usually less. Pitching moments may be unpredictably, increased or decreased. The cause lies in the interference between adjacent aerodynamic surfaces. The airflows around wing and body junctions usually interacting in such a way as to spoil the simple clean flows experienced in isolation.



a. General arrangement of one of the original Blackburn B.103 studies.

b. General arrangement of the Blackburn Buccaneer S1.

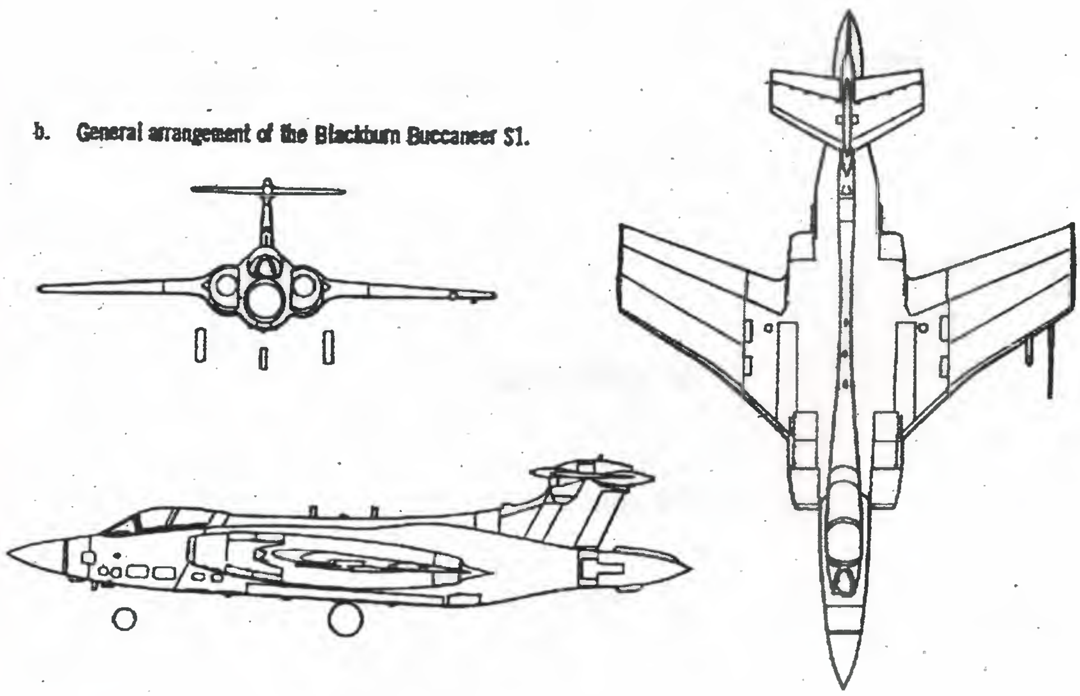


Figure 2.1 The effect of circulation control upon the areas of lifting surfaces needed to meet a requirement

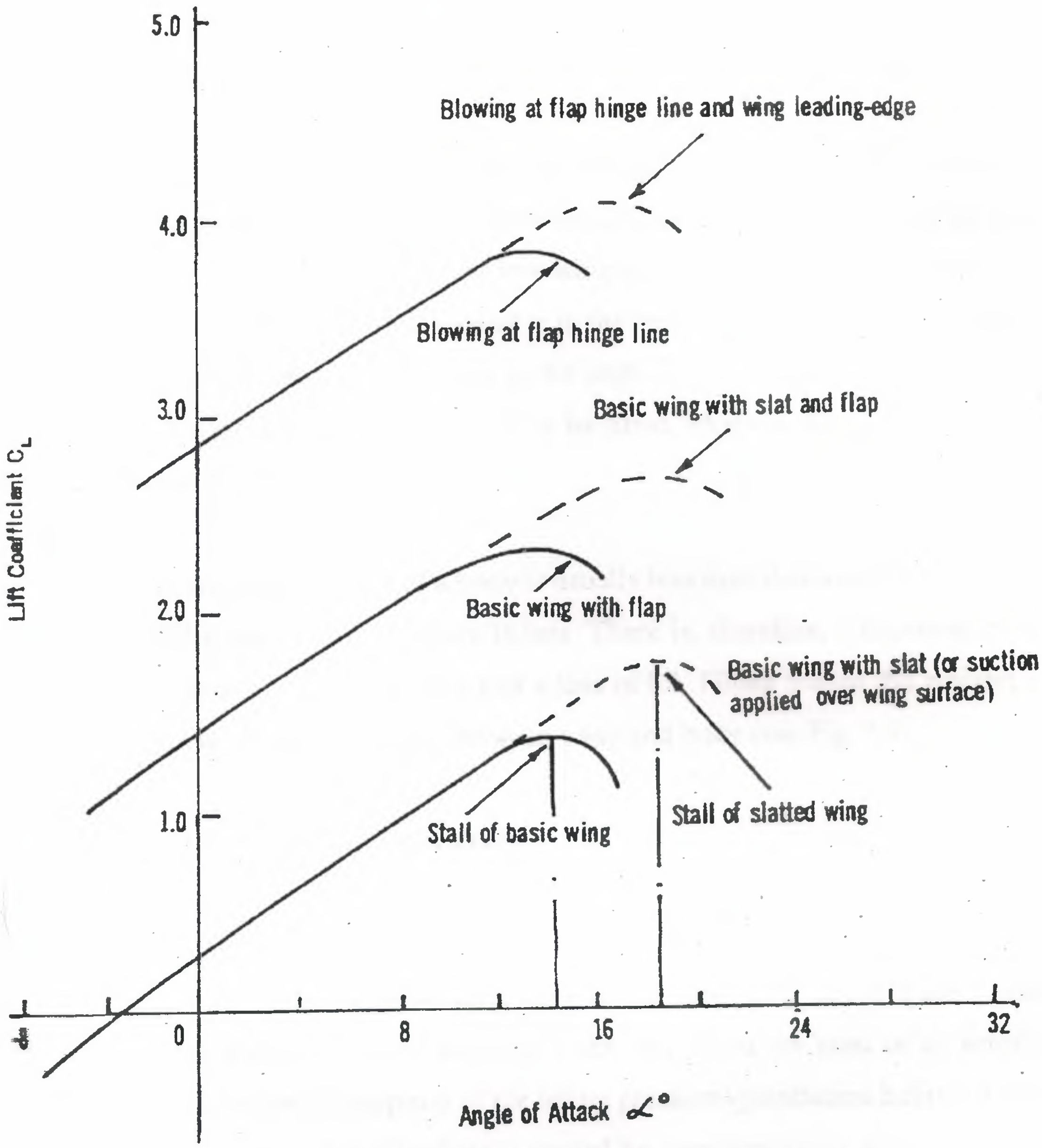


Figure 2.2 Generalized effects of flap, slat, suction and blowing upon lift of basic wing

The effects of such interference are manifold, the commonest being airframe buffeting, premature stalling of one wing before the other, poor acceleration and reduced airspeeds as shown in Figure 2.2. Interference effects all arise from decreased velocities in local relative airflows, which cause adverse pressure gradients and premature separation of the boundary layer.

SUBSONIC AIRFLOWS

At subsonic speeds any increase in the cross-sectional area of a flow results in decreased velocity and increased static pressure. When a wing-body junction is right angled there is no marked interference. But if a high or low wing is mated with a curved body cross-section, then the cross-sectional area available to the relative airflow increases towards the leading and trailing edges of the wings as the angle between body and wing surface becomes increasingly acute. Fillets must then be fitted where surfaces meet at acute angles to maintain smooth airflows.

The relative airflow along the side of a body is usually less than that over the crest of an aerofoil surface, because body curvature is less. There is, therefore, a decrease in the airflow velocity over a wing at the root and a loss of lift. Fillets reduce the amount of lift lost by reducing velocity gradients between wing and body (see Fig. 2.4).

SONIC AND SUPERSONIC AIRFLOWS

In sonic and supersonic airflows it is necessary to control shock formation as far as possible, because the sharp adverse pressure-gradient through a shock wave causes boundary layer separation. A shock forming in the vicinity of the crest of an aerofoil surface can cause complete disruption of the lifting pressure-distribution behind it. The buffeting and sharp loss of lift (Shockstall) caused by compressibility gave rise to the early misconception of a 'sound-barrier', beyond which man might not fly.

We have already seen that most important component of the relative airflow over a surface is that normal to the local isobars. When two swept aerofoil surfaces are joined in isolation from a body, the airflow over each wing affects the other, giving rise to centre-line effects of a reduction in isobar sweep. Effects similar to those occurring at a centre-line are caused at a junction where an aerofoil is cranked in planform (where there is a change of sweep). For example, the M-wing was suggested some years ago as a possible transonic-cruise planform that avoided aeroisoclinic distortion (the nose-down twisting of a swept wing towards the tip, caused by bending due to lift) and center-line effects would therefore have been present at three places across the span at the two cranks and at the centre-line. The addition of a properly shaped body straightens the isobars at the root, or junction.

A delta wing and part of an M-wing are shown in Fig. 2.5. The initial curvature of the isobars across the span is shown to be altered by the addition of a fuselage and, in the case of the M-wing, by the addition of engine nacelles at the crank of each wing. The bodies are indented in accordance with area-rule theory. Streamwise tips have been added to straighten the isobars at the wing tips.

For tractable handling characteristics at the onset of compressibility many recent high-subsonic transport aircraft have featured negative camber at wing roots to locally straighten the isobars, and revised wing-body fairings that are quite unlike that shown in Fig. 2.4. A typical root section and body fairing is shown in Fig. 2.6. The negative camber is only the root-end of several possible changes of camber across the span which, when allied with wash-in and wash-out (increase and decrease in wing incidenc the angle at which the wing is rigged and, hence, angle of attack) of different parts of the wing, serve to make every part of the wing work at the same lift coefficient. In so doing the root is made to stall at the same time as the tip.

The fairing is seen to be, in effect, a slab-sided distension of the fuselage, which the wings meet almost at right angles. In this way the local flow is least altered between the leading and trailing edges of the wings, while the additional volume usefully increases the stowage-volume, which is always in demand. Such a bulge beneath a wing is less critical than above, because the relative velocity of the airflow below is not so near ~ It should be noted that many high speed jet aircraft now feature slab-sided body fairings, with rounded corners, at wing and tail junctions.

