PRINCIPLES OF FLIGHT

BY SAEED KAZEMIZAD (KAZ)

AIRFRAMES.

The **airframe** comprises the main structural elements of the aircraft which support the loads to which the aircraft is subjected in the air and on the ground. The principal components of the airframe are the **fuselage**, the **wings**, the **tail assembly** and the **flying controls**. In this chapter we look not only at the **airframe**, but also at the loads applied to the airframe, the aircraft **emergency equipment** and certain **safety checks** and **emergency drills**.

FUSELAGE.

The **fuselage** is the main structure or body of the aircraft *(see Figure 1.1)*. It carries the **passengers** and **crew** in safe, comfortable conditions.

The **fuselage** also provides space for **controls**, **accessories** and other equipment. It transfers loads to and from the **mainplanes** or **wings**, the **tailplane**, **fin, landing gear** and, in certain configurations, the **engines**.

Figure 1.1 Fuselage.

There are three main types of **fuselage** construction. First there is the **truss** or **framework** type *(see Figure 1.2)* which is generally used for light, non-pressurised, aircraft. Then there is **monocoque** construction, which was mostly used during the early twentieth century. Finally, there is the **semi-monocoque fuselage** *(see Figure 1.4)* which is in use on most aircraft other than non-pressurised aircraft. The latter two types of structure - **monocoque** and **semi-monocoque -** are more generally referred to as **stressed skin constructions**.

Truss or Framework Construction.

When **truss** or **framework construction** is used for the fuselage, the framework consists of light steel tubes of minimal wall thickness which are welded together to form a space frame of triangular shape. This gives the most rigid of geometric forms. Each tube carries a specific load, the magnitude of which depends on whether the aircraft is airborne or on the ground. This type of fabrication is strong, easily constructed and gives a relatively trouble free basic arrangement. The framework is normally covered by a lightweight aluminium alloy or fabric skin to form an enclosed, aerodynamically efficient load carrying compartment. Examples of aircraft using this construction are the Auster J6 and Piper Cub.

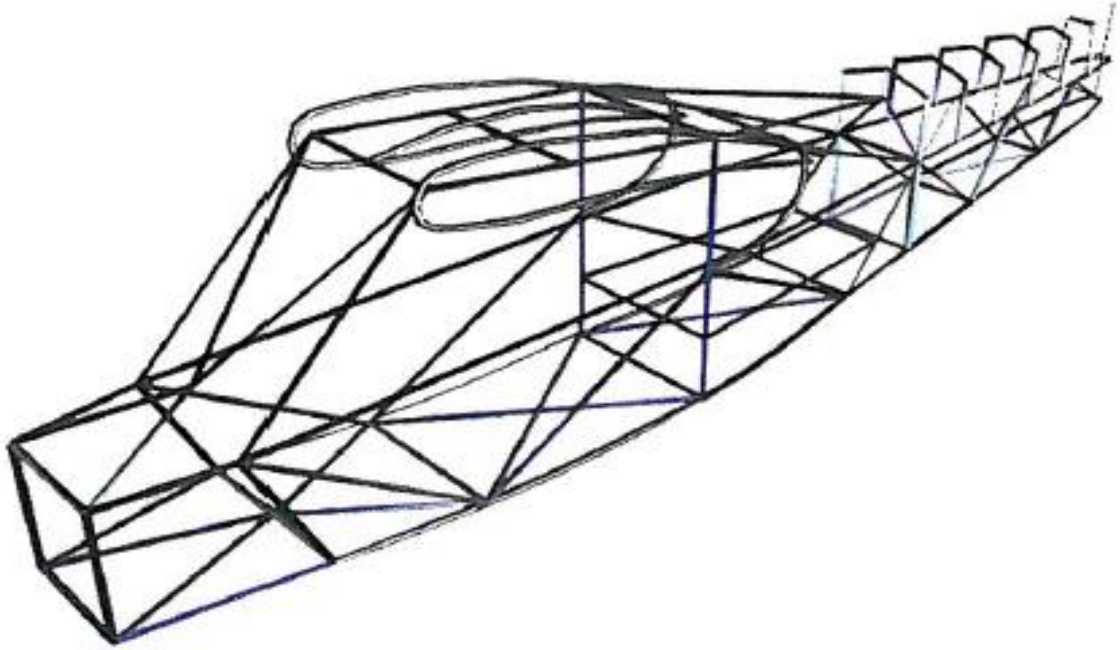

Figure 1.2. Framework Construction.

Stressed Skin Construction: Monocoque Construction.

Monocoque is a French word meaning 'single shell.' In a **monocoque structure** all the loads are absorbed by a **stressed skin** with just light internal frames or formers to give the required shape.

Figure 1.3. An Ostrich egg is a monocoque construction.

With a **stressed-skin** structure, even slight damage to the skin can seriously weaken the structure.

Stressed Skin Construction: Semi - Monocoque Construction.

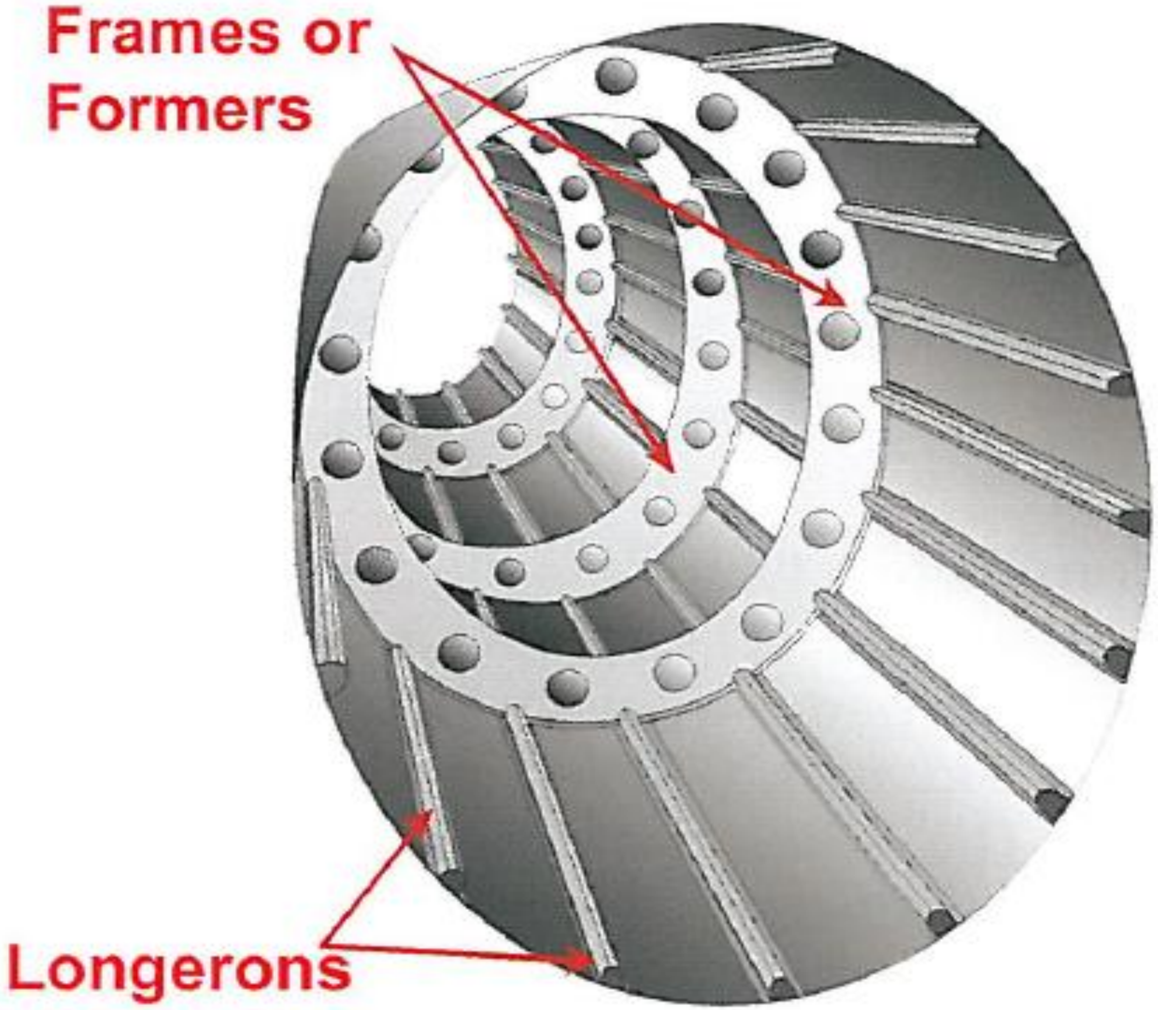

Figure 1.4. Semi - Monocoque Construction.

As aircraft became larger and the air loads greater, the pure monocoque structure was found not to be strong enough. Additional structural members known as **longerons** were added to run lengthwise along the fuselage joining the **frames** together. A light alloy **skin** was then attached to the **frames** and **longerons** by riveting or adhesive bonding. This type of **stressed-skin** fuselage construction is called **semi-monocoque** *(see Figure 1.4)*.

In **semi-monocoque** fuselages, then, **longerons** and **frames** stiffen the **skin**, and flight loads are shared between the **skin** and the **structure** beneath.

COMPONENT PARTS OF THE AEROPLANE

AIRFRAMES.