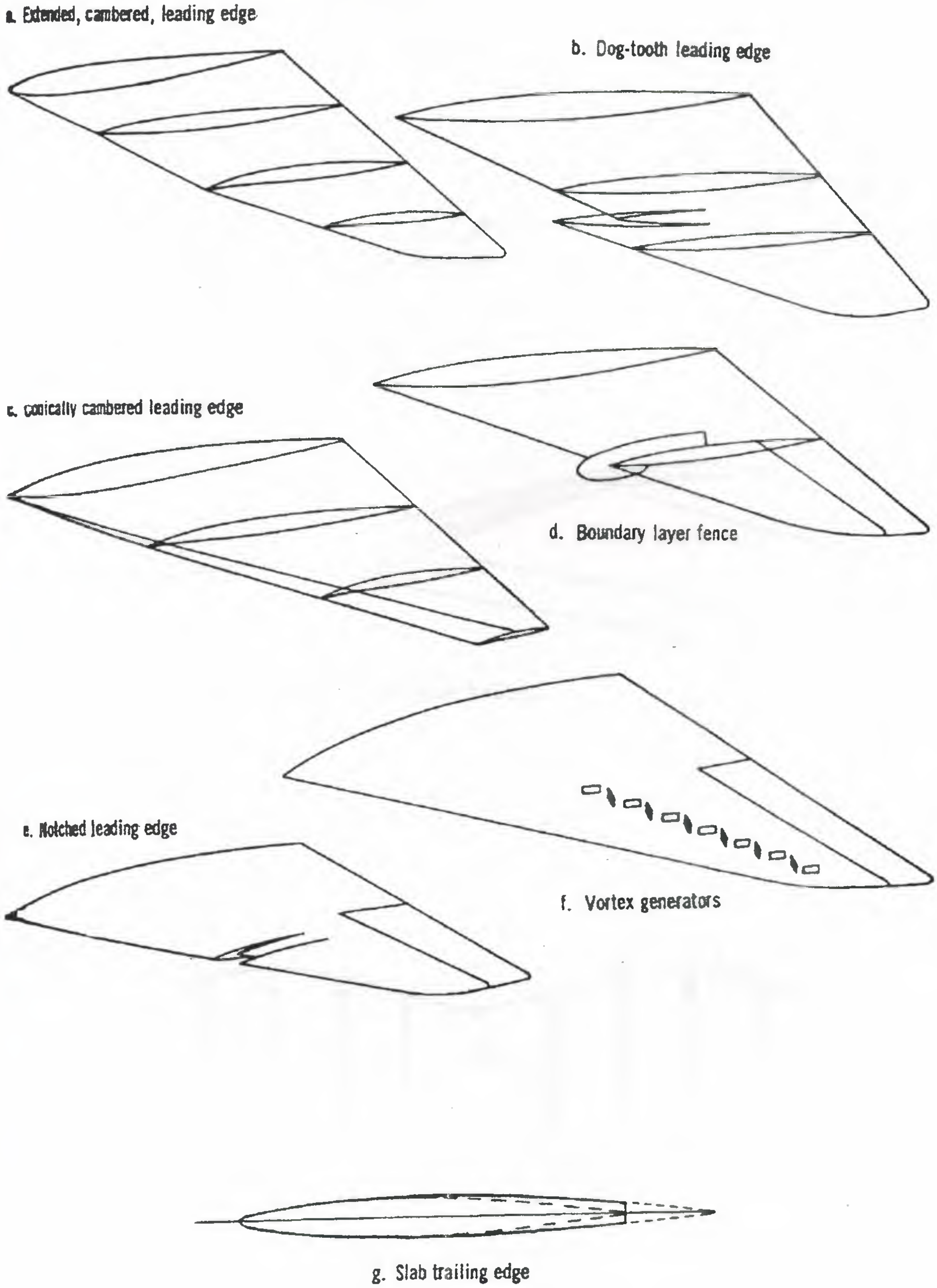
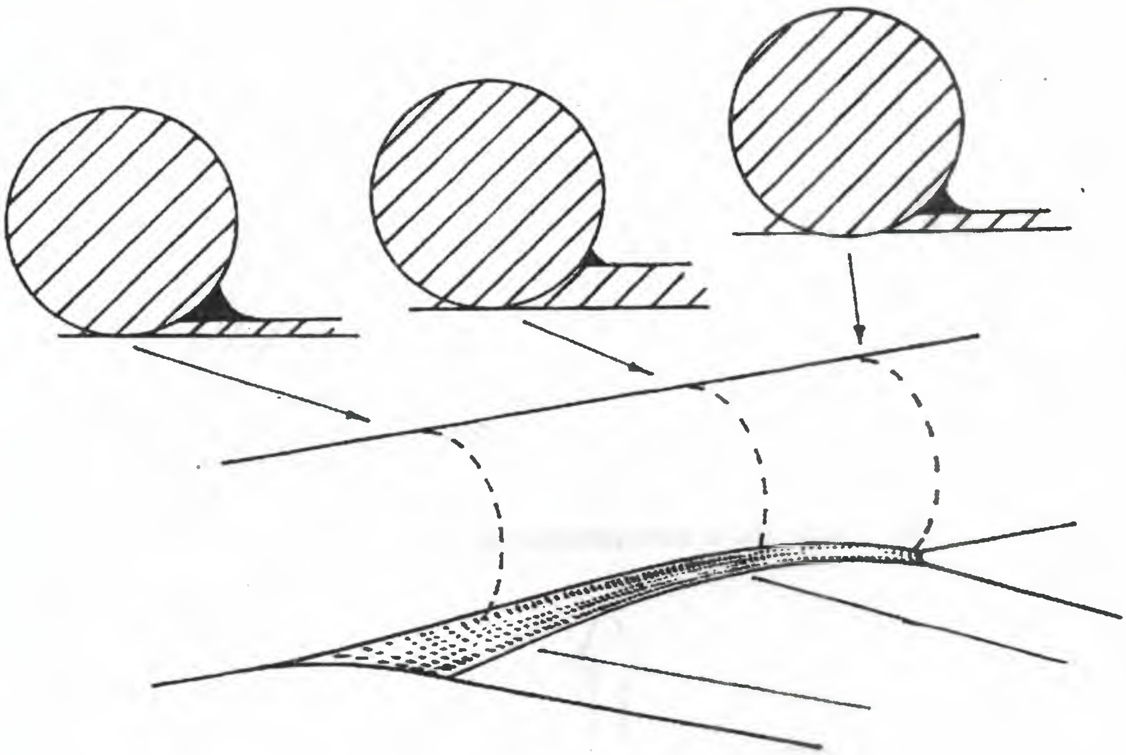
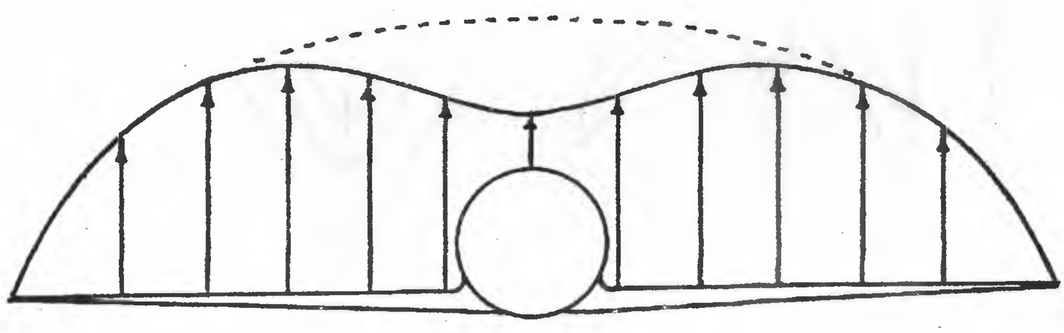


Figure 2.3 Aerodynamic palliatives for improving local airflows over wings



a. Typical fillet at a low wing body junction.



b. Loss of lift due to presence of a body.

Figure 2.4 The subsonic wing-body junction

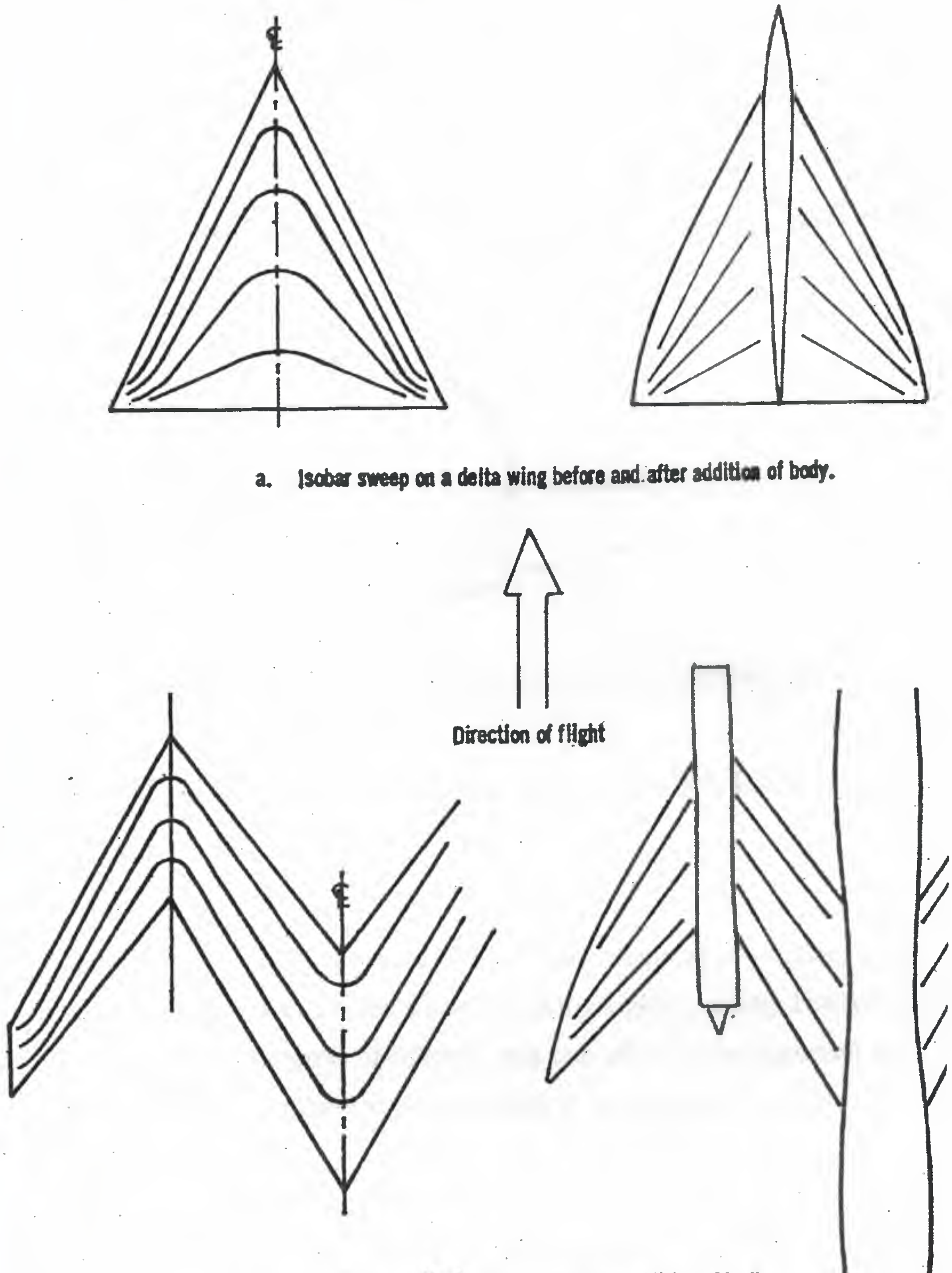


Figure 2.5 The effect of favorable junctions and streamwise tips on isobar sweep at the design point

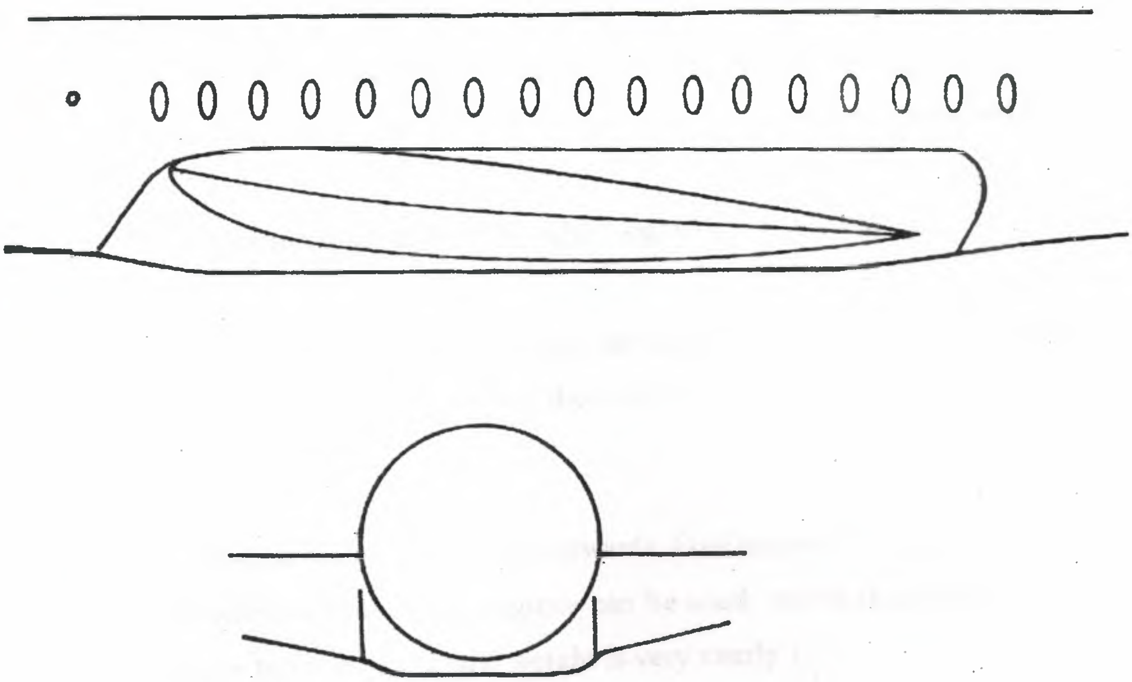


Figure 2.6 Negative cambers at wing root, and body-fairing to reduce compressibility effects

2.3 DESIGNS FOR OPTIMUM LIFT/DRAG WHEN RANGE FLYING

In being able to control lift and drag and, under certain conditions, to vary both at will beyond the range of values achievable with the basic shape of an airplane, we are able to extend the efficiency over a much wider part of the flight envelope. The aerodynamic efficiency is measured in terms of lift/drag, and one of the most important aspects of performance is that an airplane should be able to fly as far as possible on a given quantity of fuel.

Although the range-flying efficiency of an airplane depends, aerodynamically, upon the attainment of high lift/drag in practice the maximum value is not used. The actual value, $(L/D)_R$, is within a few per cent of the maximum. Using this value, Equation can be restated as:

$$\text{Range varies as; } (L/D)(M/c')\log_e(W_O/(W_O - W_F))$$

All of the terms do not have the same influence upon the equation and to understand why they must be recombined. In the recombination the propulsive term, ($1/c'$), which is the reciprocal of the thrust specific fuel consumption, must be considered with:

$$\text{For calculating structural weight; } \log_e (W_O / (W_O - W_F))$$

The faster the design cruising speed the greater the drag and the thrust required from the engines. The higher the thrust, the thirstier the engines, and the more the fuel needed to fly a *given distance*.

Jet aeroplanes cruise at speeds of $M = 0.6$ upwards. Fortuitously, throughout the whole range of speeds where air-breathing engines can be used, which is up to $M = 10$, the product; propulsive term and structural weight is very nearly 1.

$$(1/c') \log_e (W_O / (W_O - W_F))$$

In fact it rises to 2 at high Mach numbers, but even then the effect of the product upon the whole equation is much less than that of the rest, which varies more widely. Therefore we may say that, for simple practical purposes:

$$\text{Range varies as } M (L / D)_R$$

As the range is specified we see that as the cruising Mach number is increased by the requirements, the cruising lift/drag may be allowed to fall. It is this fact that has enabled a fruitful search to be made for supersonic cruising shapes with apparently low lift/drag ratios.