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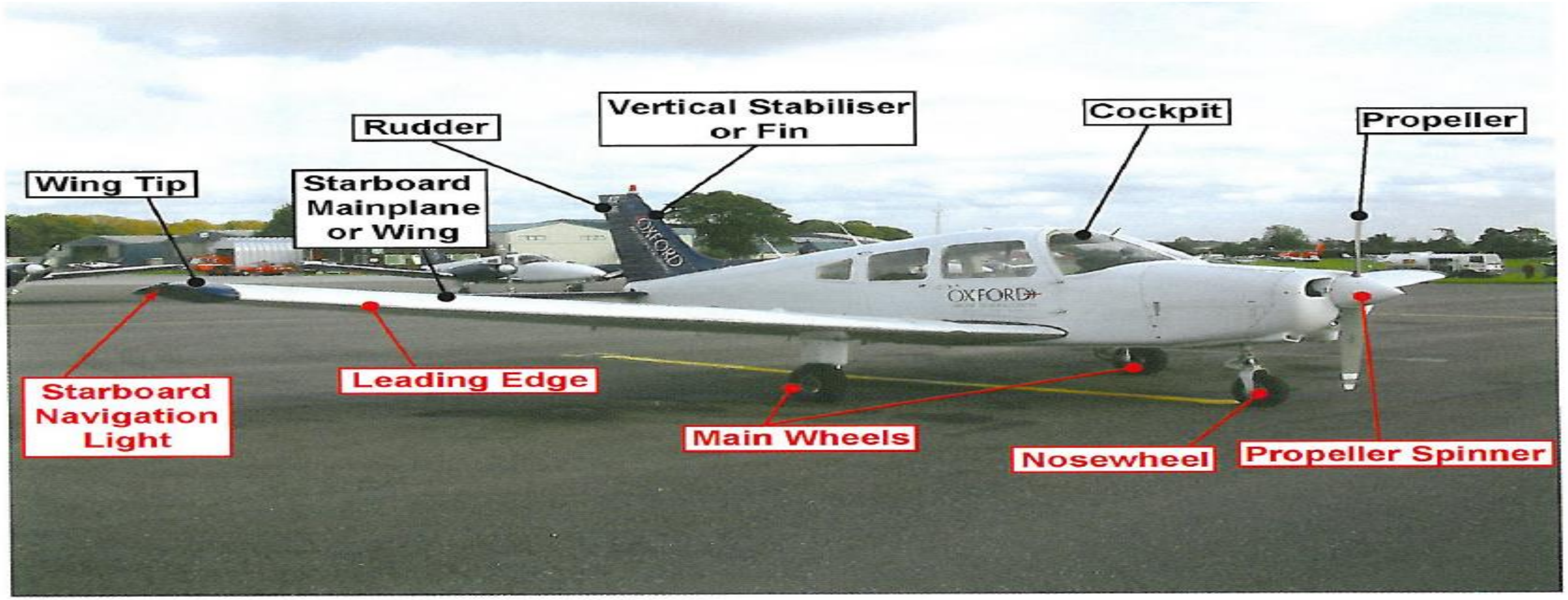
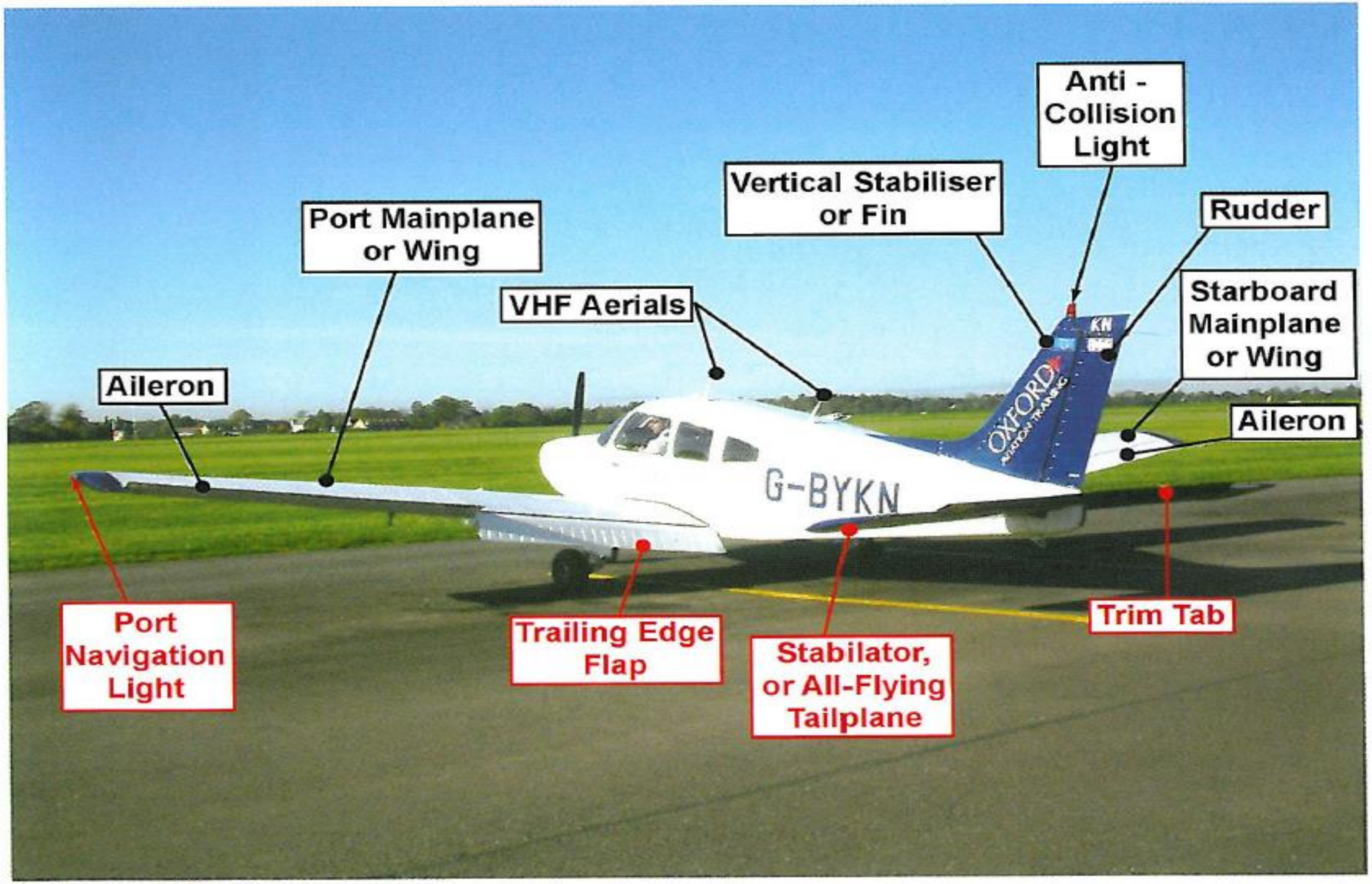
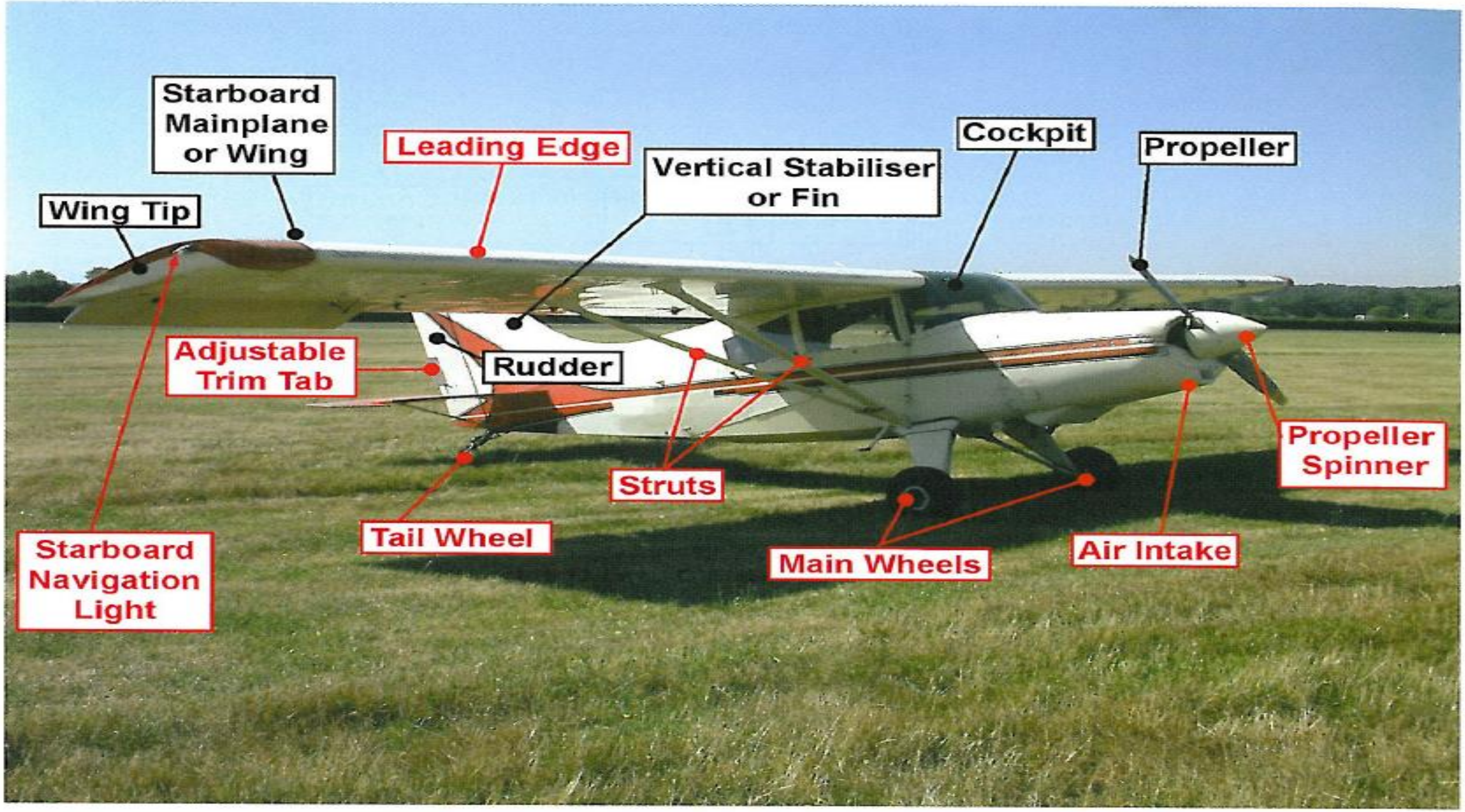
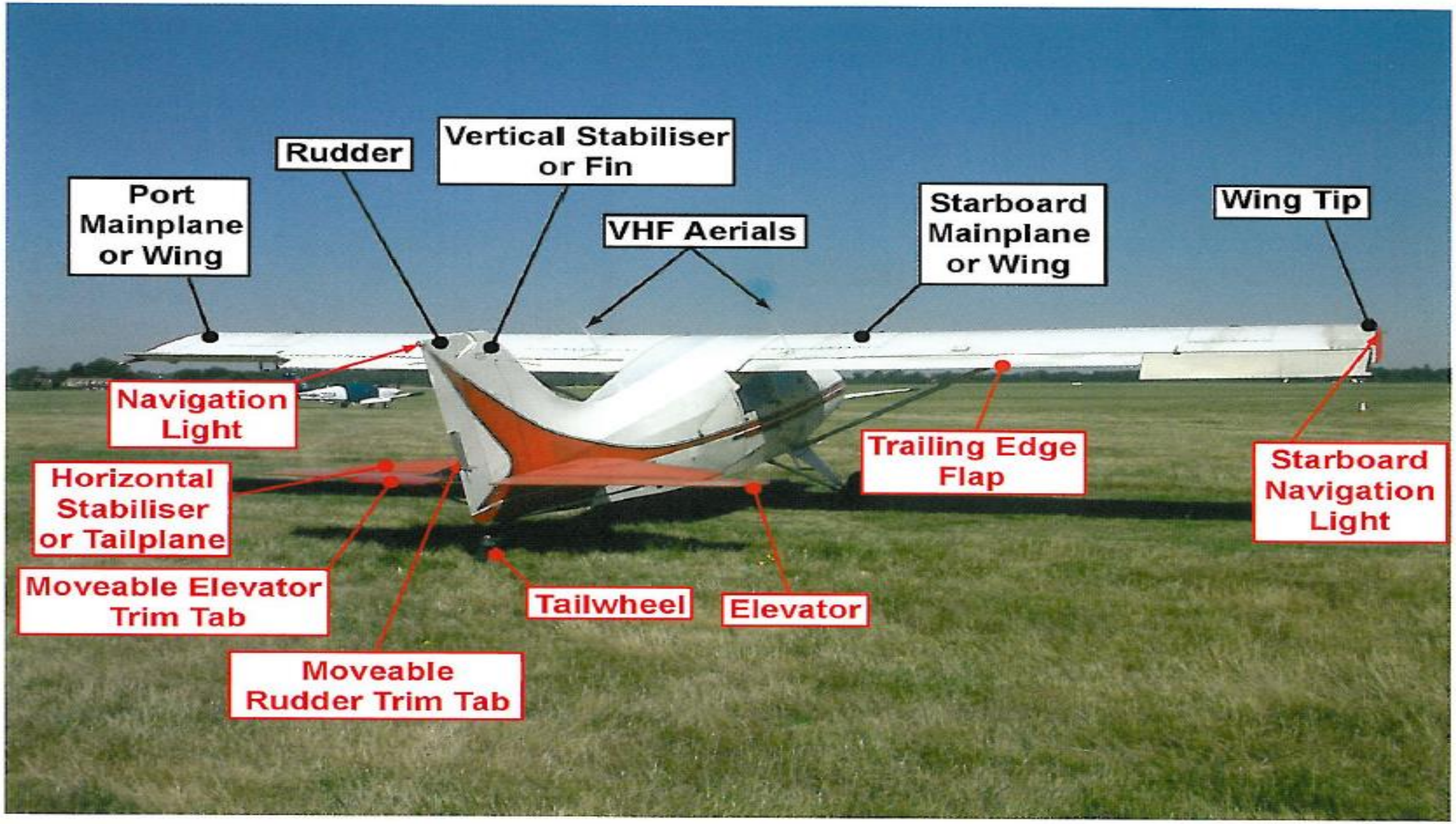



Anti - Collision Light
Vertical Stabiliser or Fin
Rudder
Port Mainplane or Wing
VHF Aerials
Starboard Mainplane or Wing
Aileron
Aileron
G-BYKN
OXFORD
Port Navigation Light
Trailing Edge Flap
Stabilator, or All-Flying Tailplane
Trim Tab


Starboard Mainplane or Wing
Leading Edge
Vertical Stabiliser or Fin
Cockpit
Propeller
Wing Tip
Adjustable Trim Tab
Rudder
Struts
Propeller Spinner
Tail Wheel
Main Wheels
Air Intake
Starboard Navigation Light



Rudder
Vertical Stabiliser or Fin
Port Mainplane or Wing
VHF Aerials
Starboard Mainplane or Wing
Wing Tip
Navigation Light
Horizontal Stabiliser or Tailplane
Trailing Edge Flap
Starboard Navigation Light
Moveable Elevator Trim Tab
Tailwheel
Elevator
Moveable Rudder Trim Tab

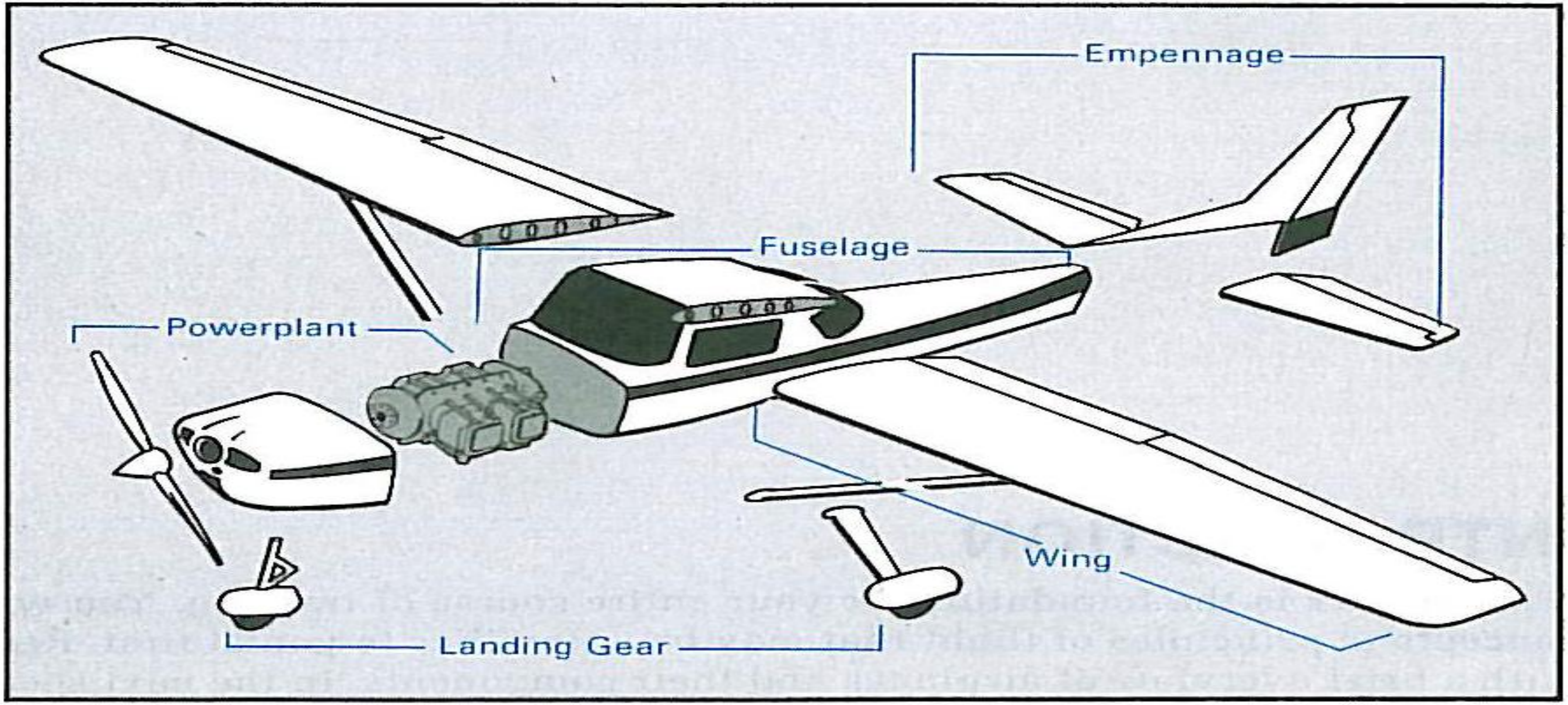


Figure 1-1. Typically, an airplane is made up of five major parts. The fuselage is considered to be the central component, since the powerplant, wings, empennage (tail section), and landing gear are attached to it.