The cruising Mach number is directly proportional to range. One may consider flying the Atlantic at $M = 2$, but it would be uneconomical to consider flying only 500 nml at the same speed, simply because the large value of M does not have enough time to affect the block speed, upon which economy depends. The 4,000 nml or more to the west coast of America may be flown with reasonable economy from European airports at $M = 3$ before very long. Various design studies have yielded the following formula for calculating 'good' values of $(L/D)_R$ for transatlantic distances of around 3,000 nml:

$$\text{Range (R)} = 4\,(M + 3) \tag{2.1}$$

So that:

$$M\,(L/D)_R = 4(M + 3)$$

i.e.,

$$(L/D)_R = 4(1 + (3/M)) \tag{2.2}$$

Evaluation of this equation results in a band of state of the art values as shown in Figure 2.7, that falls, that falls asymptotically from around lift/drag ratio 20 at M=0.5 to 5, around M=4, The shape of the figure should be compared with Figure 1.20.

2.3.1 THE EFFECT OF ASPECT RATIO

Imagine that an airplane is cruising at constant weight, and therefore lift how exactly does drag vary with airspeed? We know that the total drag has two terms drag at zero lift, and lift dependent drag;

$$D = D_F + D_L \tag{2.3}$$

$$C_D = C_{DF} + C_{DL} \tag{2.4}$$

Where;

- C_D is the drag coefficient
- C_{DL} is the lift dependent drag coefficient
- C_{DF} is the zero lift drag coefficient
- D is the total drag of airplane
- D_F is the zero lift drag
- D_L is the lift dependent drag

As long as flight is at a subcritical Mach number there is no wave drag and C_{DF} remains sensibly constant with airspeed. When flight is at a supercritical Mach number C_{DF} is increased by wave drag components. The vortex drag, on the other hand, must decrease with speed, because the wing flies at a small angle of attack, and the circulation

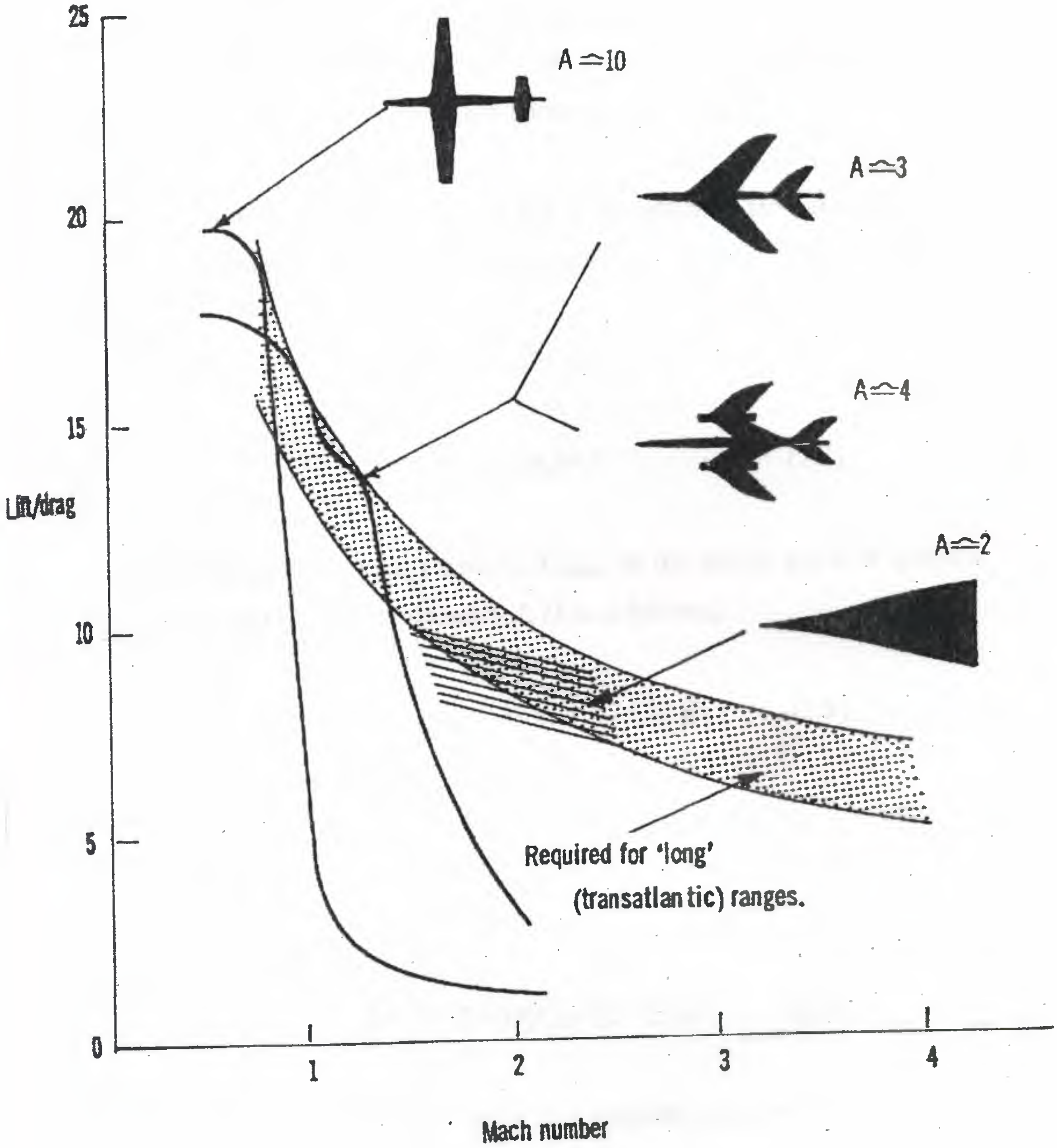


Figure 2.7 Shape trends giving 'good' lift/drag ratios for typical long ranges of transatlantic order (3000 nml)

causing the vortex system varies directly with angle of attack. In fact, at subcritical speeds the lift-dependent drag coefficient can be calculated as;

$$C_{DL} = K(C_L)^2 / (\pi A) \qquad (2.5)$$

where π, C_L and A have their conventional meanings and K is a factor measuring the efficiency of the planform. When the planform and lift distribution are elliptical C_{DL} is a minimum when K = I. For normal planforms K varies between 1.1 and 1.3. In fact K might reasonably be called the inefficiency factor of the planform.

The total drag may be plotted as shown in Fig. 2.8a, which is similar to the minimum drag, corresponding with maximum lift/drag, occurs where $C_{DF} = C_{DL}$;

$$C_{Dmin} = 2K(C_L)^2 / \pi A \qquad (2.6)$$

$$C_L = \sqrt{(C_{DF}\ \pi A)} / K \qquad (2.7)$$

Now, the best lift/drag corresponds with C_L/C_{Dmin} at the design point in question, so that from Eq. (2.6) and (2.7), the maximum *L/D* is as follows;

$$(L / D)_{max} = ½ \sqrt{(\pi A / C_{DF} K)} \qquad (2.8)$$

The speed for best speed/drag, *i.e., MID,* at constant lift is, in fact, the speed for best $M(LID)_R$. It may be seen from Fig. 2.8(b) that $(L/D)_R$ is about 0.94 $(L/D)_{max}$, from which we obtain;

$$A = (9 / 2\pi) KC_{DF} ((L / D)_R)^2 \qquad (2.9)$$

The aspect ratio, planform efficiency factor and zero-lift drag coefficient all lie within the control of the designer. If a particular planform is chosen to match the design point: wing-sweep for Mach-characteristics, section for both Mach-characteristics and stowage volume, then the essentially constant terms can- be evaluated with the aid of wind-tunnel tests to leave the relationship that aspect ratio is as follows;

$$A \text{ varies as } C_{DF} ((L / D)_R)^2$$

The planforms shown in Fig. 2.7 have aspect ratios and shapes that gives good cruising lift/drag values at their design points. Note that the classical subsonic aeroplane has an aspect ratio around 10, while the slender delta, with an aspect ratio around 2, satisfies the transatlantic range requirements from M = 2 onwards. When Fig. 2.8 is compared with Fig. 1.20 the efficiency of variable geometry is made doubly apparent; provided one is willing to pay the price of mechanical complexity and increased first cost.

2.3.2 THE EFFECT OF WETTED AREA

The calculation of $(L/D)_{max}$ can be approached in another way, although it is one that involves making a broad assumption that the zero lift drag depends more upon akin friction than upon pressure effects. This is reasonable because the highest lift/drag is achieved in subsonic (subcritical) flight, where pressure usually has a much smaller effect than friction upon the zero lift/drag.

We saw from Eq. (2.6) that CD_{min} occurs where $C_{DF} = C_{DL}$, and assuming that C_{DF} depends upon friction alone in subcritical flight, where:

$$C_{DF} = (A_w / S)\, C_{D\,fric} \qquad (2.10)$$

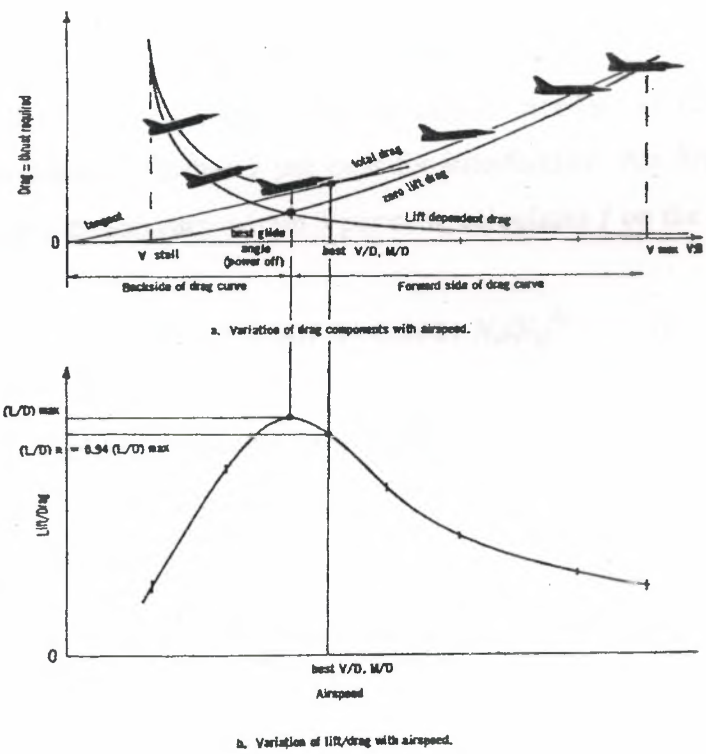


Figure 2.8 Variation of drag and lift/drag with airspeed at constant weight

we may therefore write:

$$C_{Dmin} = 2\, C_{DF}$$
$$= 2\,(A_w / S)\, C_{D\,fric} \qquad (2.11)$$

This should be compared with Eq. (2.6), while variation in A_w / S can be seen in Fig. 1.10.

Now, drag at zero lift in subcritical flight can be written as follows;

$$C_{DF} = f / S \qquad (2.12)$$

Where f is a term, called the 'equivalent parasite area of an aircraft: the sum of every of surface area times the $C_{D\,fric}$ of each element. In subcritical flight $C_{D\,fric} \cong C_{DF}$. The $C_{D\,fric}$ of each element depends upon the surface roughness and the degree of turbulence in the boundary layer. The slipstream from propellers increases the C_{DF} of an aircraft by about 33 per cent over that of an equivalent machine powered by turbojets.

Values of $C_{D\,fric}$ vary between different parts of the airframe. Typical values are; 0.003 for the wing, 0.0024 for the fuselage, 0.006 the engine nacelles, 0.0025 the stabilizers, to all of which is added a further 5 per cent for interference. An American formula, which is said to have an accuracy within 3 per cent, calculates f on the basis:

$$f = 1.10 + 0.128\, N_P + 0.007\, S + 0.0021\, N_e (F_e)^{0.7} \qquad (2.13)$$

The number 1.10 repents the area of nose and tail of the fuselage.

Where; Np is number of passengers

S is wing area

N_e is number of engines

F_e is static sea level thrust per engine,

The wetted area of an aircraft is the area of surface exposed to the air. In calculating values of wetted area certain components are blanketed by others. The wing and tail, for example, have not the same gross areas used for calculation of aspect ratio instead the net area lying outside the fuselage and engine nacelles must be used. Similarly, areas of fin, nacelles and fuselage, where wing and tail join to body, must be subtracted from the total area.

The wetted area of a wing is a little more than twice the net area a reasonable estimate is to add about 1/3 of the thickness ratio of the section. A wing with a *t/c* ratio of 12 per cent would have, therefore, a wetted area (2+0.12/3), or 2.04 times the net wing area. The surface area of a body can reasonably be approximated to a gross solid of revolution and the wetted area calculated by multiplying the area in side view by π.

Returning to the condition for $C_{D\,min}$ we see from Eq. (2.6) and Eq. (2.11) that:

$$K (C_L)^2 / \pi A = (A_w / S)\, C_{D\,fric}$$

$$C_L = \sqrt{\left(\pi (b^2/S^2)\, (A_w/K) C_{D\,fric} \right)} \qquad (2.14)$$

We may rewrite the equation as

$$(L/D)_{max} = (\sqrt{\pi}\,) / 2 \sqrt{\left(b^2 / (C_{DF}\, SK) \right)}$$

we may then substitute for $C_{DF}\,S$ by transposing Eq. (2.10) to give:

$$(L / D)_{max} = (\sqrt{\pi}\,) / 2 \sqrt{\left(\{ b^2 / A_w \}\ 1 / (K\, C_{D\,fric}) \right)} \qquad (2.15)$$

The term (b^2/A_w) is the span^2/wetted area, a relative of the aspect ratio, (b^2/S). Some idea of the range of values may be deduced from a consideration of Fig. 1.10. Typical values of $C_{D\,fric}$ vary from 0.002 to 0.003, and taking account of the variation in K for normal planforms is shown in Fig. 2.9 . This shows the importance of wing span in the design of aircraft for high aerodynamic efficiency in the subsonic regime. It also gives some idea of the need for high quality surface finish, and of the likely benefits accruing from the use of boundary layer control. If, as results suggest, the zero-lift drag may be reduced to 1/5 normal values by the use of distributed suction,then Eq. (2.15) shows that $(L/D)_{max}$ might at least be effectively doubled.

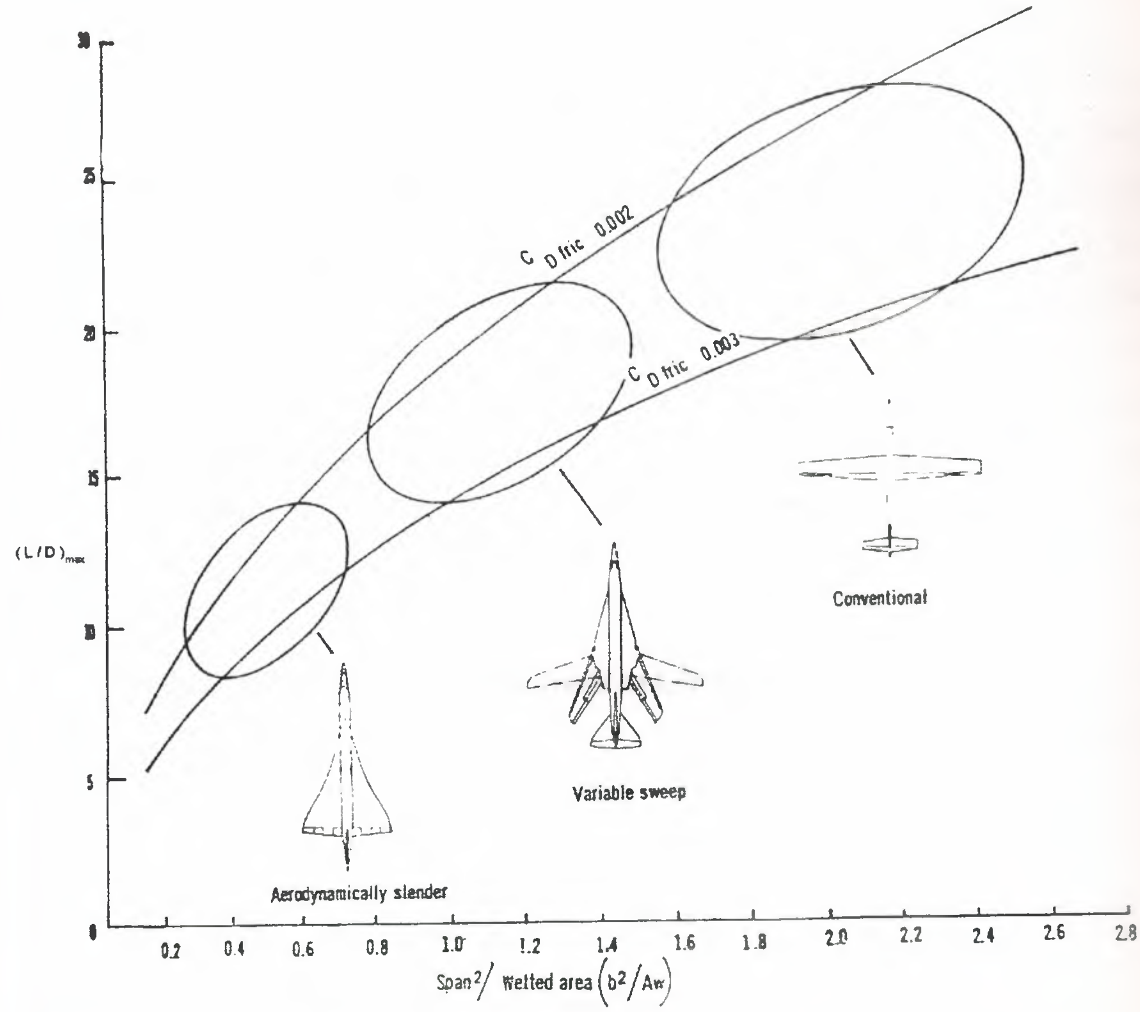


Figure 2.9 Subsonic (subcritical) cruise relationship between span, wetted area and frictional drag coefficient

2.3.3 THE IMPORTANCE OF LOW SPAN LOADING

It was said that once the planform of a wing is fixed the lift dependent vortex drag depends upon span loading not upon aspect ratio for the span loading is a measure of the average pressure difference between the upper and lower surfaces. The lower the span loading, the lower the pressure difference, and the lower the pressure difference the further away is the wing operating from those conditions where separation becomes critical.

The argument can be shown mathematically as follows:

$$D_L = C_{DL}\, qS \qquad (2.3a)$$

Where;

q is the Dynamic Pressure

S is the Wing Area

$$C_{DL} = K(C_L)^2 / \pi A \qquad (2.5)$$

Where;

A is the Aerodynamic aspect ratio

And $$q = ½\, \rho V^2$$

In level flight L = W (Specified applied load) and, from equation

$$C_L = W / qS$$

And, $$qS = W / C_L$$

Therefore; $$D_L = C_{DL} (W / C_L)$$

And, as $$A = b^2 / S$$

Where;

b is the Wing Span

From combining these we may restate that;

$$D_L = K / (\pi\ q) (W / b)^2 \qquad (2.16)$$

Hence, the lift dependent drag at a given speed and height varies as the planform efficiency factor, K and the span loading $(W/b)^2$. It follows that the lift dependent drag changes with the weight of the aeroplane, as long as the planform remains unchanged by variable geometry.

SUMMARY

In this chapter it is observed that no matter how carefully the basic shape of an aeroplane may be combined with variable geometry to maintain high aerodynamic efficiency, there are inevitable local of interference that cause the airflow to break down under certain conditions. Sometimes the effects are small enough to be ignored, or lived with, at other times the effects may be of critical importance. For our purposes we shall divide the fixed modifications to the geometry of the aeroplane into: palliatives, in the main designed to improve airflow over the lifting surfaces; and the design of wing-body junctions. Palliatives, such as vortex generators, may be found extensively around fuselages as well as wings and tails, so one should not think of them as being exclusive to the Lifting surfaces.

In order to control lift and drag and, under certain conditions, to vary both at will beyond the range of values achievable with the basic shape of an aeroplane, we are able to extend the efficiency over a much wider part of the flight envelope. The aerodynamic efficiency is measured in terms of lift/drag, and one of the most important aspects of performance is that an aeroplane should be able to fly as far as possible on a given quantity of fuel.

CHAPTER 3

THE STRUCTURE

Throughout the project there has been built up the picture of an aeroplane as an essentially aerodynamic shape, an envelope of specially shaped airframe surfaces. Within the envelope lie the masses of payload, fuel, engines and equipment. Outside the envelope lies the supporting air. The reaction of the air to the presence of the aeroplane can be resolved into component pressures which, when related to specific areas of airframe surface, serve to express the various forces making up the total lift and drag. The airframe is, therefore, a means of distributing a loading upon the surrounding air. But in making the air do work the airframe must also protect what it contains. Clearly, to do work on the air while serving a protective function the airframe must be strong and stiff, but economically so, in that the weight of structural materials must be no more than is absolutely necessary otherwise the payload and fuel load will be reduced and the economy jeopardized. Much of the art of aircraft design lies in the creation of economical airframe structures. It follows that the structural engineer cannot produce a good structure if he has not been given an accurate distribution of air-loading by the aerodynamicist.

While seeking economy of structural shape the structural engineer must also include a capacity for potential development. Many aircraft have been known to increase in all-up weight by fifty per cent or more during a useful life. A future supersonic transport with a payload of only 4 or 5 per cent could have the payload or range critically reduced by a structure only slightly heavier than it might have been. A unit increase in percentage structure weight can increase the all-up weight by as much as 10 per cent, because of the additional power, fuel load and fuel system requirements needed to carry the additional weight a set distance at a given speed. An increase of 10 per cent in all-up weight can increase the take-off distance by more than 20 per cent, and decrease the ceiling and sea-level rate of climb by 10 per cent. Most airframe structures lie between 20 and 40 per cent of the All-up weight, as shown in Fig. 3.1.

While aiming for structural economy it is also necessary to ensure that skins are reasonably smooth and free from large scale wrinkles, A marked difference from smoothness on the ground with wings unloaded. Smoothness at higher normal accelerations is unimportant because of the transience of such conditions. Smoothness requirements with limitations on steps and waviness measured in thousandths of an inch are almost impossibly hard to achieve on a large scale, although modern methods of manufacture are now reducing the magnitude of the original problem.

Structural design affects the achievable flight envelope, stability and control, the operational role and the development potential of an aeroplane. To understand how such effects come about we must know something of the principles involved

3.1 STRENGTH OF MATERIALS

A wide range of materials is used in the construction of an aeroplane: aluminium alloys, steel, copper wiring, rubber, magnesium, titanium, tungsten and phosphor-bronze, plastics, fabrics, glass, wood, lead. All of the materials have unique mechanical and chemical properties that must be known and used to the best advantage: some materials react electrolytically, for example, certain aluminium alloys and steels and they should not be used in combination. Under some conditions, such as contact with sea-water, the use of certain materials must be considered from the point of view of corrosion. Non-magnetic materials only should be used in the vicinty of magnetic compasses.

The mechanical properties of greatest importance are a high strength/weight, particularly at high temperatures, and high specific stiffness. The strength/weight is sometimes, expressed as the specific strength, the ratio of the ultimate strength in tension, or compression, or shear (depending upon what is required), to the density of the material. The specific stiffness is the ratio of Young's Modulus of Elasticity to the density. The modulus of elasticity is the ratio of the stress to strain within a specified working range of a material. To understand the nature of strength and stiffness we must look at stress and strain and their connection with the elasticity of a material.

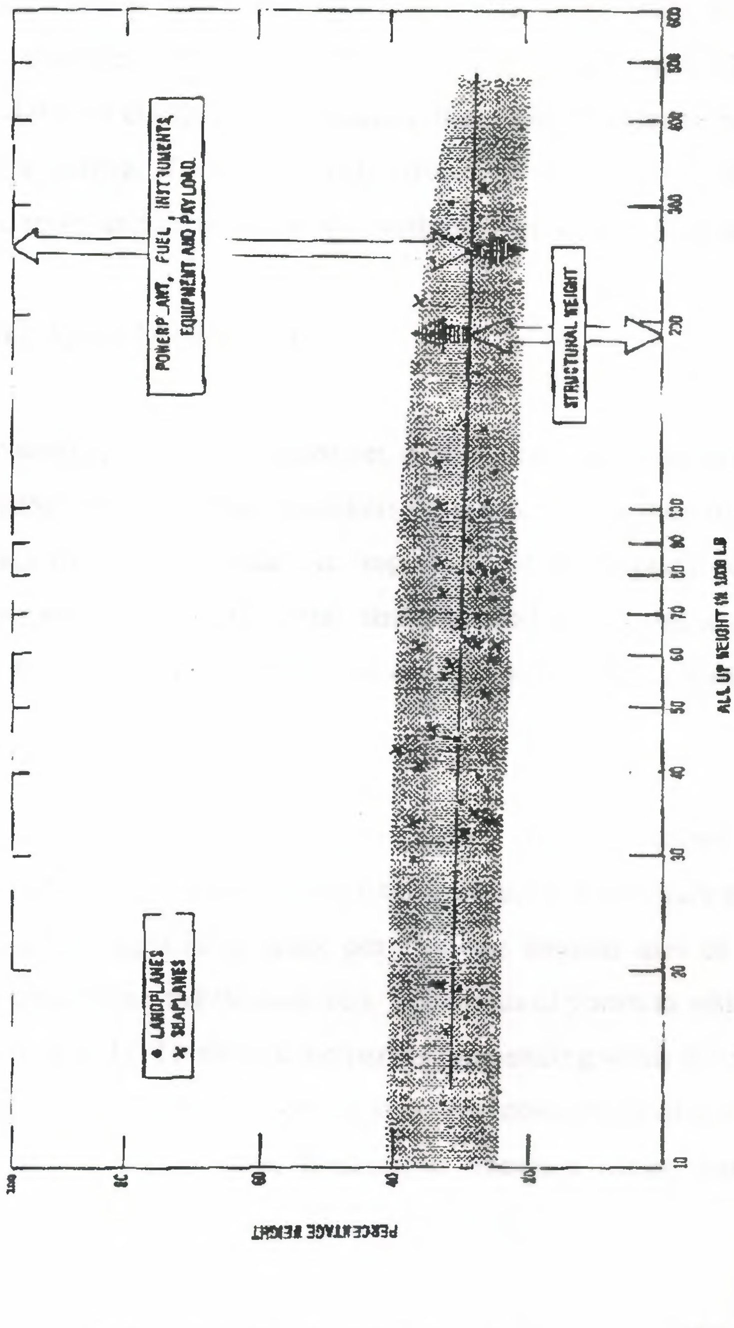


Figure 3.1 Typical structural weights

The mechanical properties of greatest importance are a high strength/weight, particularly at high temperatures, and high specific stiffness. The strength/weight is sometimes, expressed as the specific strength, the ratio of the ultimate strength in tension, or compression, or shear (depending upon what is required), to the density of the material. The specific stiffness is the ratio of Young's Modulus of Elasticity to the density. The modulus of elasticity is the ratio of the stress to strain within a specified working range of a material. To understand the nature of strength and stiffness we must look at stress and strain and their connection with the elasticity of a material.