FUSELAGE.

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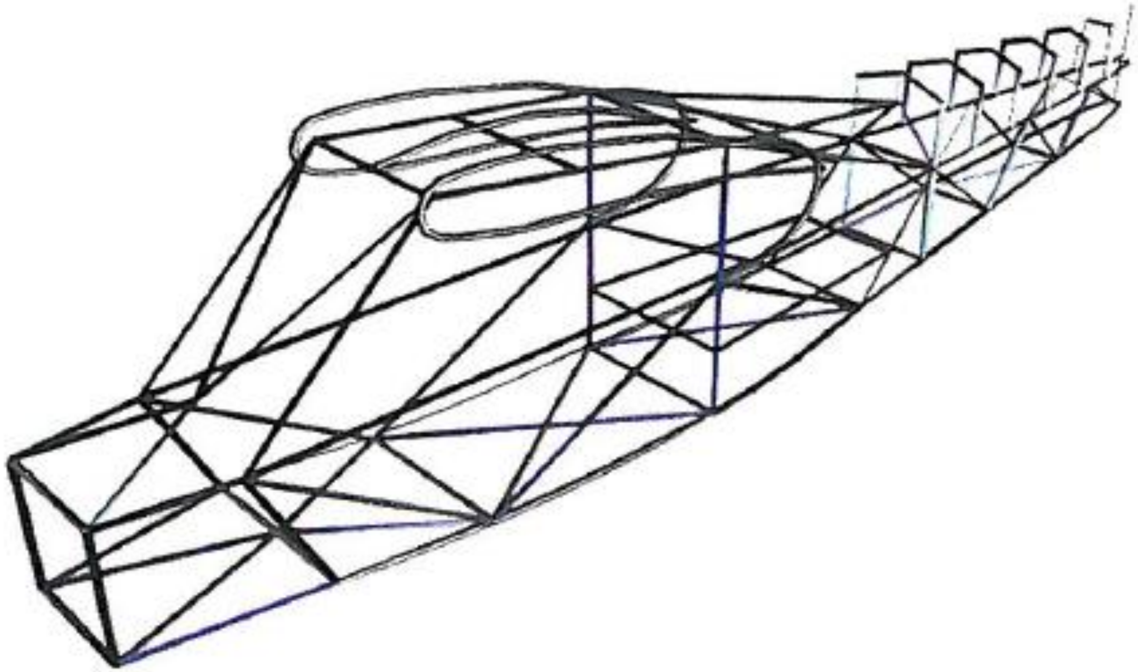

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With a **stressed-skin** structure, even slight damage to the skin can seriously weaken the structure.

Figure 1.3. An Ostrich egg is a monocoque construction.

To be a true **monocoque** the structure would have no apertures in it at all, like an ostrich egg; but for practical purposes, in an aircraft, apertures have to be provided for access and maintenance. The apertures have to be reinforced so that the integrity of the structure is maintained. But, once the aircraft doors are closed and all the hatches and access panels are fitted, the fuselage is to all intents and purposes a **monocoque structure**. Two aircraft constructed in accordance with the **monocoque** principle were the plywood construction Roland CII (1915), and the Ford Trimotor (1926).

Stressed Skin Construction: Semi - Monocoque Construction.

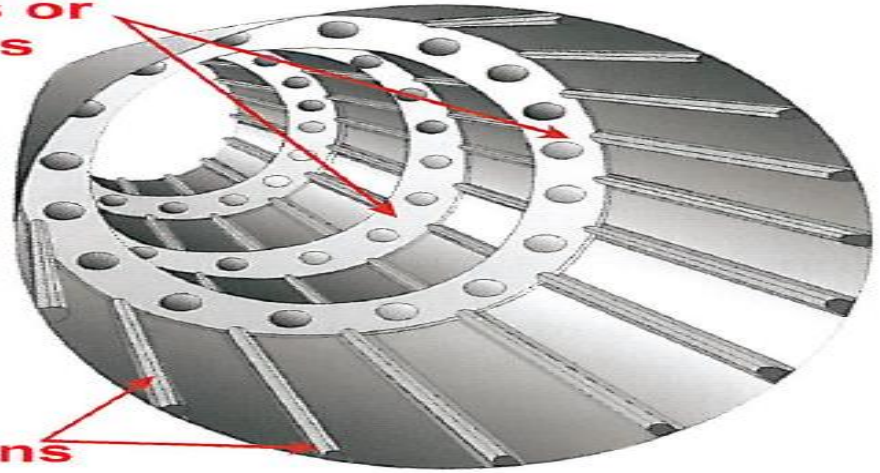


Figure 1.4. Semi - Monocoque Construction.

As aircraft became larger and the air loads greater, the pure monocoque structure was found not to be strong enough. Additional structural members known as **longerons** were added to run lengthwise along the fuselage joining the **frames** together. A light alloy **skin** was then attached to the **frames** and **longerons** by riveting or adhesive bonding. This type of **stressed-skin** fuselage construction is called **semi-monocoque** *(see Figure 1.4)*.

In **semi-monocoque** fuselages, then, **longerons** and **frames** stiffen the **skin**, and flight loads are shared between the **skin** and the **structure** beneath.

Figure 1.5. An Engine Bulkhead.

Bulkheads *as illustrated in Figure 1.5,* are set in place to separate the different sections of the **semi-monocoque** fuselage; for instance, between the engine compartment and the passenger compartment. The **bulkhead** has the same basic shape as the **frames** or **formers**, but almost completely isolates one compartment from the other. However, holes have to be made in the bulkhead. These allow control fittings, pipework and electrical cables to pass through the length of the fuselage.

Bulkheads are usually much more substantially built than the **frames** because they are subject to greater loads. Additionally, the **bulkhead** which separates the engine from the passenger compartment serves to retard the passage of fire from the engine rearwards, should a fire break out.

MAINPLANES (WINGS).

The **wings** or **mainplanes** generate **lift** and, in steady flight, support the **weight** of the aircraft in the air. When the aircraft is manoeuvring, the **wings** will have to support **loads** which are several times the **weight** of the aircraft. Therefore, the **wings** must have sufficient strength and stiffness to be able to do this. The degree of strength and stiffness is determined by the thickness of the wing, with the thickness and type of construction used being dependent on the speed requirements of the aircraft. Various types of **wing construction** are **bi-plane, braced monoplane** and **cantilever monoplane**.

THE FUSELAGE

The fuselage serves several functions. Besides being a common attachment point for the other major components, it houses the cabin, or cockpit, which contains seats for the occupants and the controls for the airplane. The fuselage usually has a small baggage compartment and may include additional seats for passengers.

THE WING

When air flows around the wings of an airplane, it generates a force called "lift" that helps the airplane fly. Wings are contoured to take maximum advantage of this force, as you will see in Section B. Wings may be attached at the top, middle, or lower portion of the fuselage. These designs are referred to as high-, mid-, and low-wing, respectively. The number of wings can also vary. Airplanes with a single set of wings are referred to as **monoplanes**, while those with two sets are called **biplanes**.

To help you fly the airplane, the wings have two types of control surfaces attached to the rear, or trailing, edges. They are referred to as ailerons and flaps. **Ailerons** extend from about the midpoint of each wing outward to the tip. They move in opposite directions — when one aileron goes up, the other goes down. **Flaps** extend outward from the fuselage to the midpoint of each wing. They always move in the same direction. If one flap is down, the other is down. [Figure 1-2]

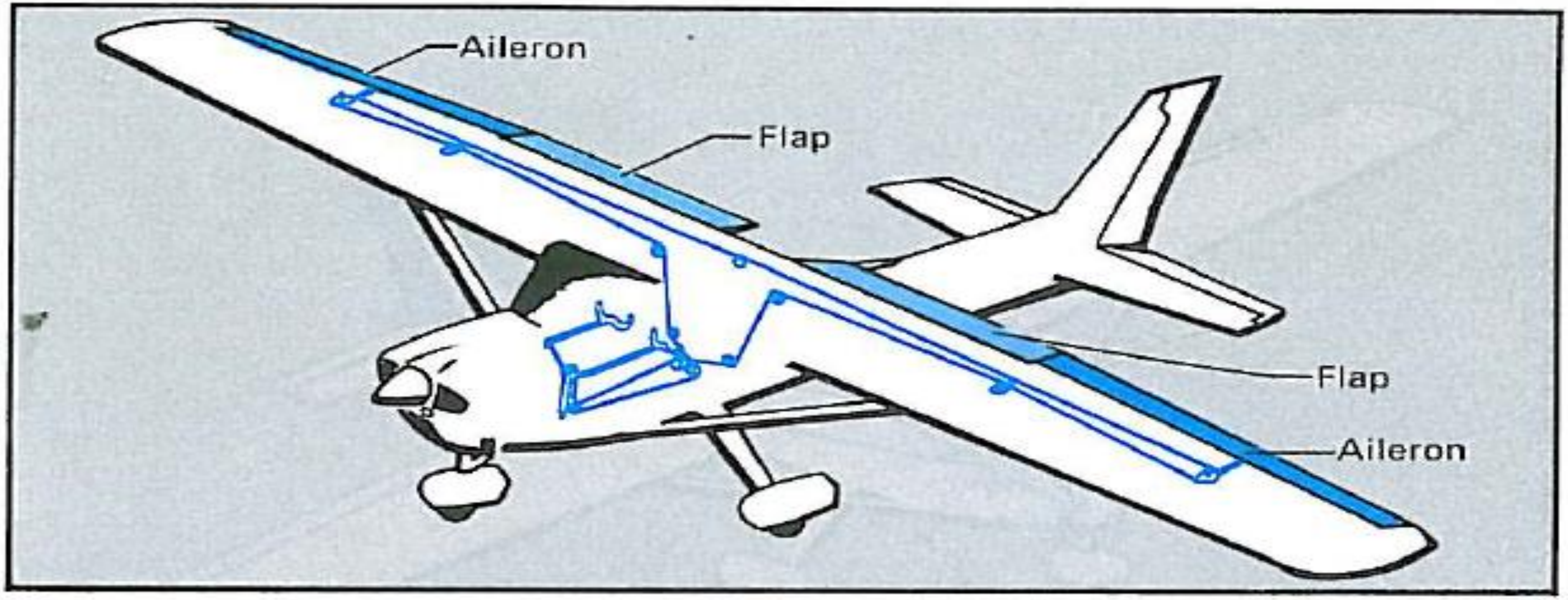


Figure 1-2. You can move the ailerons by turning the control wheel in the cockpit. When you turn the wheel to the left, the left aileron moves up and the right moves down. During flight, this is how you start a turn to the left. Turning the wheel to the right has the opposite effect. You can operate the flaps using a switch or handle located in the cockpit. They are used primarily for takeoffs and landings.

Bi-plane Construction.

Very few **bi-planes** fly at more than 200 knots in level flight, so the air loads are low, which means that a truss type design, which is covered in fabric, is usually satisfactory. The wing spars, interplane struts and bracing wires form a lattice girder of great rigidity which is highly resistant to bending and twisting. Unfortunately the struts and bracing wires also generate a relatively large amount of drag, which accounts for the modest speed of **bi-planes** *(see Figure 1.6).*

Figure 1. 6 Bi-plane Construction.

Braced Monoplane.

This type of design is also used on low speed aircraft.

In the **braced monoplane**, the wings are strengthened or 'braced' by external struts, which help relieve the bending loads applied to the wing spars in flight. One of the most famous **braced monoplanes** was the **'Spirit of St Louis'** *(see Figure 1.7.)* which Charles Lindbergh piloted in his epic, solo transatlantic flight.

Figure 1.7 The Spirit of St. Louis. Picture, courtesy of Peter Chambers.

Cantilever Monoplane.

On a **cantilever monoplane**, the wings are **unbraced**, being supported at one end only. Most modern aircraft are **cantilever monoplanes**. Cantilever wings have to absorb the stresses due to lift and drag in flight and their own weight when on the ground *(see Figure 1.8).*

Figure 1.8 Cantilever Monoplane.

CONSTRUCTION OF THE CANTILEVER WING.

The load bearing ability of a **cantilever wing** is achieved by building the wing around one or more main load bearing members known as **spars** *(Figure 1.9)*, which are constructed so that they will absorb the downwards bending stresses when on the ground, and the upwards, rearwards and twisting stresses when in flight.

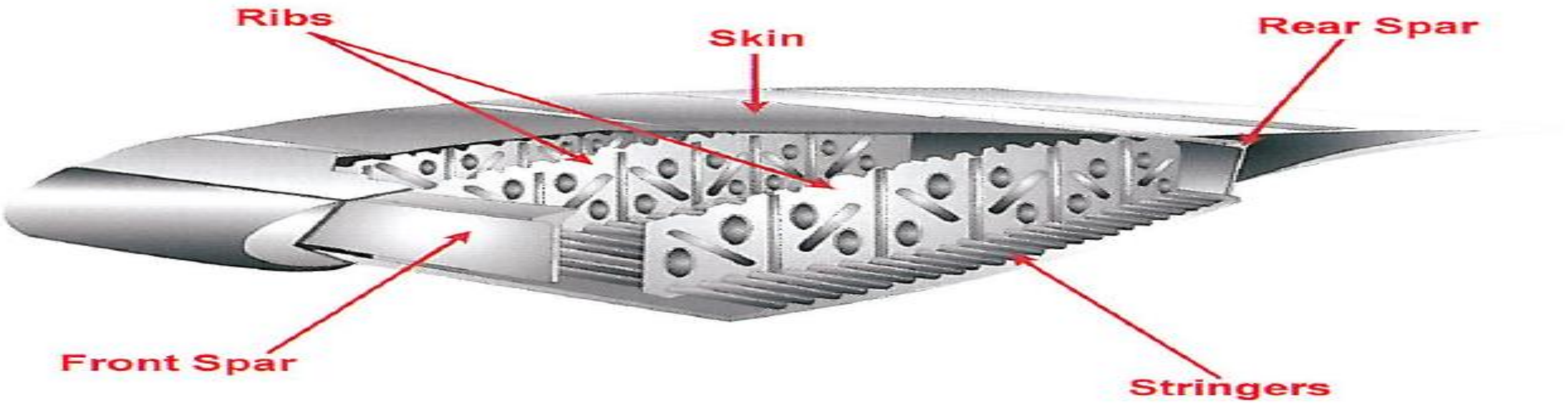


Figure 1.9 Cantilever Wing Construction.