3.1.1 BENDING AND TORSION

The shape of an aeroplane is such that tension, compression and shear are rarely found in isolation. For economy the various members of a structure must be made to take as much simultaneous stress as possible. An important aid in structural analysis is the Principle of Superposition: that the total strain caused by a load-system may be considered as the sum of the individual strains caused by the various load components, taken in isolation.

The system of stresses applied to the structure of an aeroplane comes mainly from bending and torsion (twisting). The difference between them is that pure bending alone takes place when a load applied at some point on the flexural axis of a member is reacted at another point along the flexural axis. Tthe locus of points at which an applied load produces bending only. Torsion accompanies the bending when either the applied load or its reaction is offset from the flexural axis. The conception of a flexural axis is useful and reasonably accurate when thinking of unswept wings, but it becomes inaccurate though still useful when applied to swept wings.

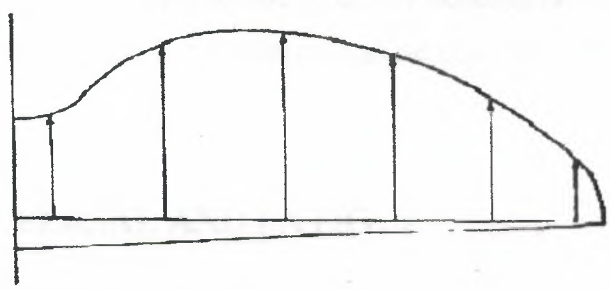
Imagine a beam fixed at one end and supporting a weight at the other. Between the upper and lower surfaces it is possible to define an imaginary neutral axis which, when the end of the beam is bent downwards relative to the root, forms the boundary between the upper fibres that are stretched in tension and those below that are shortened by compression. In a similar way a neutral axis can be drawn in the skin of a pressurized cabin for, as the pressure causes the skin to bulge outwards, on matter how slightly, the outer surface is placed in tension and the inner in compression. Returning to the beam: if the applied load is *W*, then the load exerts a bending moment at any section *X-X* distance *x* from the point of application. The moment is given by;

$$M_x = W_x \qquad (3.4)$$

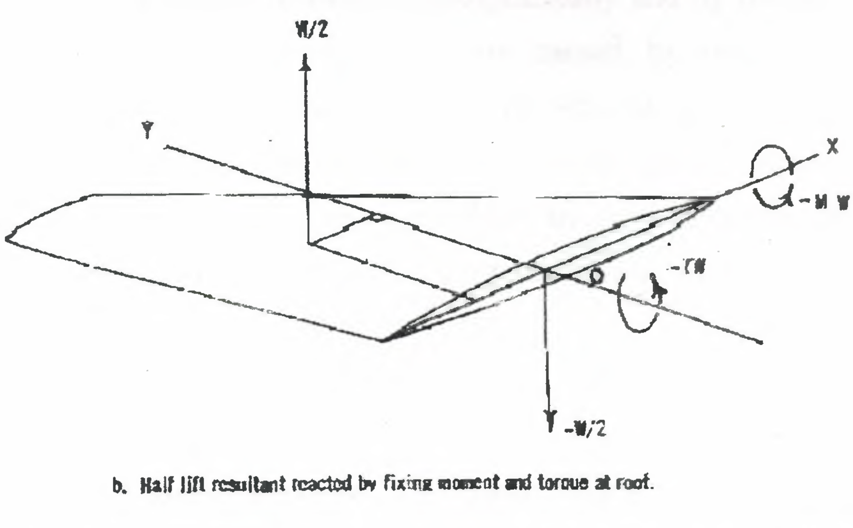
If the beam is such that the load *W* is acting at a distance *L* from the root, then there must be an equal and opposite fixing moment at the root:

$$-M = -(WL) \qquad (3.4a)$$

The bending and fixing moments are not the total values in the example, they only represent the incremental increases due to the addition of some load *W*. The weight of the beam must also be taken into account, as well as any other distributed or point loadings, and it is in this way that the principle of superposition comes to our aid.



a. Lift distribution giving rise to W/2.



b. Half lift resultant reacted by fixing moment and torque at root.

Figure 3.2 Bending moment and torque reactions at a wing root due to lift alone

If, in the example given, the load W was offset some distance y from the flexural axis, then the load would also apply a torque along the length of the beam equivalent to:

$$T = Wy$$

It follows that to fix the beam under these conditions the root must exert an equal and opposite torque $-T$.

These ideas can be applied to the airframe, where they can be visualized in the case of a swept aerofoil surface, Fig 3.2 The lift of the surface, for example a wing, is equal to half the weight of the aeroplane, which acts at the aerodynamic centre for the purposes of calculation (but which really acts at a point downwind of the aerodynamic centre, called the centre of pressure—the difference is irrelevant here). The torque of $+W/2$ about the 0-Y axis is reacted at the root by the torque $-T_w$. The bending is reacted at the root by a fixing moment $-M_w$. To complete the picture a shear reaction $-W/2$ must be added at the wing root.

3.2 STRESS, STRAIN REVERSAL AND FATIGUE

In flight the aerodynamic loading on the airframe is constantly changing and the inertia loading with it. Variations are caused atmospherically and by the pilot through his flying controls, while further variations are caused by pressurization and de-pressurization of the cabins, acoustically by jet effluxes and when taxying on the ground. Fatigue failure, *i.e.*, cracking of members under repeated stresses much lower than the ultimate static tensile stress is exhibited by most metals and their alloys, by some plastics, woods, and other materials that possess some ductility.

It is only recently that a study of the mechanism of fatigue has become possible, with such instruments as the electron microscope. The fatigue characteristics of a material are related to its atomic structure: the atomic lattice. It is impossible to make homogenous materials with perfect lattices and dislocations appear in effect irregularities in the pattern of the atoms that allow certain lines of atoms to move unevenly under the influence of shear stresses. The lines of atoms move in planes, one plane slipping over another. A dislocation causes some planes to slip individually. Eventually a minute portion of material is extruded, squeezed out, along a slip-plane. It is thought that the extrusion leaves behind it the embryo crack. When the crack appears the cross-sectional area of the remaining material is reduced and the stress intensity rises.

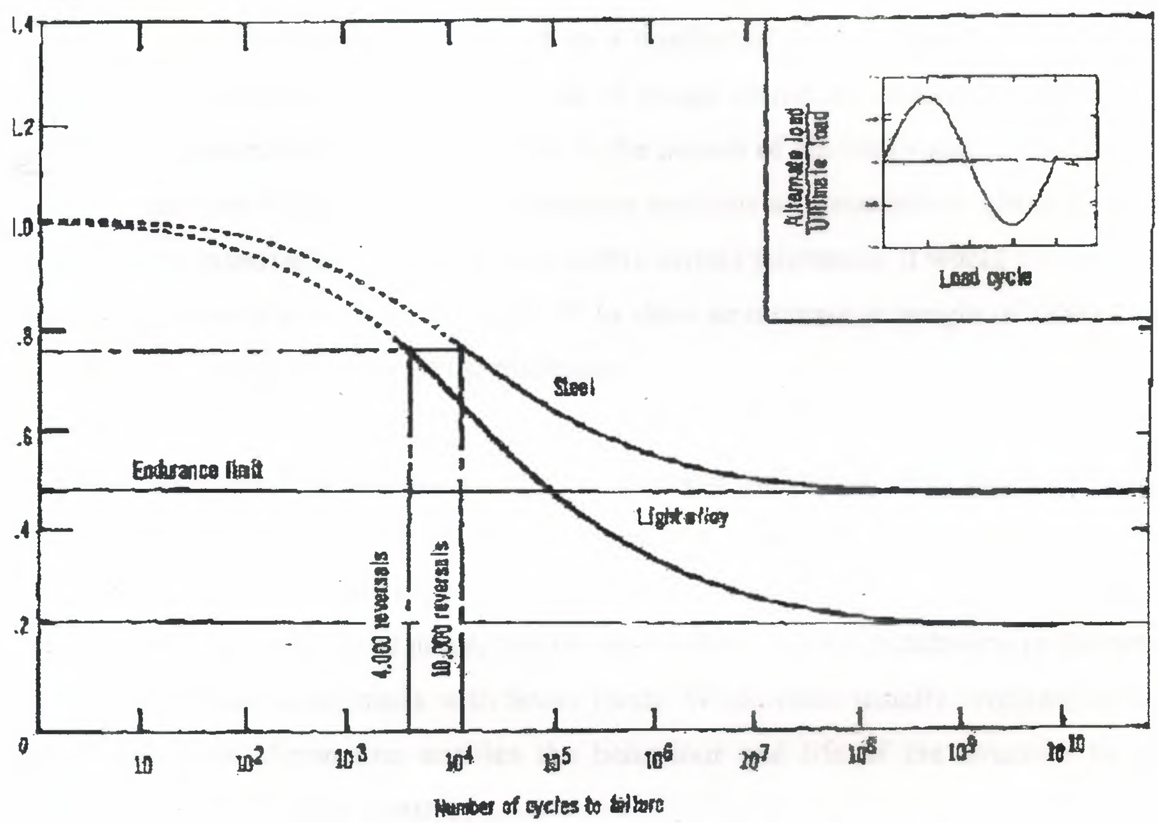


Figure 3.3 Typical S-N fatigue curves for steel and aluminium alloy. Modern 'high duty' aluminium alloys do not exhibit such a marked resistance to fatigue failure as the older, softer, aluminium alloys although they have much higher ultimate strength.

Typical fatigue curves for steel and aluminium alloy are shown in Fig. 3.3. Apparently modern 'high-duty' alloys do not exhibit such a marked resistance to fatigue failure as the older, softer, aluminium alloys although they have much higher ultimate strengths.

3.3 FABRICATION

Early aeroplanes were made of spruce, fabric and piano-wire, and this form of construction is still to be found in some light aeroplanes. Later the welded steel tube framework, fabric covered, became the standard for light aircraft engineering, with plywood sandwiched balsa wood as a good material for light monocoque structures.

Airframes made from strip and sheet metal are riveted, welded, or stuck together with special glues. Sheet metal is provided in a number of standard thicknesses, called gauges, and one uses the next thickness of gauge above the required thickness of material as determined by stress analysis. In the pursuit of efficiency and low weight in large aircraft one must turn to more expensive methods of manufacture. Using gauged sheet, that is manufactured in stock sizes within certain tolerances, it would be possible for an aircraft with a wing area of 2,000 ft^2 to show an increase in weight of 3,000 Ib if the skin was on the high side of the tolerance.

Modern manufacturing techniques involve machine milling of skins and stabilizing members as complete units from solid billets of material. Machining is expensive, but for large, costly, aircraft the expense is worth the dividends. Chemicals are used to etch and dissolve away unwanted metal, and the use of chemicals and machining in this way enables structures to be made with fewer joints. Weaknesses usually originate in the joints and their elimination enables the behaviour and life of the structure to be predicted with far greater accuracy.

New techniques are being introduced in the manufacture of light aeroplanes, and other low subsonic aircraft that have become so long established as to be rated traditional designs. Skins can be made of fibreglass, or plastic sheet sandwiching foam plastic or honeycomb filling. Honeycomb structures in effect corrugated walls forming hexagonal cells, in which the walls run more or less at right angles to the confining skin can be made in both plastic and metallic materials, welded or bonded together. Thin metal skins have been successfully stabilized by bonding foam plastic sheeting on the inside.

SUMMARY

In this chapter the structural design effects the achievable flight envelope, stability and control, the operational role and the development potential of an aeroplane. To understand how such effects come about we must know something of the principles involved. For example the materials used in the construction of an aeroplane, there mechanical and chemical properties. To understand the nature of strength and stiffness we must look at stress and strain and connection with elasticity of a material. The shape of an aircraft is such that tension, compression and shear are rarely found in isolation. For economy the various members of a structure must be made to take such simultaneous stress as possible. An important aid in structural analysis is the principle of superposition.

When in the flight there occurs changes in the airframe and the inertia loading with it this could lead to fatigue failure. It is only recently that a study of the mechanism of fatigue has become possible with such instruments as the electron microscope. Historically the main parts of an aircraft structure are fuselage, wings and tail. Most bodies are built in the same way as a fuselage, most aerofoils surfaces in the same way as wings. The remaining shape of an aeroplane is largely non-structural, in that it consists of fairings, cowlings and fillets. These items are made of shaped skin, stabilizing by stringer and formers. Early aeroplanes were made of spruce, fabric and piano wire and this type of construction is still to be found in some light aeroplanes but now a days new techniques are being introduced in the manufacture of light aeroplane. Skins are made of fiberglass, or plastic sheet sandwiching foam plastic or honeycomb filling.

CHAPTER 4

TYPES OF AIRPLANES

There are a wide variety of types of airplanes. Land planes, carrier-based airplanes, seaplanes, amphibians, vertical takeoff and landing (VTOL), short takeoff and landing (STOL), and space shuttles all take advantage of the same basic technology, but their capabilities and uses make them seem only distantly related.

LAND PLANES

Land planes are designed to operate from a hard surface, typically a paved runway. Some land planes are specially equipped to operate from grass or other unfinished surfaces. A land plane usually has wheels to taxi, take off, and land, although some specialized aircraft operating in the Arctic or Antarctic regions have skis in place of wheels. The wheels are sometimes referred to as the undercarriage, although they are often called, together with the associated brakes, the landing gear. Landing gear may be fixed, as in some general-aviation airplanes, or retractable, usually into the fuselage or wings, as in more-sophisticated airplanes in general and commercial aviation.

CARRIER-BASED AIRCRAFT

Carrier-based airplanes are a specially modified type of land plane designed for takeoff from and landing aboard naval aircraft carriers. Carrier airplanes have a strengthened structure, including their landing gear, to handle the stresses of catapult-assisted takeoff, in which the craft is launched by a steam-driven catapult; and arrested landings, made by using a hook attached to the underside of the aircraft's tail to catch one of four wires strung across the flight deck of the carrier.

SEAPLANES

Seaplanes, sometimes called floatplanes or pontoon planes, are often ordinary land planes modified with floats instead of wheels so they can operate from water. A number of seaplanes have been designed from scratch to operate only from water bases. Such seaplanes have fuselages that resemble and perform like ship hulls. Known as flying boats, they may have small floats attached to their outer wing panels to help steady them at low speeds on the water, but the weight of the airplane is borne by the floating hull.

AMPHIBIANS

Amphibians, like their animal namesakes, operate from both water and land bases. In many cases, an amphibian is a true seaplane, with a boat hull and the addition of specially designed landing gear that can be extended to allow the airplane to taxi right out of the water onto land. Historically, some flying boats were fitted with so-called beaching gear, a system of cradles on wheels positioned under the floating aircraft, which then allowed the aircraft to be rolled onto land.

VERTICAL TAKEOFF AND LANDING AIRPLANES

Vertical Takeoff and Landing (VTOL) airplanes typically use the jet thrust from their engines, pointed down at the Earth, to take off and land straight up and down. After taking off, a VTOL airplane usually transitions to wing-borne flight in order to cover a longer distance or carry a significant load. A helicopter is a type of VTOL aircraft, but there are very few VTOL airplanes. One unique type of VTOL aircraft is the tilt-rotor, which has large, propeller-like rotating wings or rotors driven by jet engines at the wingtips. For takeoff and landing, the engines and rotors are positioned vertically, much like a helicopter. After takeoff, however, the engine/rotor combination tilts forward, and the wing takes on the load of the craft.

The most prominent example of a true VTOL airplane flying today is the AV-8B Harrier II, a military attack plane that uses rotating nozzles attached to its jet engine to direct the engine exhaust in the appropriate direction. Flown in the United States by the

Marine Corps, as well as in Spain, Italy, India, and United Kingdom, where it was originally developed, the Harrier can take off vertically from smaller ships, or it can be flown to operating areas near the ground troops it supports in its ground-attack role.

SHORT TAKEOFF AND LANDING AIRPLANES

Short Takeoff and Landing (STOL) airplanes are designed to be able to function on relatively short runways. Their designs usually employ wings and high-lift devices on the wings optimized for best performance during takeoff and landing, as distinguished from an airplane that has a wing optimized for high-speed cruise at high altitude. STOL airplanes are usually cargo airplanes, although some serve in a passenger-carrying capacity as well.

SPACE SHUTTLE

The space shuttle, flown by the National Aeronautics and Space Administration (NASA), is an aircraft unlike any other because it flies as a fixed-wing airplane within the atmosphere and as a spacecraft outside Earth's atmosphere. When the space shuttle takes off, it flies like a rocket with wings, relying on the 3,175 metric tons of thrust generated by its solid-fuel rocket boosters and liquid-fueled main engines to power its way up, through, and out of the atmosphere. During landing, the shuttle becomes the world's most sophisticated glider, landing without propulsion.

4.1 THREE DIMENSIONAL WING

Wings designed to operate at high speeds are generally thin and employ sweepback in order to increase the critical Mach number. In some instances the sweep is variable to accommodate operation at both low and high speeds. Many airplanes for which the primary mission involves supersonic flight employ delta planforms. Figure 4.1 illustrates various types of planforms utilized on high-speed airplanes. The swept wing is common to all subsonic jet transports and to subsonic military airplanes. It is also used on supersonic airplanes but with much lower aspect ratios than are found on subsonic transports. The delta wing and the swing-wing, or variable-sweep, are employed primarily on supersonic airplanes. The best known airplane that uses the ogee planform is the Concorde, the only operational supersonic transport. For subsonic applications, these configurations incur both aerodynamic, weight, and cost penalties.

Table 4.2 lists a number of airplanes selected from the 1991-92 issue of Reference for which the sweepback and operating Mach number could be obtained. There are generally four types of airplanes included in the table: high subsonic airplanes with swept wings, supersonic airplanes with swept wings, supersonic airplanes with variable sweep, and supersonic airplanes with delta wings. This data is graphed in Figure 4.2, which presents the Mach number normal to the leading edge as a function of the free-stream Mach number. Admittedly, the sample is small, but it is interesting to observe that all of the high-subsonic airplanes designed to operate at around Mach number 0.8-0.9 employ sweepback, which reduces the normal Mach number to approximately 0.7. It is also interesting to note that the design normal Mach number increases progressively in going from swing-wings to delta wings to fixed-swept wings.

The sweep angles for the fixed-swept airplanes are probably a compromise between supersonic and subsonic flight. For landing, swing-wings are brought forward to a point where there is practically no sweep. In high-speed flight, the wings can be swept back to an angle that provides subsonic flow normal to the leading edge.

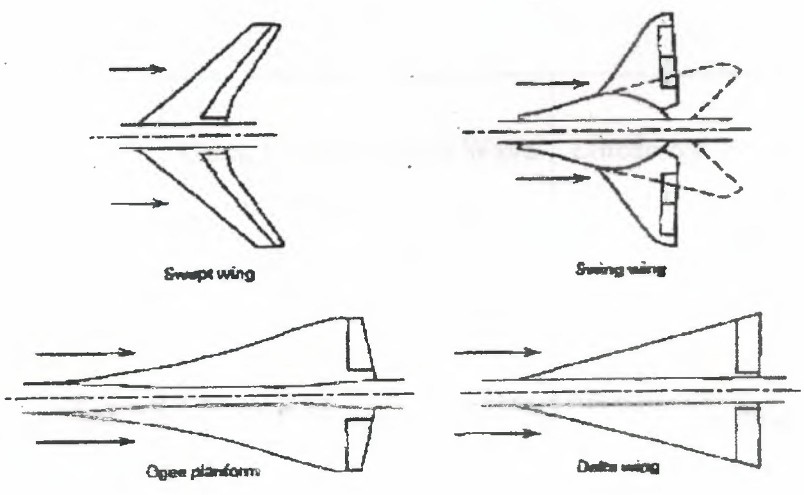


Figure 4.1 Types of swept planform shapes to operate at high Mach numbers.

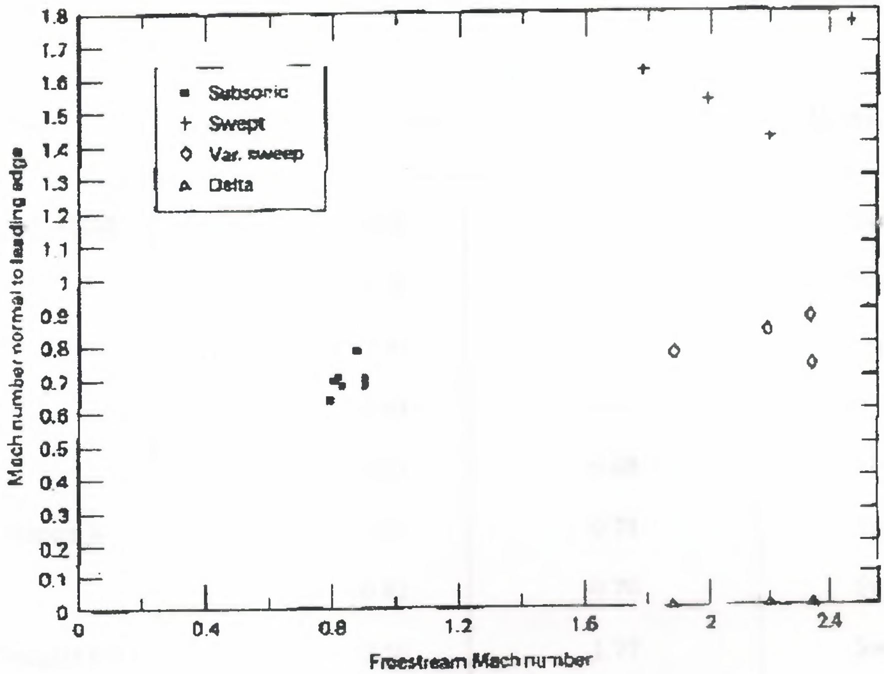


Figure 4.2 Mach number normal to leading edge as related to free-stream Mach number

TABLE 4.1

Predicted Characteristics of a Symmetrical, 10% thick, Double Wedge Airfoil at a 2° Angle of Attack and a Mach Number 2.0

	Using Oblique Shock Wave and Prandtl-Meyer Relationships	Linearized Ackeret Theory
C_l	0.0830	0.0806
C_{dw}	0.0260	0.0259
C_m	-0.0364	-0.0403
Center of Pressure	0.4386	0.5000

TABLE 4.2 CHARACTERISITICS OF SWEPT WINGS AIRPLANES

Airplane	Sweep	Mach No.	Mach No. Normal to Leading Edge	Wing Type
British Aerospace Hawk	26.00	0.88	0.79	Swept
Boeing E-6a	36.00	0.79	0.64	Swept
Boeing 747	41.00	0.90	0.68	Swept
Boeing 757	30.00	0.80	0.69	Swept
Boeing 777	35.00	0.83	0.68	Swept
Cessna 750 Citation X	38.00	0.90	0.71	Swept
Airbus A300	31.00	0.82	0.70	Swept
McDonnell-Douglas F-15	45.00	2.50	1.77	Swept
McDonnell-Douglas F-18	26.00	1.80+	1.62	Swept
Dassault Mirage F1	50.00	2.20	1.41	Swept
GD F-16	40.00	2.00	1.53	Swept
MiG-23	72.00	2.35	0.73	Variable Sweep
Tupolev TU-160	66.00	1.88	0.76	Variable Sweep
Panavia Tornado	68.00	2.20	0.82	Variable Sweep
Grumman F-14A	68.00	2.34	0.88	Variable Sweep
Dassault Mirage 2000 N	60.00	2.20	1.10	Delta
Dassault Rafale C	47.00	2.00 E	1.36	Delta canard
Eurofighter EFA	52.00	1.80 +	1.11	Delta canard

E = estimated
\+ means M in excess of number

4.2 LOCKHEED F-117 A STEALTH FIGHTER Vs F-22 ADVANCED TACTICAL FIGHTER

Figure 4.3 and Figure 4.4 present two modern aircraft, which were designed not simply to satisfy aerodynamic performance requirements but stealth requirements as well. The specifics of each aircraft's performance are classified, but generally, it can be said that the Lockheed F-117A is designed to operate at high subsonic speeds, whereas the F-22 is supersonic. The sweepback of the F-117A is approximately 67° whereas the F-22, with a modified diamond planform, has a sweepback of 42°. This was decreased from the YF-22A prototype value of 48°, was done to improve aerodynamic performance.

Figure 4.3 Lockheed F-117A stealth fighter.