The major structural components of the **cantilever wing** are generally manufactured from aluminium alloys, with composite materials such as glass-reinforced plastic, carbon-reinforced plastic and honeycomb structures being used for fairings, control surfaces and flaps etc.

Relief of bending stress is aided by positioning the major fuel tanks within the wing.

Cantilever wings may be of **single spar**, **twin spar** or **multispar construction**. A conventional mainplane structure would consist of front and rear spars, with metal skin attached to the spar booms to form a torsion box, which counteracts twisting forces.

STABILISING SURFACES.

The stabilising surfaces are designed to return the aircraft to balanced flight in the pitching and yawing planes when the aircraft has been disturbed from steady, straight flight. On conventional aircraft, the primary stability surfaces are the **tailplane** (or **horizontal stabiliser**), and the **fin** (or **vertical stabiliser**).

Figure 1.10 A T-Tail.

Tail Units.

The **tail unit**, which is sometimes called the **empennage**, comes in many different designs. It can be **conventional**, **T-tail**, **H-tail** or **V-tail**.

Figure 1.11 An H-Tail.

An example of each of the less common of these types of **tail units** is shown in *Figures 1.10, 1.11 and 1.12.*

The tail unit, as a whole, provides longitudinal and directional stability and control.

Figure 1.12 A V-Tail.

However, in some aircraft, longitudinal stability and control is provided by **foreplanes**, called **canards** *(see Figure 1.13).*

Figure 1.13 A Canard Foreplane.

The Tail Plane.

The horizontal fixed tail surface, which is known as the **tailplane** or **horizontal stabiliser**, provides **longitudinal stability** by generating upwards or downwards forces as required.

Structurally the tail unit components are generally smaller versions of the mainplanes in that they use spars, ribs, stringers and skin in their construction. They also use the same basic materials as are employed in the manufacture of mainplanes; for instance, aluminium alloys or composites with honeycomb structures.

The Fin.

The fixed vertical surface, known as the **vertical stabiliser** or **fin**, generates sideways forces as required to give **directional stability**.

THE EMPENNAGE

The empennage consists of the **vertical stabilizer**, or fin, and the **horizontal stabilizer**. These two surfaces are stationary and act like the feathers on an arrow to steady the airplane and help you maintain a straight path through the air. [Figure 1-3]

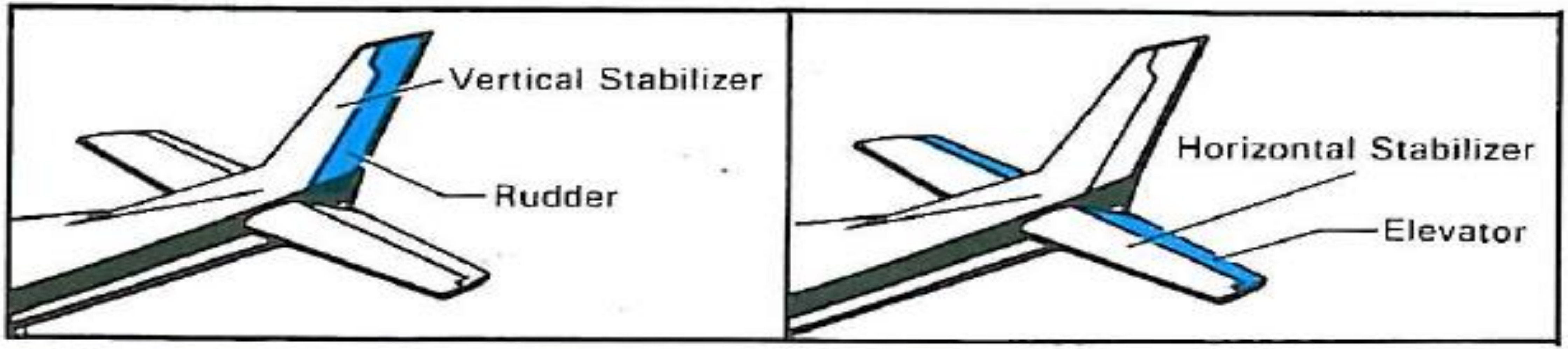


Figure 1-3. Besides the two fixed components, the empennage has two important movable surfaces called the rudder and the elevator.

The **rudder** is attached to the back of the vertical stabilizer. You use it to move the airplane's nose left and right. Actually, you use the rudder and ailerons in combination during flight to initiate a turn. You will learn the details about this later. [Figure 1-4]

The **elevator** is attached to the back of the horizontal stabilizer. During flight, you use it to move the nose up and down so you can direct the airplane to the desired altitude, or height. [Figure 1-5]

STABILATOR

Some empennage designs vary from the type of horizontal stabilizer just discussed. They have a one-piece horizontal stabilizer that pivots up and down from a central hinge point. This type of design, called a **stabilator**, requires no elevator. You move the stabilator using the control wheel, just as you would the elevator. When you pull back, the nose moves up; when you push forward, the nose moves down. An antiservo tab is mounted at the back of the stabilator, to provide you with a control "feel" similar to what you experience with an elevator. Without the **antiservo** tab, control forces from the stabilator would be so light that you might "over control" the airplane or move the control wheel too far to obtain the desired result. The antiservo tab also functions as a trim tab. [Figure 1-6]

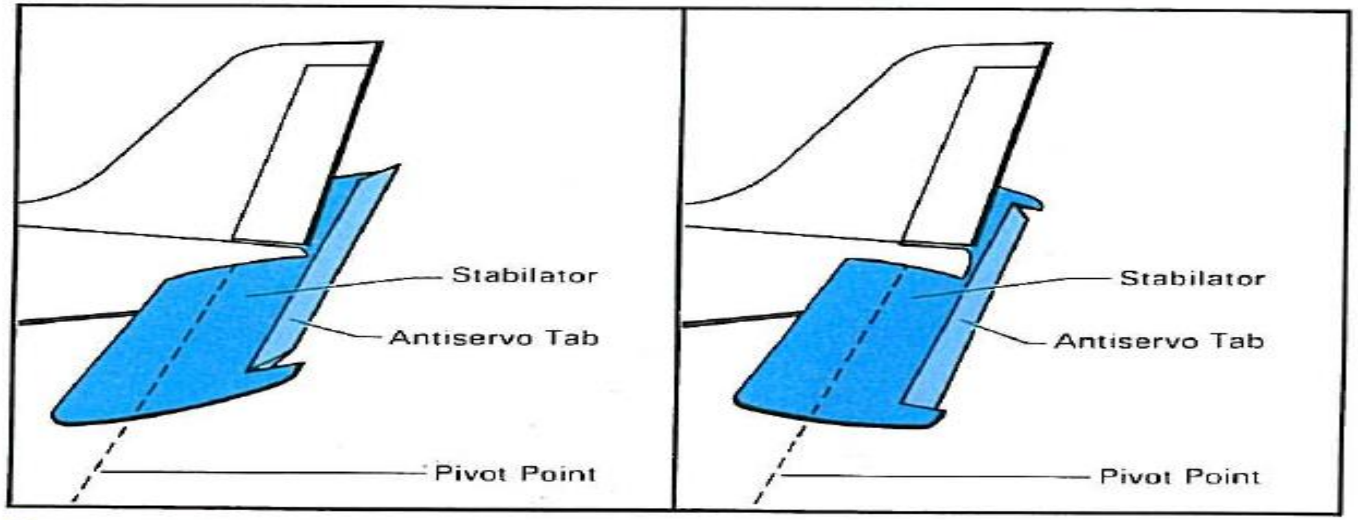


Figure 1-6. The stabilator pivots up and down as you move the control wheel. The antiservo tab moves in the same direction as the trailing edge of the stabilator.

TRIMMING.

An aeroplane is **trimmed** when it will maintain its attitude and speed without the pilot having to apply a force to the cockpit controls. If it is necessary for a control surface to be deflected to maintain balance of the aircraft, the pilot will need to apply a force to the cockpit control to hold the surface in its deflected position. This force may be reduced to zero by operation of the **trim controls** which cause the **trim tabs**, fitted to the rear edges of the main flying control surfaces to move so as to hold the control surfaces in their deflected position.

Figure 1.19 Elevator Trim Mechanism.

The aircraft may need to be **trimmed** in pitch as a result of changes of attitude and speed, changes of power or varying **centre of gravity** positions. An elevator **trim mechanism** and **trim tab** are shown in *Figure 1.19*.

Trimming in yaw will be needed as a result of changes in propeller torque, or if there is an engine failure on a twin engined aircraft. **Trimming** in roll is less likely to be needed, but would be required if there was a lateral displacement of the **centre of gravity**: for example if the contents of the fuel tanks in each wing were allowed to become unequal, or, in the case of a twin engine aircraft, if one engine had failed.

Fixed Tabs.

Some **trimming tabs** are not adjustable in flight, but can be adjusted on the ground by an aircraft technician to correct a permanent out-of-trim condition. **Fixed trimming tabs** are most commonly found on the ailerons *(see Figure 1.16)*.

LANDING GEAR

The landing gear absorbs landing loads and supports the airplane on the ground. It typically is made up of three wheels. The two **main wheels** are located on either side of the fuselage. The third may be positioned either at the nose or at the tail. If it is located at the tail, it is called a **tailwheel**. In this case, the airplane is said to have **conventional landing gear**.

Conventional gear is common on older airplanes, as well as on some newer ones. It is desirable for operations on unimproved fields, because of the added clearance between the propeller and the ground. However, airplanes with this type of gear are more difficult to handle during ground operations.

When the third wheel is located on the nose, it is called a **nosewheel**. This design is referred to as **tricycle gear**. An airplane with this type of gear has a steerable nosewheel, which you control through use of the rudder pedals.

Landing gear can also be classified as either fixed or retractable. **Fixed gear** always remains extended, while **retractable gear** can be stowed for flight to reduce air resistance and increase airplane performance.

LANDING GEAR TYPES - FIXED OR RETRACTABLE.

With slow, light aircraft, and some larger aircraft on which simplicity is of prime importance, a fixed, **non-retractable landing gear** is often fitted. On light, training aircraft, for instance, the reduced performance caused by the drag of the fixed landing gear during flight is offset by its simplicity, its reduced maintenance and also its low initial cost. On high speed aircraft, drag becomes progressively more important, so the landing gear is retracted into the wings or fuselage during flight. There are, however, penalties of increased weight, greater complication and additional maintenance with retractable undercarriages.

Fixed Landing Gear.

There are three main types of **fixed landing gear**: those which have **spring steel legs**, those which employ **rubber cords** to absorb shocks, and those which have **oleo-pneumatic struts** to absorb shocks.

Spring Steel Legs.

Spring steel legs are usually employed at the main undercarriage positions. The leg consists of a tube, or strip of tapered spring steel, the upper end being attached by bolts to the fuselage and the lower end terminating in an axle on which the wheel and brake are assembled *(see Figure 2.3)*.

Figure 2.3 Spring Steel Legs.

Rubber Cord.

When **rubber cord** is used as a shock-absorber, the undercarriage is usually in the form of tubular struts, designed and installed so that the landing force is directed against a number of turns of rubber in the form of a grommet or loop.

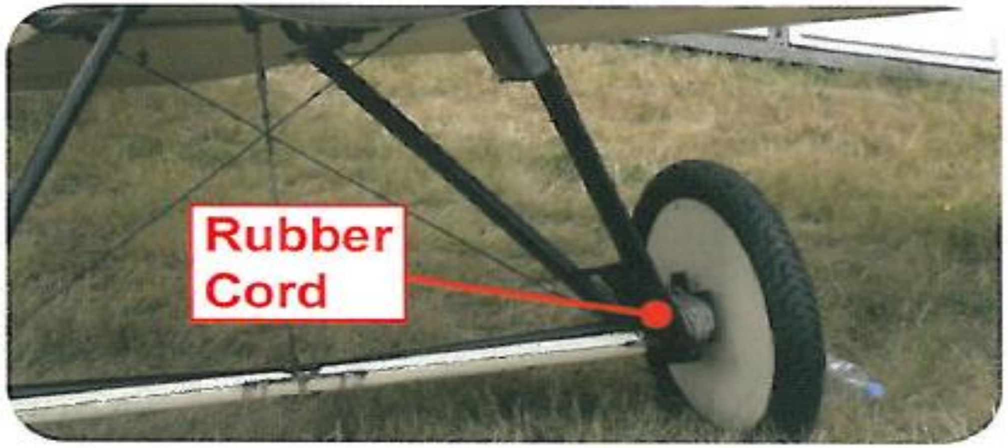


Figure 2.4 Rubber Cord.

Oleo-pneumatic Struts.

Some fixed main undercarriages, and most fixed nose undercarriages, are fitted with an **oleo-pneumatic shock absorber strut**. The design of oleo-pneumatic struts varies considerably. Some may be fitted with fairings to reduce drag.

Spats.

Spats may be fitted to the undercarriage in order to reduce drag.

One drawback to their use is that **spats** may pick up mud when landing or taking off from grass airfields. This can add considerably to the weight of the aircraft and may affect take-off performance. To avoid this eventuality, if any mud has been picked up, the **spats** must be removed, cleaned and replaced before the next take-off.

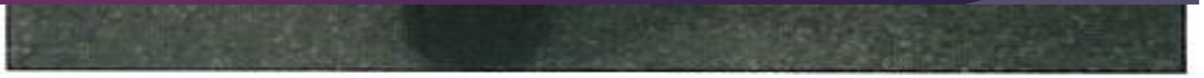


Figure 2.5 An Oleo-Pneumatic Strut.