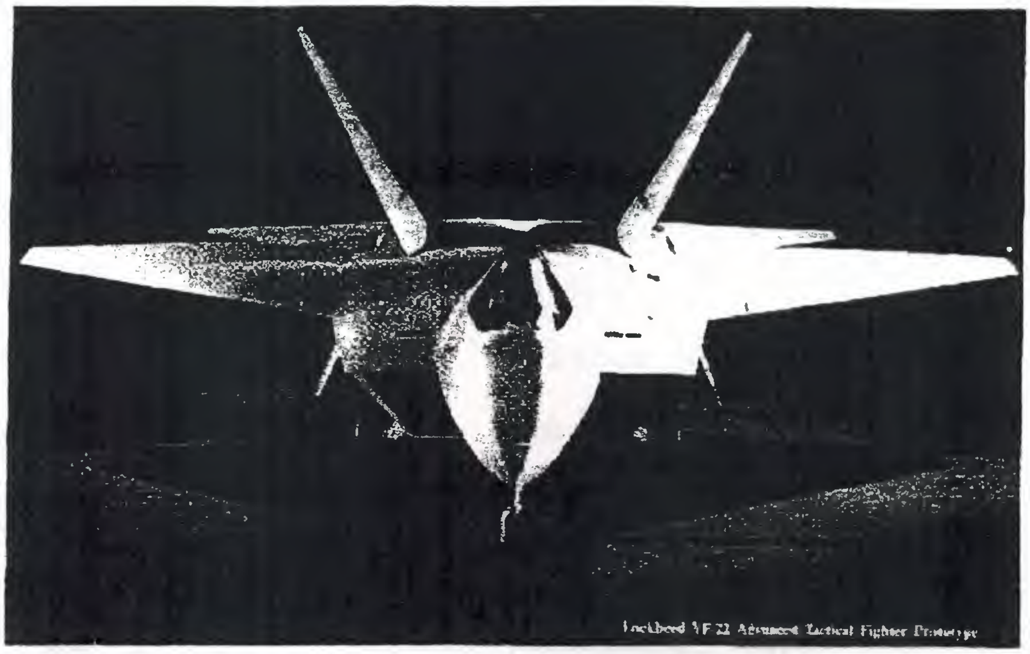


Figure 4.4 YF-22A and F-22 advanced tactical fighter.

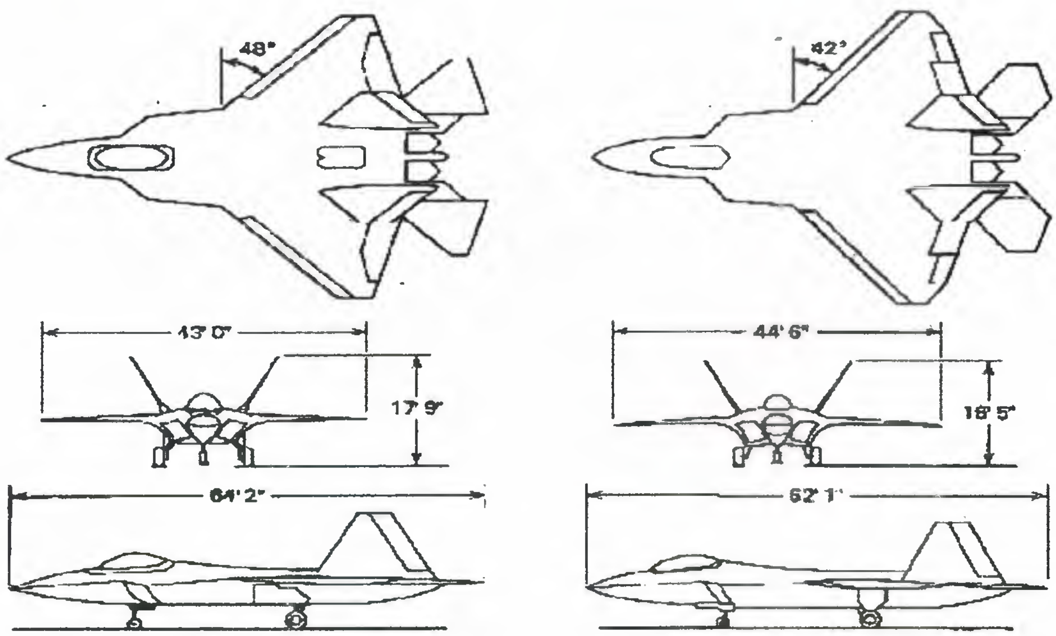


Figure 4.5:- YF-22A and F-22 advanced tactical fighter (Three-view stectch)

TABLE 4.3 AIRPLANE DATA FOR LOCKHEED F-117-A STEALTH FIGHTER

Length:	65 ft 11 in
Wing span	43 ft 4 in
Wing sweep	67 deg
Wing area	1140 ft^2
Height	12 ft 5 in
Vertical tail sweep	20 deg
Weight empty	29,500 lb
Max. gross weight	52,500 lb
Max. speed	0.9 Mach @ 35,000 ft
Max alt.	52,000 ft
Max range	1250 mi / internal fuel
Powerplant (two)	GE F404-GE-FID2 (10,800 lb T class)
T.O. speed at combat weight	165 kt
Ldg. Speed at combat weight	150 kt

TABLE 4.4 AIRPLANE DATA FOR F-22 ADVANCED TACTICAL FIGHTER

Length	62 ft 1 in
Span	44 ft 6 in
Height	17 ft 9 in
Wing sweep	42 deg
Max. speed	>M = 2
Wing area	830 ft^2
Weight emplty	30,000 lb (est)
Max T.O. weight	58,000 lb
Max. level speed	M = 1.58 (supersonic) (demonstrated)
	M = 1.7 @ 30,000 ft after burning
Absolute ceiling	50,000 ft
Max level speed at SL	800 kt (target)

The F-22 is not yet fully operational, although the prototype has undergone extensive flight testing, which apparently has met or exceeded predictions. The F-117A, which played a major role in the Persian Gulf War, was developed and flew in only 31 months under the strictest security, flying for almost 8 y before its existence became public. The F-117A is an unusual design with its exterior being composed of flat panels, not exactly what the aerodynamicist would desire. Their purpose is, of course, to reflect radar signals away from, and not return them to, the radar that is transmitting the signals.

The aerodynamic design of the F-22, while still a stealth aircraft, is certainly more pleasing to the aerodynamicist. Some of the key aerodynamic elements in its design as shown in Figure 4.5 are listed as follows;

- Blended wing-body with internal weapons bays and sufficient fuel volume for meeting long endurance missions
- Modified diamond wing with a wing span compatible with existing aircraft shelters.
- Constant chord, full leading edge flaps
- Two-dimensional, convergent-divergent exhaust nozzles with independent throat and exit area actuation and pitch axis thrust vectoring.
- Free-stream fixed geometry supersonic inlets with swept cowl lips, boundary layer bleed and overboard bypass systems, and a relatively long subsonic dif-fuser having 100% line-of-sight RF blockage.
- All exterior edge angles aligned with either the wing leading or trailing edge angles.

4.3 EFFECT OF MACH NUMBER ON THE ZERO LIFT DRAG OF TWO AND THREE DIMENSIONAL SHAPES

In subsonic flow, the drag of nonlifting shapes is relatively unaffected by Mach number until a critical value is reached. Below M_{cr}, the drag, excluding that due to lift, results from skin friction and the unbalance of normal pressures integrated around the body. The estimation of this drag has been covered in some detail in the preceding chapter. As shown in Figure 4.6 As the Mach number is increased, a value is reached where local shock waves of sufficient strength to produce separation are generated. At this point, the drag coefficient begins to rise. As the Mach number continues to increase, C_D will increase through the transonic flow region until supersonic flow is established. Depending on the particular shape, the rate of increase of C_D with M diminishes. C_D

may continue to increase with M, but a lower rate, it can remain fairly constant, or it can actually decrease with increasing Mach number. The behaviour of C_D in the supersonic flow regime depends on the composition of the drag. Excluding the drag caused by lift, the remainder of the drag is composed of skin friction drag, wave drag and base drag.

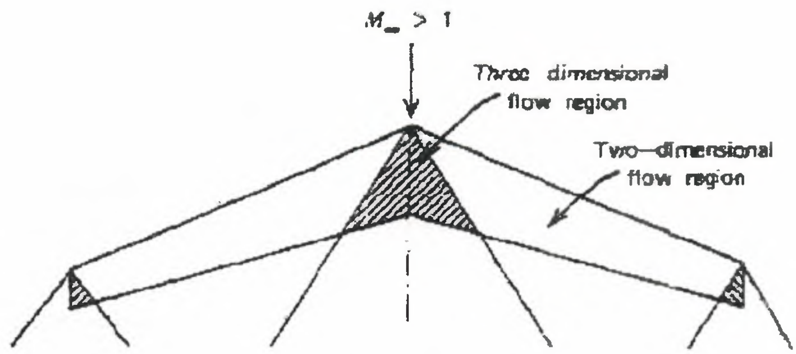


Figure 4.6 Supersonic wing over which the flow is mostly two dimensional.

4.4 COMPUTE PROGRAME (FORTRAN LANGUAGE)

```
C     This program computes the spanwise lift distribution and
C     induced drag of planar wings using a discrete vortex
C     representation of the wake and a concentrated bound vortex.
C     Lift and Cl distributions are written to the file Wing.dat.
C
C
C
C
C     Declarations
C     ------------

      implicit none

      real SWEEP, TAPER, AR, BETA, CL, CD, Cm, MACH, LSUM, MSUM, DSUM
      real TANSW, SECEFF, COSEFF, SINEFF, CROOT, WIDTH, X, RN, RT, RNI
      real RTI, RY, RX, RYI, WT, WTI, R0, R1, R0I, R1I, WB, WBI,
WSHOUT
      real ALPHA, W, R, RIMAGE, BARL, PI, D2R, BETAI, E, CLSEC, SECLFT
      integer NPANEL, i, j, j1, NOW, MAXPAN

      parameter (MAXPAN = 300)

      REAL Y(MAXPAN), K(MAXPAN,MAXPAN), CHORD(MAXPAN), B(MAXPAN)
      REAL L(MAXPAN), SECL(MAXPAN), X0(MAXPAN), VB(MAXPAN)
      INTEGER IP(MAXPAN), READUNIT, WRITEUNIT

      PARAMETER (READUNIT = 5,  WRITEUNIT = 6)


C     Input parameters
C     ----------------
C
      WRITE(WRITEUNIT,*)'                    Planar Wing Analysis
Program'
1     WRITE(WRITEUNIT,101)
101   FORMAT(' ',/,/,/,/,/)

      WRITE(WRITEUNIT,*) ' Wing Sweep (deg): '
      READ(READUNIT,*) SWEEP
```

```
      WRITE(WRITEUNIT,*)  ' Taper:'
      READ(READUNIT,*) TAPER
      WRITE(WRITEUNIT,*)  ' Aspect Ratio:'
      READ(READUNIT,*) AR
      WRITE(WRITEUNIT,*)  ' Number of panels (10-40):'
      READ(READUNIT,*) NPANEL
      WRITE(WRITEUNIT,*)  ' Mach Number (< 1):'
      READ(READUNIT,*) MACH

      WRITE(WRITEUNIT,'(/,A,/)')' Computing...'

C     Calculations
C     ------------
      BETA=SQRT(1.-MACH**2)
      BETAI=1./BETA
      PI=3.14159
      D2R=PI/180.
      SWEEP=SWEEP*D2R
      TANSW=TAN(SWEEP)
      SECEFF=SQRT((TANSW/BETA)**2+1.)
      COSEFF=1./SECEFF
      SINEFF=TANSW/BETA*COSEFF
C
C     The horseshoe vortices are evenly spaced along the semispan.
C     Chord and twist distributions are linear. All lengths are in
C     units of the semi-span.
C
        CROOT=4./(AR*(1.+TAPER))
        WIDTH=1./NPANEL
        DO 10 I = 1,NPANEL
           VB(I)=REAL(I)/NPANEL
           L(I)=VB(I)*SECEFF
10      CONTINUE
        VB(NPANEL)=1.-.25*WIDTH
        L(NPANEL)=VB(NPANEL)*SECEFF
C
C-----------------------------------------------------------------------
--
C       Computing influence coefficients
C
        Y(1)=VB(1)*.5
```

```
      DO 30 I=1,NPANEL
        IF (I.NE.1) Y(I)=(VB(I)+VB(I-1))*.5
        CHORD(I)=CROOT*(1.-Y(I)*(1.-TAPER))
        X=(Y(I)*TANSW+CHORD(I)*.5)*BETAI
        RN=X*COSEFF-Y(I)*SINEFF
        RT=X*SINEFF+Y(I)*COSEFF
        RNI=RN+2.*Y(I)*SINEFF
        RTI=RT-2.*Y(I)*COSEFF
        R0=SQRT(RN*RN+RT*RT)
        R0I=SQRT(RNI*RNI+RTI*RTI)

C       Loop over vortices
C       WB = downwash due to bound vortex
C       WT = downwash due to trailing vorticity
C       I after the variable designates image (left side) influence
C
        DO 20 J=1,NPANEL
          RY=VB(J)-Y(I)
          RX=X-VB(J)*TANSW*BETAI
          RYI=RY+2.*Y(I)
          WT=(1.+RX/SQRT(RX*RX+RY*RY))/RY
          WTI=(1.+RX/SQRT(RX*RX+RYI*RYI))/RYI
          R1=SQRT(RN*RN+(L(J)-RT)**2)
          WB=((L(J)-RT)/R1+RT/R0)/RN
          R1I=SQRT(RNI*RNI+(L(J)-RTI)**2)
          WBI=((L(J)-RTI)/R1I+RTI/R0I)/RNI
          K(I,J)=(WT+WB+WTI+WBI)/(4.*PI)
20      CONTINUE
30    CONTINUE
C
C


C-----------------------------------------------------------------------
--
C       L-U Decomposition of the linear system
      CALL DECOMP(NPANEL,MAXPAN,K,IP)
C-----------------------------------------------------------------------
--
C
C     Construction of tangency condition
```

```
35    WRITE(WRITEUNIT,*)' '
      WRITE(WRITEUNIT,*) ' Tip Washout:'
      READ(READUNIT,*) WSHOUT
      WRITE(WRITEUNIT,*) ' Angle of Attack:'
      READ(READUNIT,*) ALPHA
      DO 40 I=1,NPANEL
          B(I) = (ALPHA - WSHOUT*Y(I))*D2R
40    CONTINUE
C
C-----------------------------------------------------------------------
--
C       Back substitution for solution to system
        CALL SOLVE(NPANEL,MAXPAN,K,B,IP)
C-----------------------------------------------------------------------
--
C       Computing drag and section loading
C
        DO 50 I=1,NPANEL
           LSUM=0
           DO 48 J=1,NPANEL+1-I
              J1=NPANEL+1-J
              LSUM=LSUM+B(J1)
48         CONTINUE
           SECL(I)=2.*LSUM
50      CONTINUE

C       Integrations for CL,Cm,CD
        LSUM=0
        MSUM=0
        DSUM=0
        DO 60 I=1,NPANEL
           W=0
           DO 55 J=1,NPANEL
C             The downwash produced by trailing vorticity is:
              R=(VB(J)-Y(I))*4.*PI
              RIMAGE=(VB(J)+Y(I))*4.*PI
              W=W+B(J)*(1./R+1./RIMAGE)
55         CONTINUE
           BARL=SECL(I)
           LSUM=LSUM+BARL*WIDTH
           MSUM=MSUM-BARL*WIDTH*Y(I)*TANSW
```

```
         DSUM=DSUM+BARL*WIDTH*W
60      CONTINUE

        CD=DSUM*AR*.5
        CL=LSUM*AR*.5
        CM=MSUM*AR*AR*.25
        E = 0.
        IF(CD.NE.0.)E=CL*CL/(PI*AR*CD)

C----------------------------------------------------------------------
--
C     Output routine and menu
C     -----------------------
C
900   WRITE(WRITEUNIT,115)
115   FORMAT(/,/,
     >          ' Integrate for CL,CM,CD......(1)'/
     >          ' Display CL*C, CL(Y).........(2)'/
     >          ' Specify new alpha or twist..(3)'/
     >          ' Start all over..............(4)'/
     >          ' Quit........................(5)')
      READ(READUNIT,*)NOW
      IF(NOW.EQ.1)GOTO 901
      IF(NOW.EQ.2)GOTO 902
      IF(NOW.EQ.3)GOTO 35
      IF(NOW.EQ.4)GOTO 1
      IF(NOW.EQ.5)STOP
C
901    WRITE(WRITEUNIT,113)CD,E,CL,CM
113    FORMAT(/,/,
     >        ' CD =                    'F8.5,/,
     >        ' e (inviscid) =          'F8.5,/,
     >        ' CL =                    'F8.5,/,
     >        ' Cm (about root c/4) =   'F8.5)
       GOTO 900

902   OPEN(UNIT=23,FILE='Wing.dat',STATUS='NEW')
      WRITE(23,905)
905   FORMAT('Title:Wing Lift Distribution'/
     > 'xlabel:Spanwise Station'/
     > 'ylabel:Cl and Cl*c/cavg'/)
```

```
      WRITE(23,*)'head:y    Cl*c         Cl'
      WRITE(WRITEUNIT,*)'     2y/b  Cl*c/cavg    Cl'

       DO 903 I=1,NPANEL
          CLSEC=SECL(I)/CHORD(I)
          SECLFT=SECL(I)*AR*.5
          WRITE(23,112)Y(I),SECLFT,CLSEC
          WRITE(9,112)Y(I),SECLFT,CLSEC
112       FORMAT(3(2X,F6.3))
903    CONTINUE
       CLOSE (UNIT=23)

       GOTO 900
       END
```