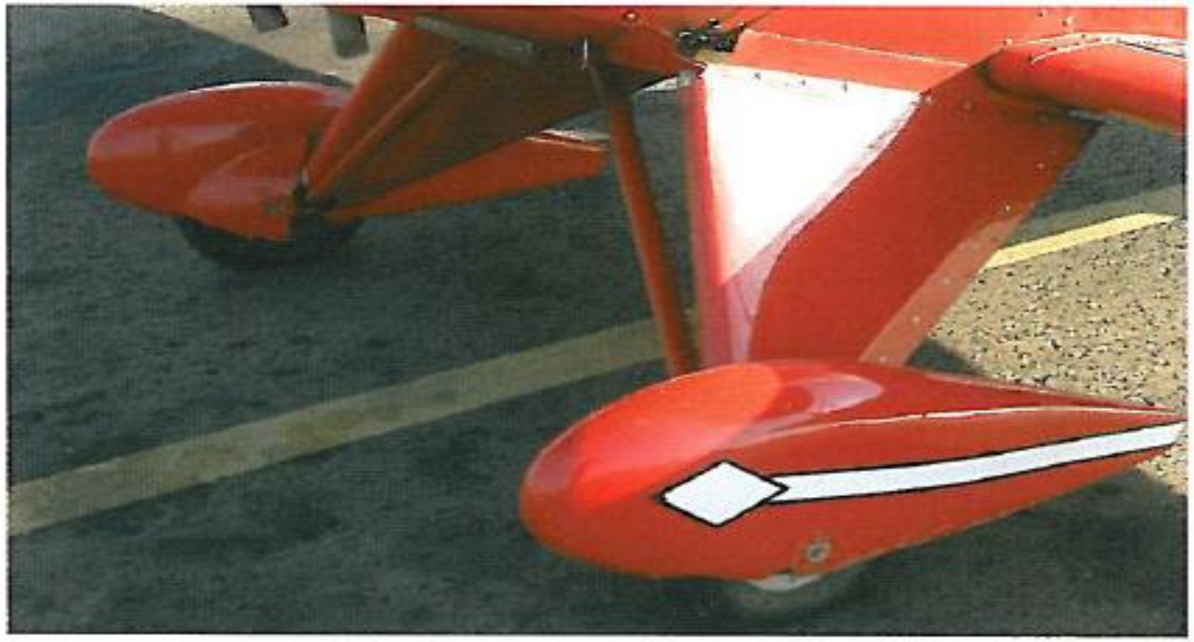


Figure 2.6 Spats, fitted to a Pitts S2a.

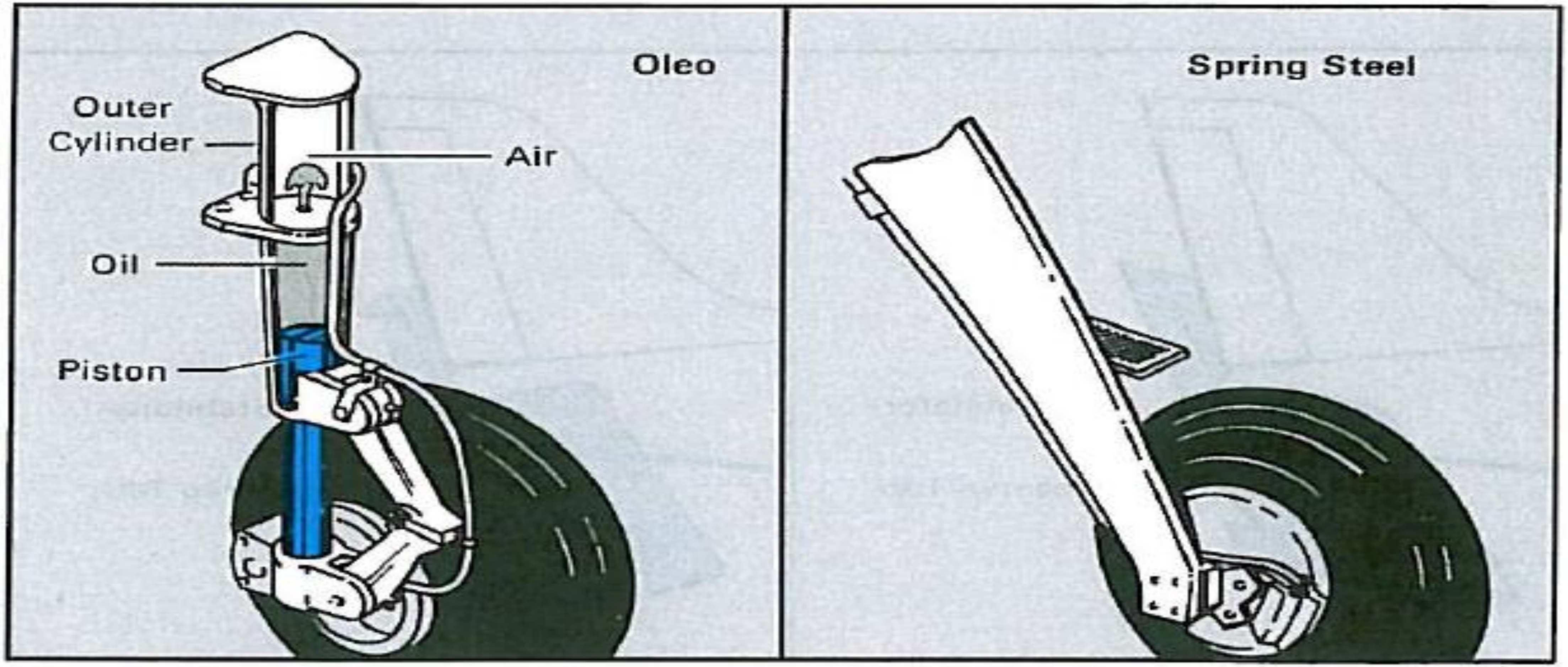


Figure 1-7. There are two primary shock-absorbing systems in use. The oleo strut consists of an enclosed cylinder which houses a piston, oil, and air. It absorbs pressure rapidly and then slowly releases it. The spring steel strut, as its name implies, is made of steel that is designed to ''give'' as pressure is applied.

THE NOSE WHEEL.

The **nose gear** is usually of a lighter structure than the main gear units since it carries less weight and is normally subject only to direct compression loads.

The **nose wheel** must be able to castor freely. Castoring is the ability of the nose wheel to turn to either side in response to differential braking on the main wheels.

Figure 2.7 Nose Gear.

Nose Wheel Steering.

A method of steering is required to enable the pilot to manoeuvre the aircraft safely on the ground.

Early methods involved the use of differential braking and free castoring nose wheels, but, today, the nose wheel of most light aircraft is steered directly by the rudder pedals.

BRAKES

Airplane brakes operate on the same principles as automobile brakes, but they do have a few significant differences. For example, airplane brakes usually are located only on the main wheels, and are applied by separate pedals. Because of this, you can operate the brake on the left independently of the brake on the right, or vice versa. This capability is referred to as **differential braking.** It is important during ground operations when you need to supplement nosewheel steering by applying the brakes on the side toward the direction of turn. In fact, differential braking is extremely important on conventional gear airplanes, since some do not have a steerable wheel.

THE POWERPLANT

In small airplanes, the powerplant includes both the engine and the propeller. The primary function of the engine is to provide the power to turn the propeller. It also generates electrical power, provides a vacuum source for some flight instruments, and, in most single-engine airplanes, provides a source of heat for the pilot and passengers. A **firewall** is located between the engine compartment and the cockpit to protect the occupants. The firewall also serves as a mounting point for the engine. [Figure 1-8]

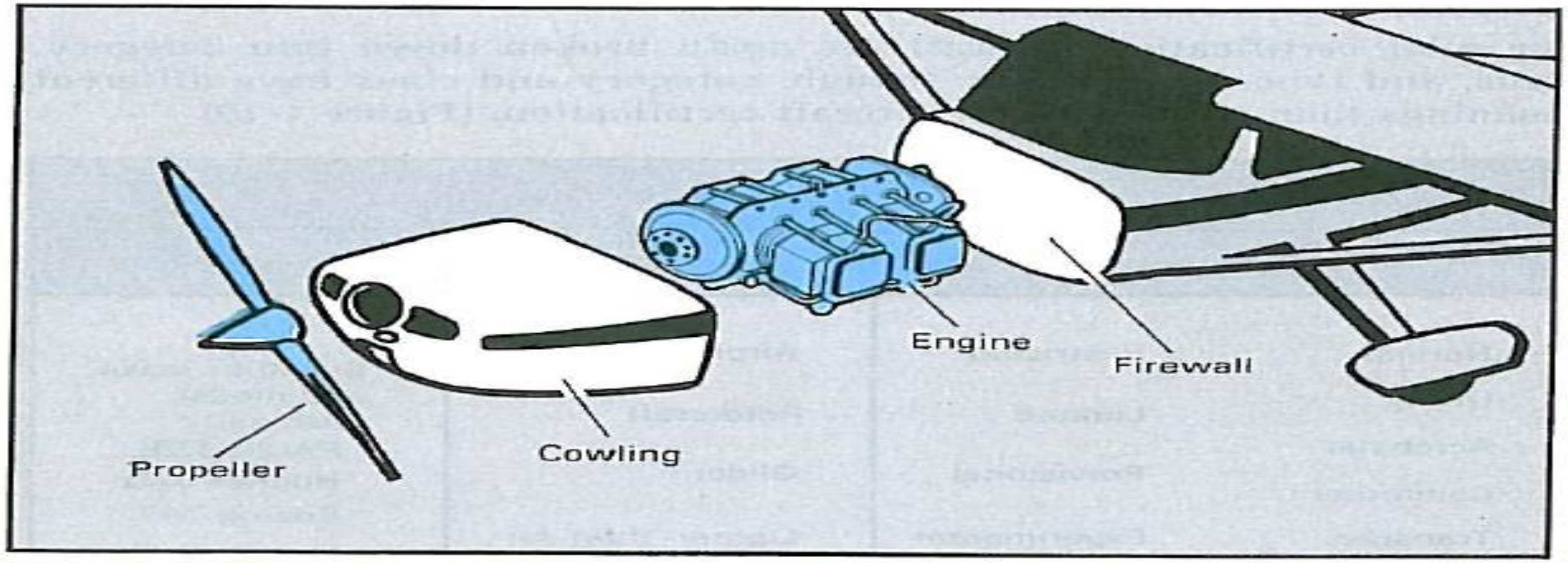


Figure 1-8. The engine compartment is enclosed by cowling, which is also called a nacelle. Besides streamlining the nose of the airplane, the cowling helps cool the engine by ducting air around the cylinders. The propeller, mounted on the front of the engine, translates the rotating force of the engine into a forward-acting force called "thrust" that helps the airplane fly.

THE AIRCRAFT'S AXES.

The Longitudinal Axis.

The aircraft's **longitudinal axis** is illustrated in *Figure 1.14*. Rotation about the **longitudinal axis** is termed **roll**. **Roll** is controlled by the **ailerons.**

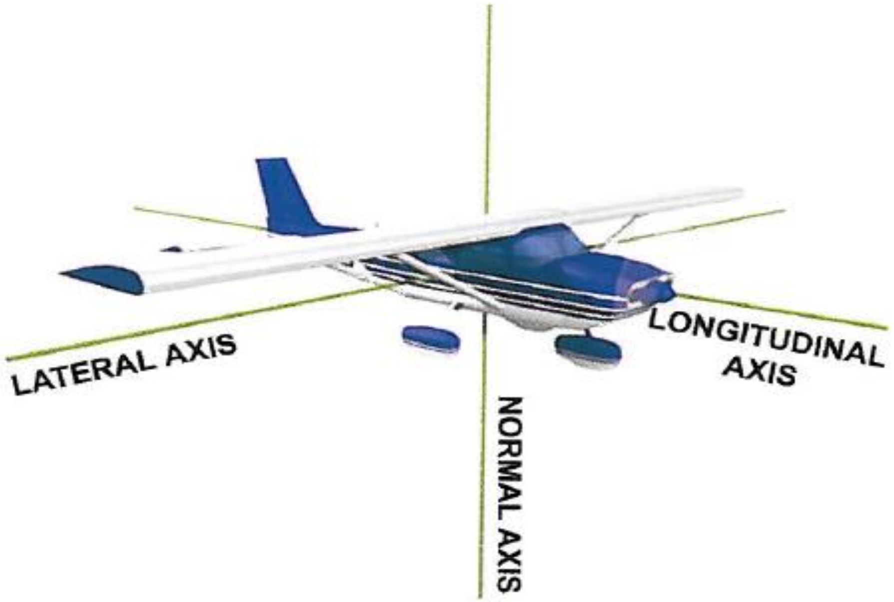


Figure 1.14 The Aircraft Axes.

The Lateral Axis.

The aircraft's **lateral axis** is illustrated in *Figure 1.14*. Rotation about the **lateral axis** is termed **pitch**. **Pitch** is controlled by either the **elevators**, or by an **all-moving tailplane** or **stabiliser**.

The Normal Axis.

The aircraft's **normal axis** is illustrated in *Figure 1.14*. Rotation about the **normal axis** is termed **yaw**. **Yaw** is controlled by the **rudder**.

THE FLYING CONTROLS.

Primary Flying Controls.

The **primary flying controls** control the aircraft in **pitch**, **roll** and **yaw**. The movement of the flying control surfaces in response to the movement of the cockpit controls in light aircraft is achieved mechanically. This means that the control surfaces are connected directly to the cockpit controls by a system of cables, rods, levers and chains.

Pitch Control.

Pitch control is obtained through the use of either **elevators** *(see Figure 1.15)*, an all moving **stabilator** *(see Figure 1.23)* or canard control *(see Figure 1.13)*. For the purpose of this chapter, we will assume that the aircraft has **elevators** fitted to the **tail plane**. The **elevator** is controlled by fore and aft movement of the control column or control wheel *(see Figure 1.17)*. Rearward movement of the control column causes upward movement of the **elevator** which causes the aircraft to **pitch** nose upwards, and vice versa.

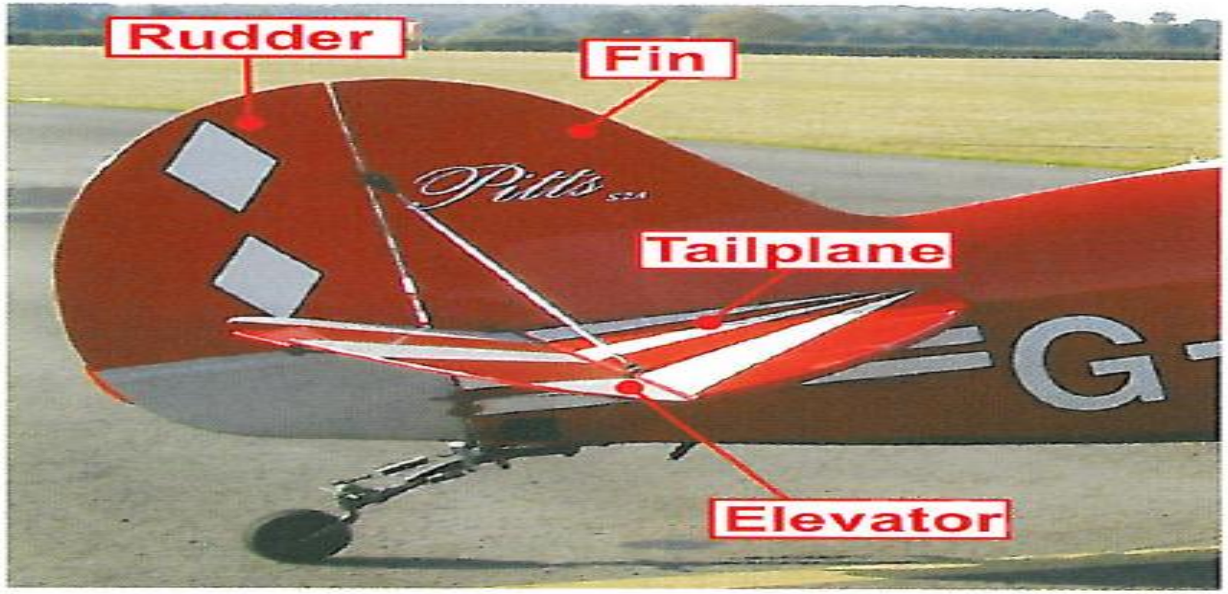


Figure 1.15 Elevators and Rudder.

Figure 1.16 An Aileron.

Roll Control.

Control in **roll** is achieved by **ailerons** *(see Figure 1.16)*. Turning the control wheel or moving the control column to the right causes the right **aileron** to move up and the left **aileron** to move down, inducing **roll** to the right and vice versa.

Yaw Control.

Control in **yaw** is achieved by the **rudder**, (*Figure 1.15.*) Moving the right **rudder pedal** forward causes the **rudder** to move to the right which, in turn, causes the aircraft to **yaw** to the right, and vice versa.

Range of Control Movement.

The movement of each control surface to either side of its neutral position is laid down by the aircraft designer so that the required control can be achieved over the full range of operating conditions.

The movement is not necessarily the same each side of neutral; for example, an elevator usually has a greater deflection upward than downward. The limit of movement of the control surface is determined by a mechanical stop *(see Figure 1.17).* The function of mechanical stops is to prevent excessive control surface deflection which may cause the aircraft structure to be over-stressed during normal operations.

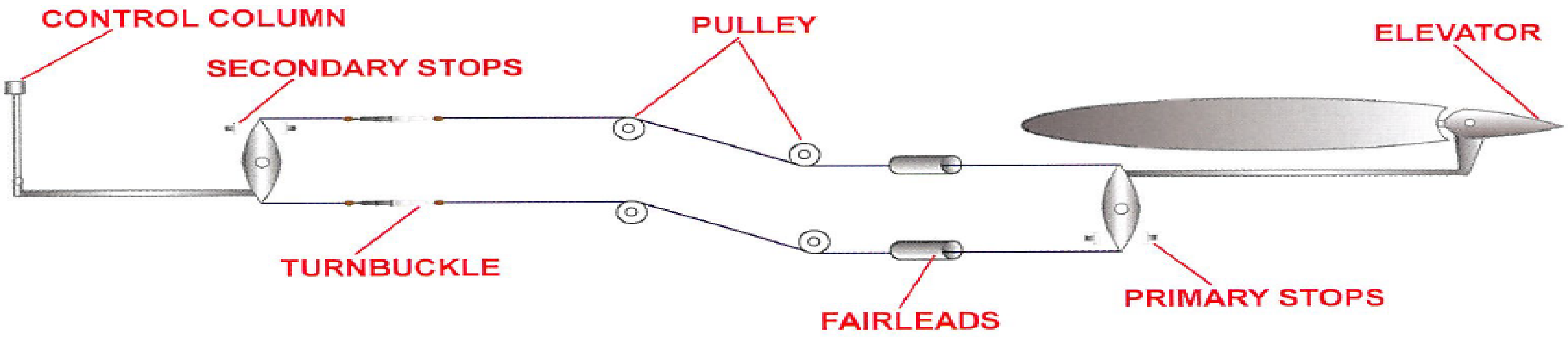


Figure 1.17 A Control Run.

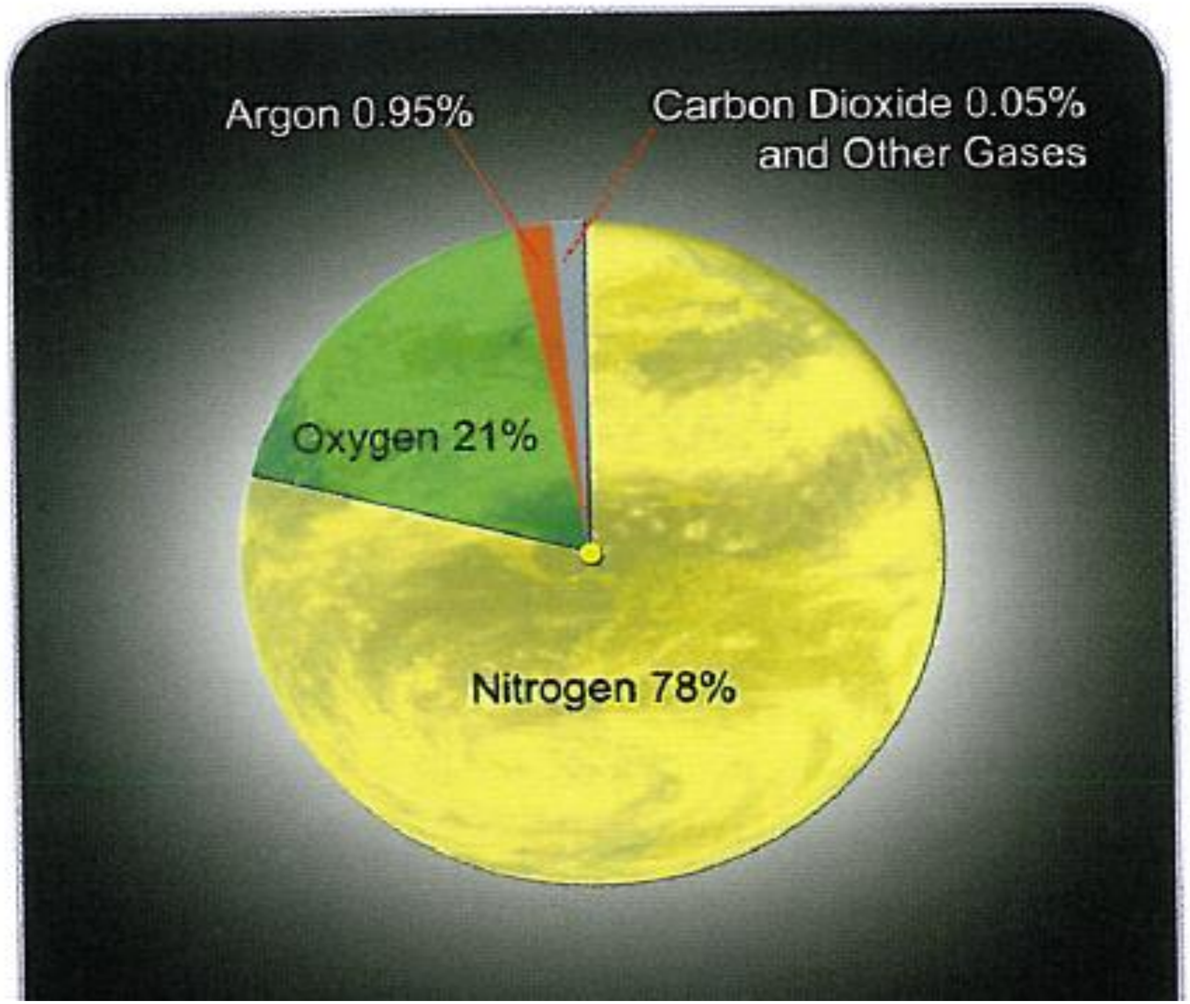
AIRCRAFT CERTIFICATION			
Category		**Class**	**Type**
Normal	Restricted	Airplane	Specifies make and model such as: PA-28-161 Hughes 500 Boeing 747
Utility	Limited	Rotorcraft	
Acrobatic	Provisional	Glider	
Commuter			
Transport	Experimental	Lighter-Than-Air	

Figure 1-9. For aircraft certification purposes, the FAA establishes broad categories first. These are further broken down into one of four classes, then into types, which are essentially the make and model.

PILOT CERTIFICATION		
Category	**Class**	**Type**
Airplane	Single-Engine Land Multi-Engine Land Single-Engine Sea Multi-Engine Sea	Specifies make and model such as: PA-28-161 Hughes 500 Boeing 747
Rotorcraft	Helicopter Gyroplane	
Glider	------------	
Lighter-Than-Air	Airship Balloon	

CHAPTER 2
THE ATMOSPHERE

The air in our atmosphere is made up primarily of **Nitrogen** (78%) and **Oxygen** (21%). *(See Figure 2.1)* The remaining 1% consists mainly of **Argon** and **Carbon Dioxide**, with traces of Carbon Monoxide, Helium, Methane, Hydrogen and Ozone. It is this mixture of gases which not only enables an aeroplane to fly but which also makes up the air which sustains human life and enables the combustion of fuel to take place to drive piston engines and gas turbine engines.



The ICAO Standard Atmosphere, with its significant values for the variation of temperature, pressure and density with altitude, is illustrated at *Figure 2.7*. Mean Sea Level air pressure in the ICAO Standard Atmosphere (which we will, henceforth in this volume, refer to as **ISA**) is 1013.2 millibars (1013.2 hectopascals) or 29.92 inches of Mercury. The ISA temperature at Mean Sea Level is 15º Celsius. In the ISA, temperature decreases with altitude at approximately 2º Celsius for every 1 000 ft.

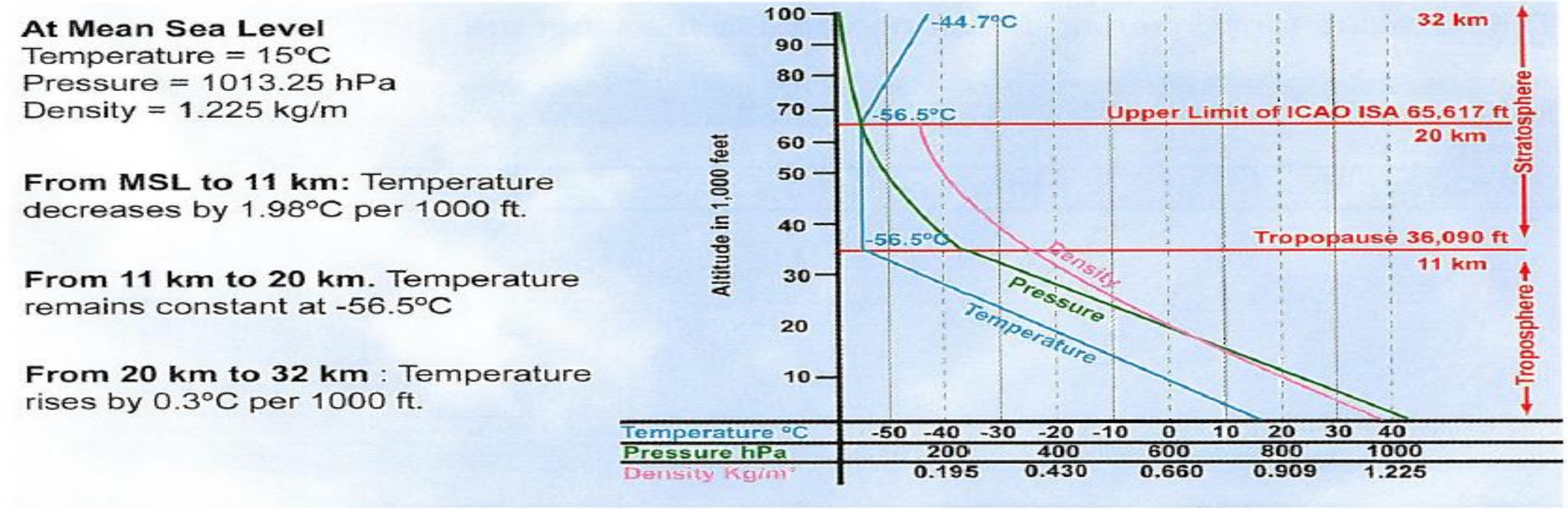


Figure 2.7 The ICAO Standard Atmosphere.

CHAPTER 3
LIFT

An aircraft, like any physical body, possesses **mass**. The Earth's **force of gravity** acting on the aircraft's **mass** gives the aircraft **weight** which acts vertically downwards towards the centre of the Earth. When an aircraft has no forward speed, its weight keeps it firmly on the ground. (Unless the aircraft is a Harrier, of course; but that is another story.)