SUMMARY

In this chapter it is observed that there are three regimes of flow around an airfoil. In the first, the flow is everywhere subsonic with relative high Mach number. The second regime is referred to as transonic flow. Here the free stream Mach number is less than unity, but sufficiently high so that the flow locally, as it accelerates over the airfoil, that is the flow becomes supersonic. The lowest free-stream Mach number at which the local flow at some points on the airfoil becomes supersonic is known as critical Mach number.

Wings designed to operate at high speeds are generally thin and employ sweepback in order to increase the critical Mach number. Many airplanes for which the primary mission involves supersonic flight employ delta planforms. The sweep angles for the fixed swept airplanes are probably a compromise between supersonic and subsonic flight.

A comparison could be seen in between the state of art aircraft technology in between the F-117 A and F-22 Advanced tactical fighter. As one operates at high subsonic speeds and the other operates at supersonic. We have seen F-117 A's work in the Persian Gulf War as this aircraft does not appears on the radars. But as it is a subsonic type it does not considered best for low altitude operations, Where comes F-22 with its diamond planform and sweepback of 42° and speed > M = 2. Mainly just not in these two, any aircraft we see once in air needs a control of lift and drag the two aerodynamic forces on which the whole aircraft depends on. The desired shape given to a aircraft is not the final shape it must satisfy all its aerodynamic conditions.

CONCLUSION

The design analysis made through out the project resulted in an ultimate fact that an airplane flies because its wings create lift as they interact with the flow of air around them. Lift is one of the four primary forces acting upon an airplane. The others are weight, thrust, and drag. Weight is the force that offsets lift, because it acts in the opposite direction. The weight of the airplane must be overcome by the lift produced by the wings. If an airplane weighs 4.5 tons, then the lift produced by its wings must be greater than 4.5 tons in order for the airplane to leave the ground. Designing a wing that is powerful enough to lift an airplane off the ground, and yet efficient enough to fly at high speeds over extremely long distances, is one of the marvels of modern aircraft technology. Thrust is the force that propels an airplane forward through the air. The airplane's propulsion system; either a propeller or jet engine or combination of the two provides it. A fourth force acting on all airplanes is drag. Drag is created because any object moving through a fluid, such as an airplane through air, produces friction as it interacts with that fluid and because it must move the fluid out of its way to do its work. Managing the balance between these four forces is the challenge of flight. When thrust is greater than drag, an airplane will accelerate, when lift is greater than weight, it will climb. An airplane traveling at less than Mach 1 is traveling below the speed of sound (subsonic). At Mach 1, an airplane is traveling at the speed of sound (transonic). At Mach 2, an airplane is traveling at twice the speed of sound (supersonic flight). Speeds of Mach 1 to 5 are referred to as supersonic. Speeds of Mach 5 and above are called hypersonic.

In Chapter 1, I mainly discussed the generation of the aerodynamic forces and the fact that once an aircraft of a given size is specified, and the design point settled, their arises the particular problem of determining the shape of an airplane. I concluded that the optimum shape of an aircraft is not the pure shape to satisfy conditions at the design point, for aircraft must be flexible enough to operate safely and with reasonable economy off-design. The basic shape in its purest form, Changes of the basic shape in flight to improve off-design performance, fixed modifications of the basic shape to improve local airflows.

Along with the information I achieved I supported my project with a fact for the design analysis of an optimum shape of an airplane when range flying, which is discussed in Chapter 2. Though the optimum shape has many design considerations but I analyzed only those, which are necessary for the shape of an airplane when it is flying in air. Such as the aspect ratio, which I found to be between 10 to 2 for different type of airplanes when range flying. The wetted area of a wing is a little more than twice the net area. A wing with a *t/c* ratio of 12 per cent would have, therefore, a wetted area (2+0.12/3), or 2.04 times the net wing area.

In Chapter 3, I concluded a fact, that in designing it is very important to find the right type of materials used in the construction of an aeroplane, their mechanical and chemical properties. To understand the nature of strength and stiffness we must look at stress and strain and connection with elasticity of a material. The shape of an aircraft is such that tension, compression and shear are rarely found in isolation. For economy the various members of a structure must be made to take such simultaneous stress as possible. But now a days in this modern age there is no need for going in complex calculations to solve the designing points of an airplane. There are readymade aircraft designing software which calculates all the aspects of the shape of an airplane and desire changes needed to be made in order to satisfy design points. One example of computer program written in basic language is shown in the project.

In Chapter 4, A comparison of F117-A Stealth Fighter and F-22 Advanced tactical fighter, the two latest aircraft is shown in the project in order to understand the design concept more clearly. Each is made for a different mission. As one travels at subsonic speed where as other travels at supersonic and both are military tactical fighter aircrafts. But where does the difference come, As F117-A is a subsonic aircraft it performs very well in high altitude missions because of its specification and the F-22 since of its supersonic behavior and variable wing geometry it is considered well for low altitude missions. Such as air combats, close destruction etc. Once an aircraft is in air in order to control it we must be able to control lift and drag values of an aircraft. The whole project describes this concept. The designs which are made and observed in this project in order to determine the shape of an aircraft are with respect to lift and drag ratios when airplane is in air.

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AERODYNAMICS GENERAL TERMS AND DEFINATIONS

Aerodynamic Center

The aerodynamic center is a point along the airfoil or wing about which the moment coefficient does not vary with an angle of attack change.

Airfoil

An airfoil is the cross section of a wing. The airfoil shape and variations in angle of attack are primarily responsible for the lift and profile drag of the wing.

Angle of Attack

The angle of attack is defined as the angle between the plane of the wing (airfoil chord) and the direction of motion (free stream velocity). The angle of attack can be varied to increase or decrease the lift acting on the wing. An increase in lift often results in an increase in drag.

Center of Pressure

A point along the airfoil about which the moment due to the lift is zero, i.e., it is the point of action of the lift. The center of pressure will change its position when the angle of attack changes.

Chord

The chord is the dimension of the airfoil from its leading edge to trailing edge.

Circulation

Circulation is a measure of the vorticity in the flow field. For an inviscid flow field, the lift is equal to the product of the circulation about the airfoil, the density and the velocity.

Computational Fluid Dynamics (CFD)

Computational fluid dynamics is the term given to a variety of numerical mathematical techniques applied to solving the equations the govern fluid flows and aerodynamics.

Density

The mass of a substance contained in a given volume divided by the volume. For a incompressible fluid, the density is considered to be constant throughout the flow field. However, for a compressible fluid, the density can vary from one location to the next in the flow field. The speed of sound in a fluid depends on the ratio of pressure changes to density changes in the fluid.

Drag

Drag is an aerodynamic force opposing the direction of motion. Drag can be due to surface viscosity (friction drag), pressure differences due to the shape of an object (form drag), lift acting on an finite wing (induced drag) and other energy loss mechanisms in the flow such as wave drag due to shock waves and inefficiencies in engines.

Drag Coefficient

The drag coefficient is defined as the drag/(dynamic pressure * reference area). The reference area is usually the plan-form or flat projection (the wing's shadow at noon) area of the wing.

Dynamic Pressure

The dynamic pressure is defied as the product of the density and the square of the velocity divided by two. The dynamic pressure has units of pressure, i.e. Force/Area. The dynamic pressure is used to non-dimensionalize forces and pressures in aerodynamics.

Flap Deflection Angle

The flap deflection angle is the angle between the deflected flap and the chord line. The angle is positive for a downwards deflection of the flap. Deflect the flap downwards to increase the airfoil's lift.

Lift

The lift is a force acting perpendicular to the direction of flight. The lift is equal to the fluid density multiplied by the circulation about the airfoil and the free stream velocity. In level flight, the lift developed by an airplane's must be equal to the weight of the entire airplane.

Lift Coefficient

The lift coefficient is defined as the lift/(dynamic pressure * reference area). The reference area is usually the plan-form area of a wing or horizontal projection of the wing.

Mean aerodynamic chord

This chord is located along the wing and has the aerodynamic property of the two-dimensional wing.

Panel Method

This numerical method places singularities along the airfoil. In the case of VisualFoil, the singularities are vortices. The vorticity is distributed linearly along the panel.

Plain Flap

A plain flap is a hinge attachment near the trailing edge of an airfoil. The length of the flap is measured as a percentage of the chord and the deflection is measured in degrees.

Pressure Coefficient

The pressure coefficient is a non-dimensional form of the pressure. It is defined as the difference of the free stream and local static pressures all divided by the dynamic pressure.

Stall

At low angles of attack, the lift developed by an airfoil or wing will increase with an increase in angle of attack. However, there is a maximum angle of attack after which the lift will decrease instead of increase with increasing angle of attack. This is know as stall. Knowing the stall angle of attack is extremely important for predicting the minimum landing and takeoff speeds of an airplane.

Streamlines

Contours in the flow field that are tangent to the velocity vector.

Wing Loading

The total weight of the airplane divided by the planform area of the wing.

Wing Span

The span is the total length of the wing.