In order that an aircraft may fly, its **weight** has to be counter-balanced by a force of equal magnitude to its weight and which acts in the opposite direction. This force is called **lift**. As we will learn, **lift** is generated as a result of the flow of air over the aircraft's surfaces, principally its mainplanes or wings. In order to create this flow of air, the aircraft is propelled forwards through the air by a force to which we give the name **thrust**. But as soon as the aircraft begins to move under the influence of **thrust**, a force arises which opposes the **thrust** force, and acts against the direction of the aircraft's motion. This force is called **drag**. The four forces we have just mentioned, **weight, lift, thrust and drag**, which act on any powered aircraft in flight, are illustrated in *Figure 3.1*. The diagram also depicts a force which is identified as the **tailplane force**. The tailplane force is not one of the principal flight forces; it is a balancing force. Do not concern yourself with it for the moment; you will meet tailplane force at the appropriate time.

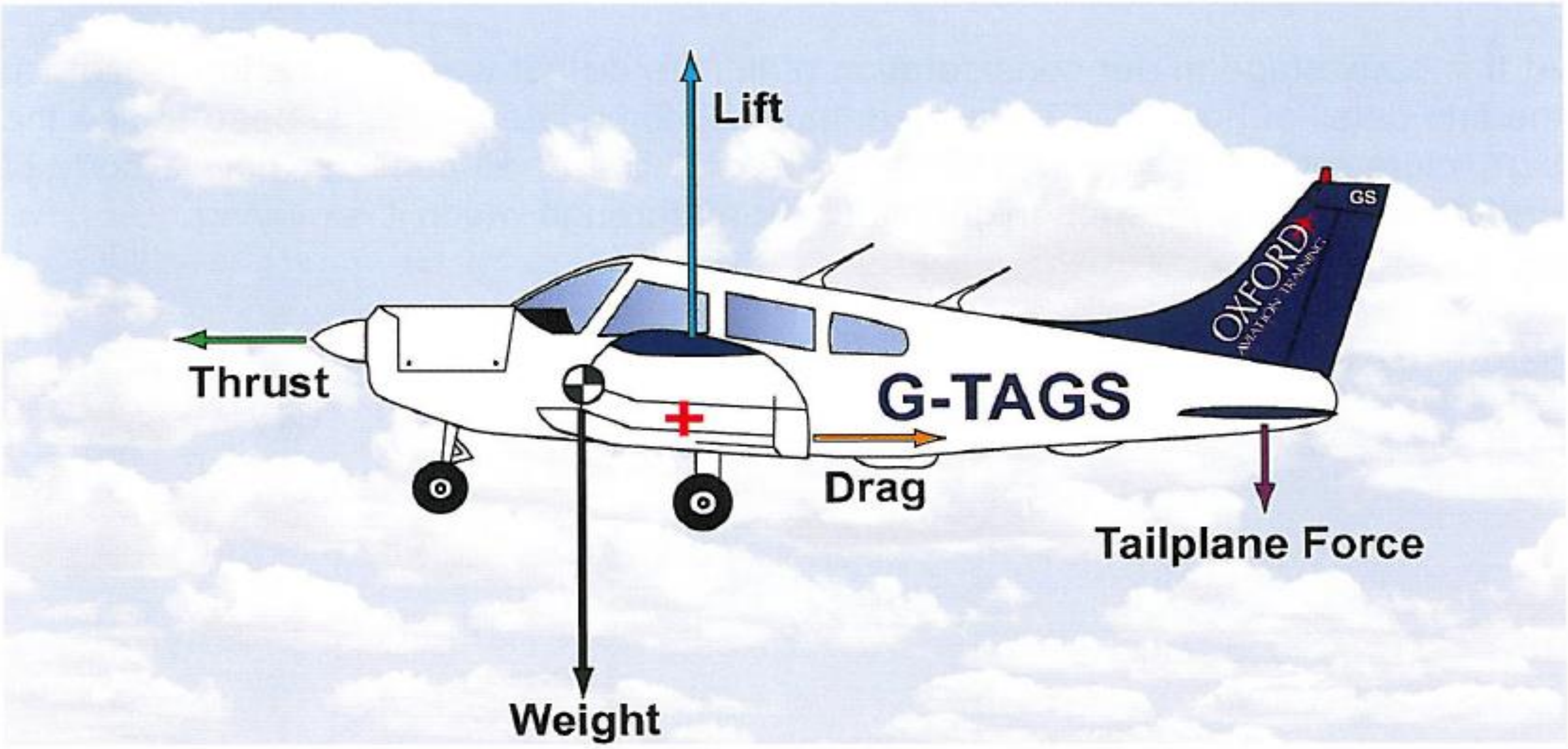
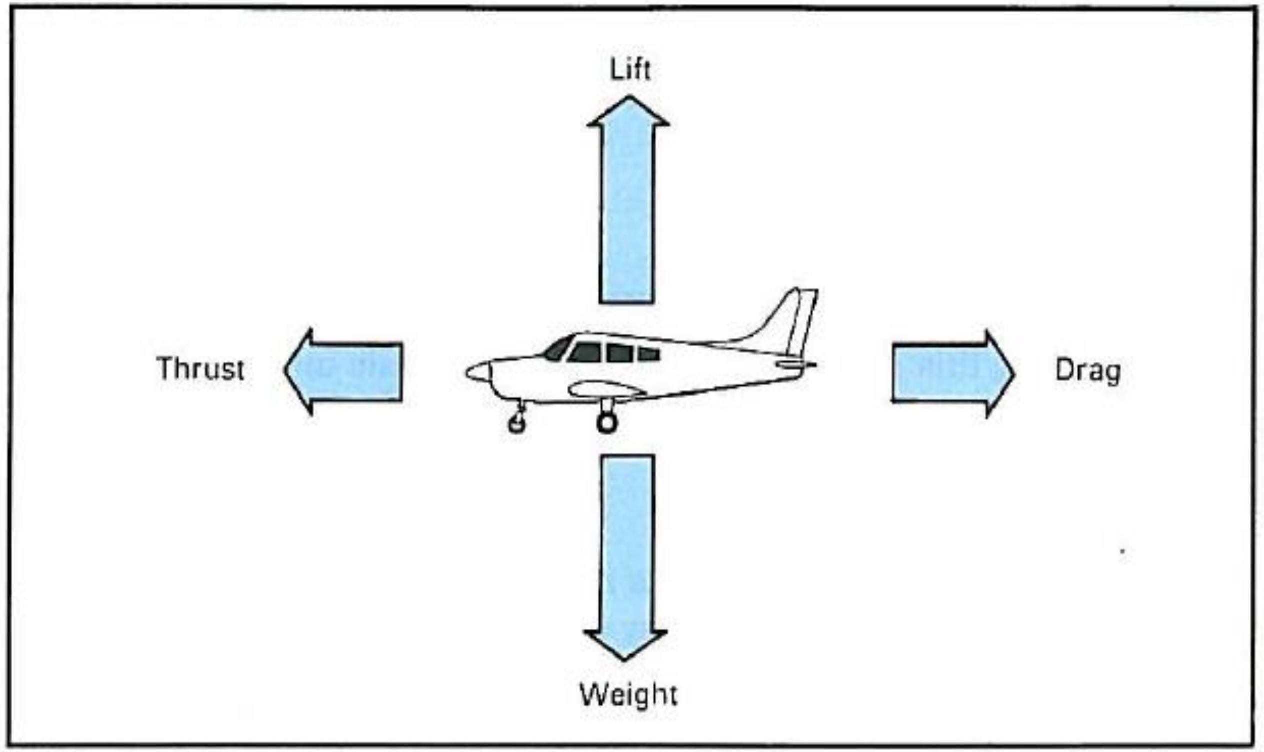


Figure 3.1 The Four Forces.


Lift
Thrust
Drag
Weight

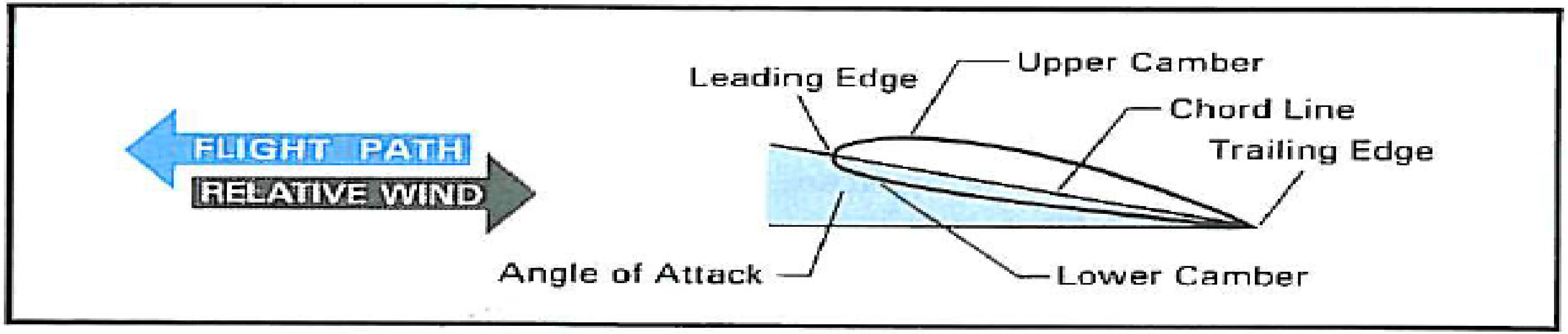
AIRFOILS

An airfoil is any surface, such as a wing, which provides aerodynamic force when it interacts with a moving stream of air. Remember, an airplane's wing generates a lifting force only when air is in motion about it. Some of the terms used to describe the wing, and the interaction of the airflow about it, are listed here. [Figure 1-16]

Leading edge — This part of the airfoil meets the airflow first.

Trailing edge — This is the portion of the airfoil where the airflow over the upper surface rejoins the lower surface airflow.

Chord line — The chord line is an imaginary straight line drawn through an airfoil from the leading edge to the trailing edge.



Camber — The camber of an airfoil is the characteristic curve of its upper and lower surfaces. The upper camber is more pronounced, while the lower camber is comparatively flat. This causes the velocity of the airflow immediately above the wing to be much higher than that below the wing.

Relative wind — This is the direction of the airflow with respect to the wing. If a wing moves forward horizontally, the relative wind moves backward horizontally. Relative wind is parallel to and opposite the flight path of the airplane.

You shouldn't confuse the actual flight path with the flight attitude of the airplane. For example, the airplane's fuselage may be parallel to the horizon while the aircraft is descending. (Figure 1-17)

Angle of attack — This is the angle between the chord line of the airfoil and the direction of the relative wind. It is important in the production of lift. (Figure 1-18)

- The straight line drawn from the centre of curvature of the **leading edge** to the **trailing edge** is called the **chord line**.

- The **chord** (c) is the distance between the **leading edge** and **trailing edge** measured along the **chord line**.

- The line joining the **leading** and **trailing edges** of the **aerofoil** which is, at all points, equidistant from the upper and lower surfaces is known as the **mean Camber Line**.

- The **maximum camber** of an **aerofoil** is the point at which the distance (d) between the **mean camber line** and the **chord line** is maximum. The **maximum camber** is expressed as a percentage of the **chord:** $\frac{d}{c} \times 100$.

OGY.

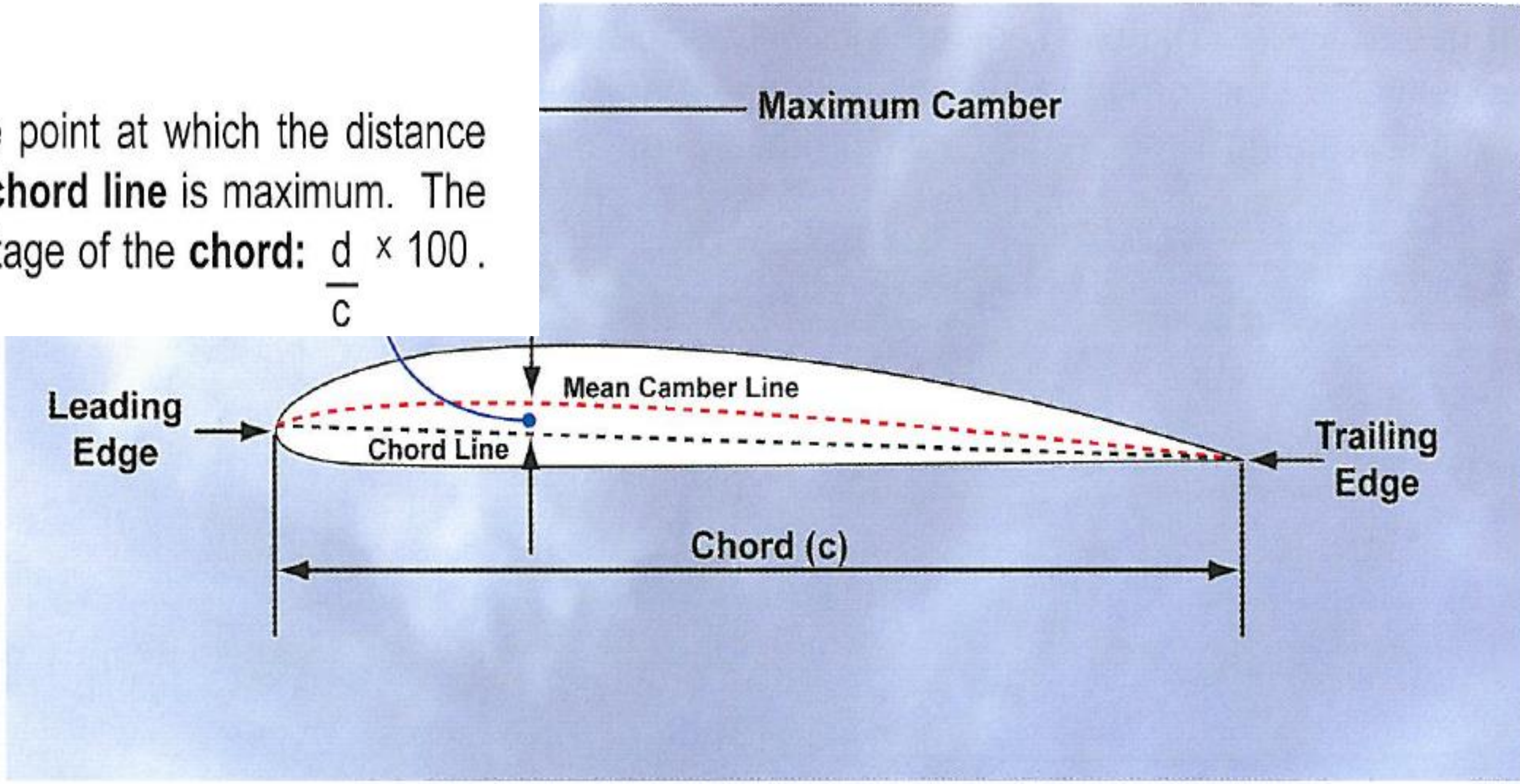


Figure 4.5 Aerofoil terminology.

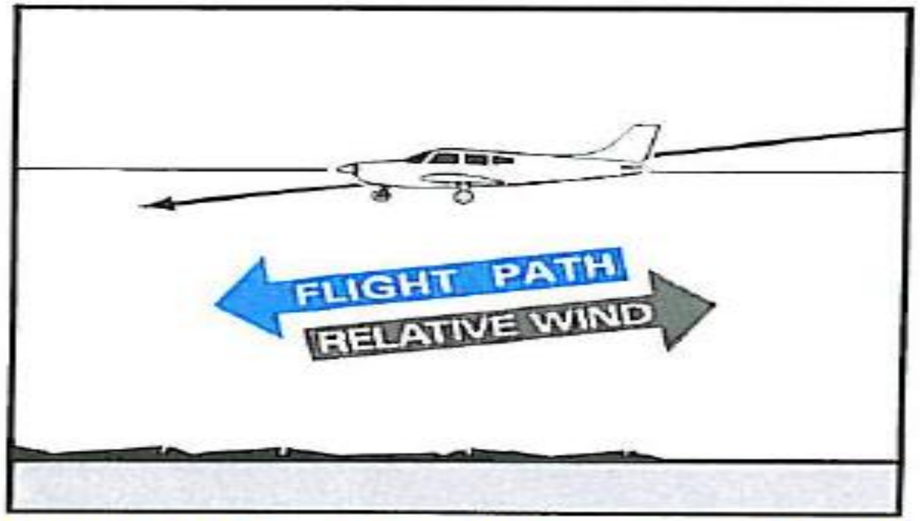


Figure 1-17. This airplane is in a level flight attitude, while the actual flight path is forward and down. Notice that the relative wind is upward and back, parallel to and opposite the flight path.

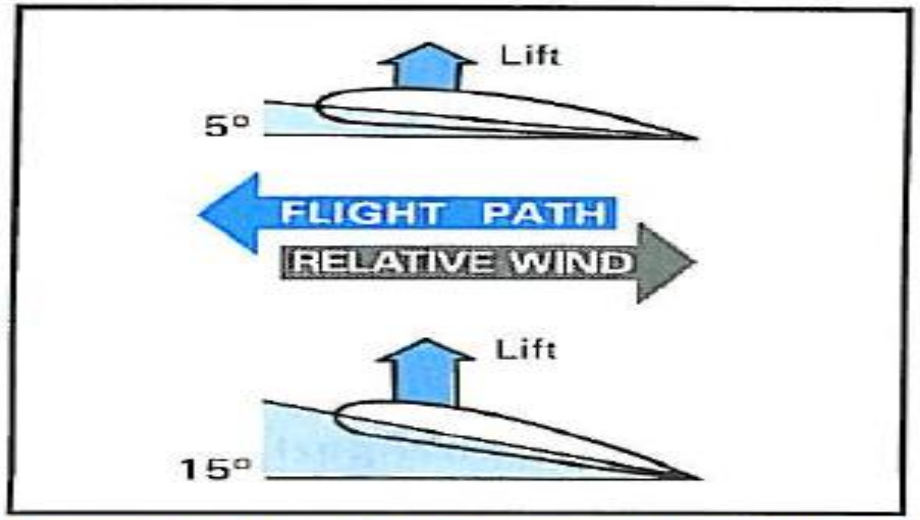


Figure 1-18. As the angle of attack increases, lift also increases. Notice that lift acts perpendicular to the relative wind, regardless of angle of attack.

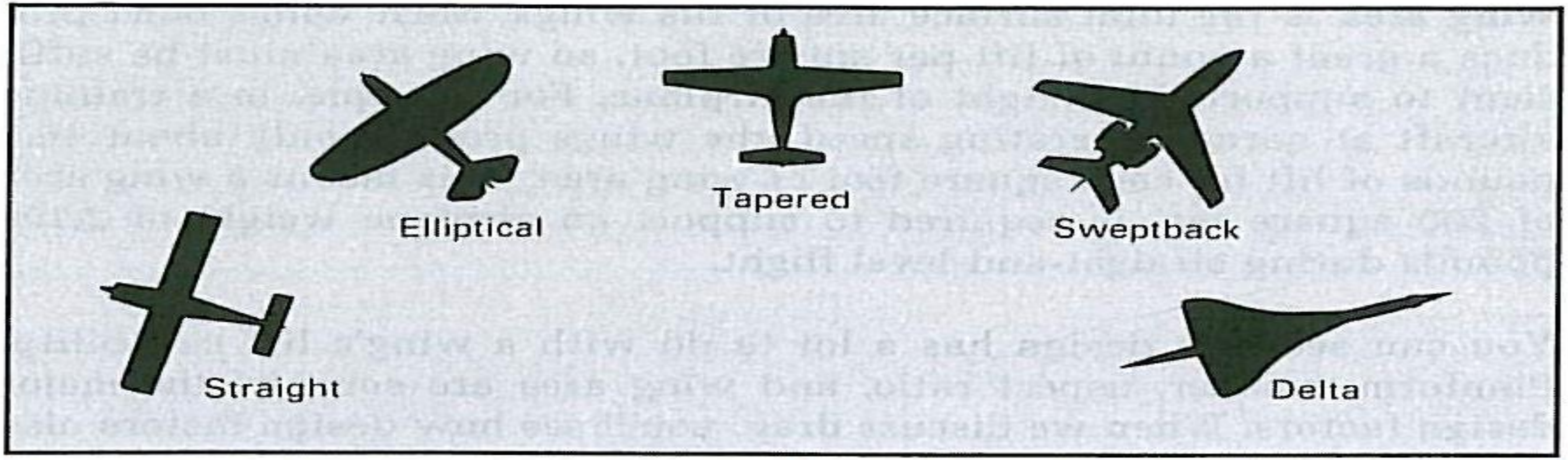
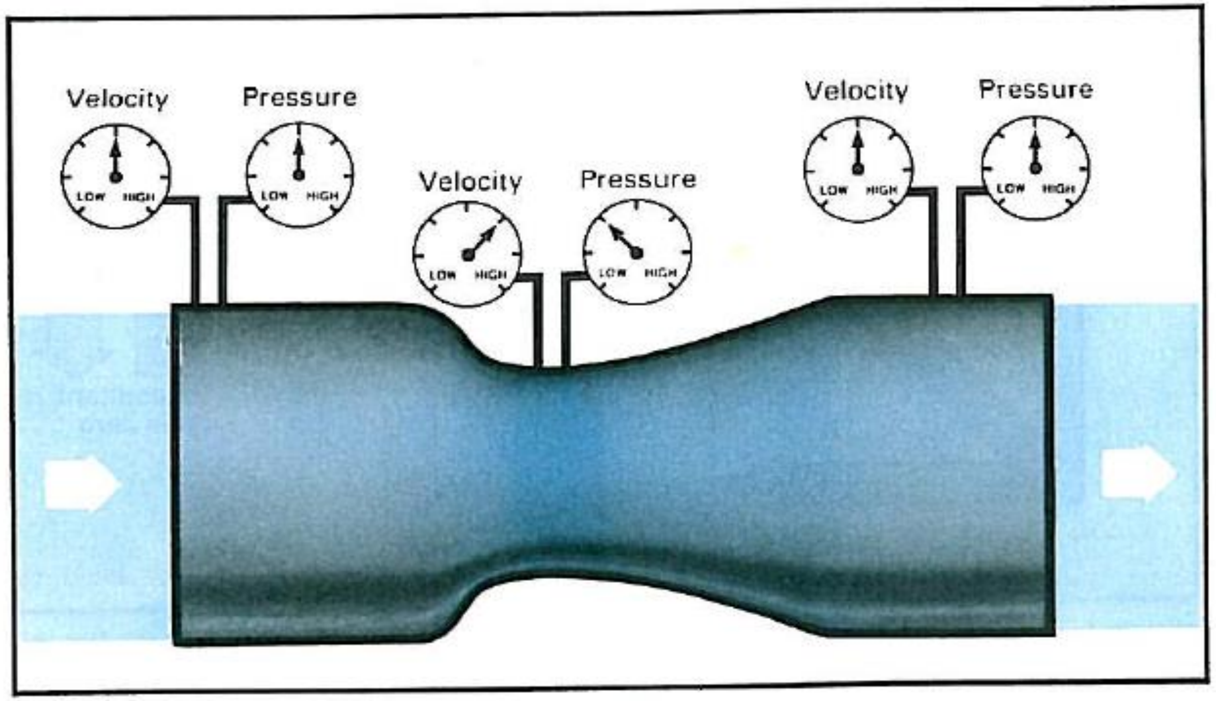


Figure 1-19. The straight wing has excellent slow-flight characteristics, and it is economical to build. However, it is inefficient from a structural, weight, and drag standpoint. The elliptical wing is more efficient in terms of weight and drag, but it has less desirable slow-flight characteristics and is more expensive. The tapered wing is relatively efficient with reasonable weight, drag, and construction costs, as well as good slow-flight capability. The sweptback and delta wings used on higher performance aircraft are efficient at high speeds, but not at low speeds.

BERNOULLI'S PRINCIPLE

The basic principle of pressure differential of subsonic airflow was discovered by Daniel Bernoulli, a Swiss physicist. **Bernoulli's Principle**, simply stated, says, "as the velocity of a fluid (air) increases, its internal pressure decreases."



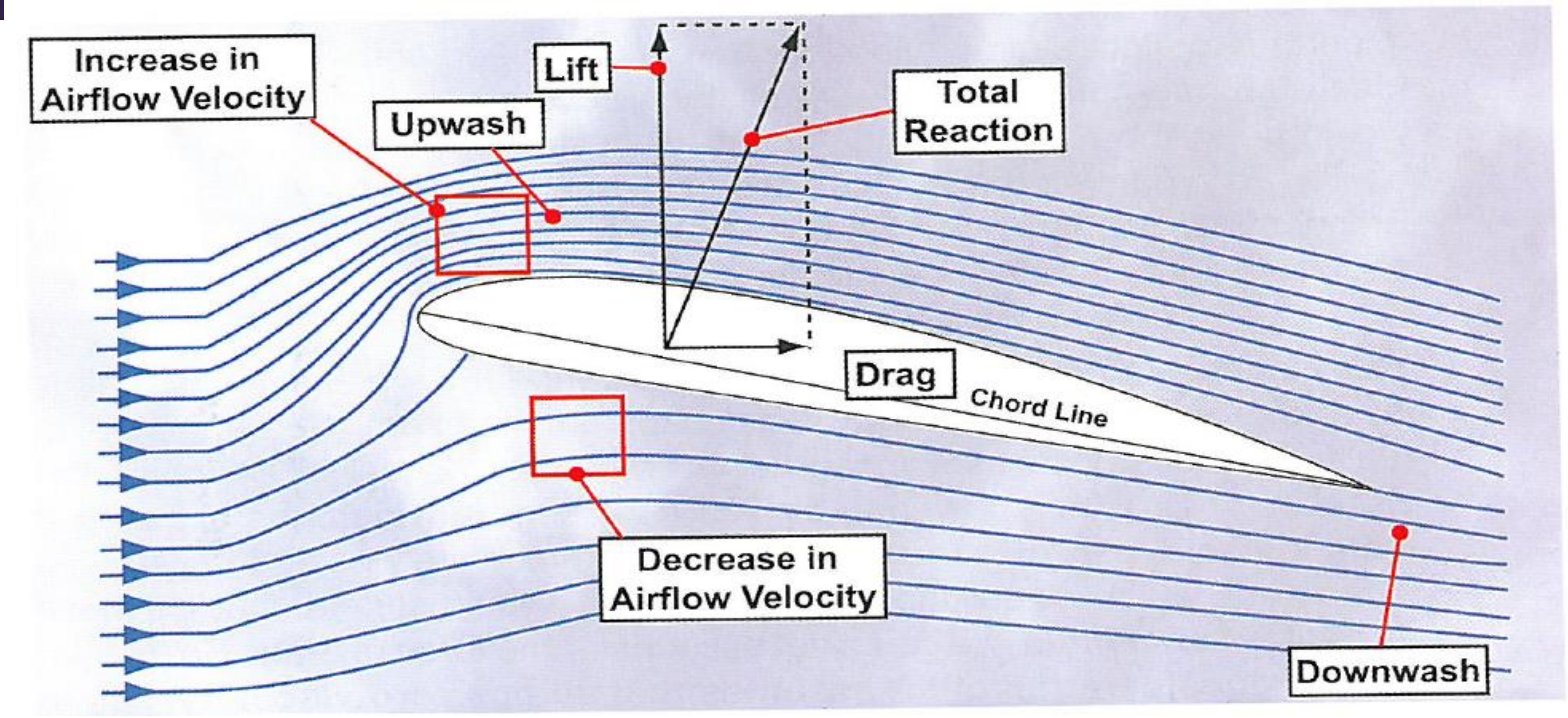
The wing of the airplane is shaped to take advantage of this principle. The greater curvature on the upper portion causes air to accelerate as it passes over the wing. The resulting pressure differential between the upper and lower surfaces of the wing creates an upward force. This difference in pressure is the main source of lift. (Figure 1-15)

NEWTON´S THIRD LAW OF MOTION

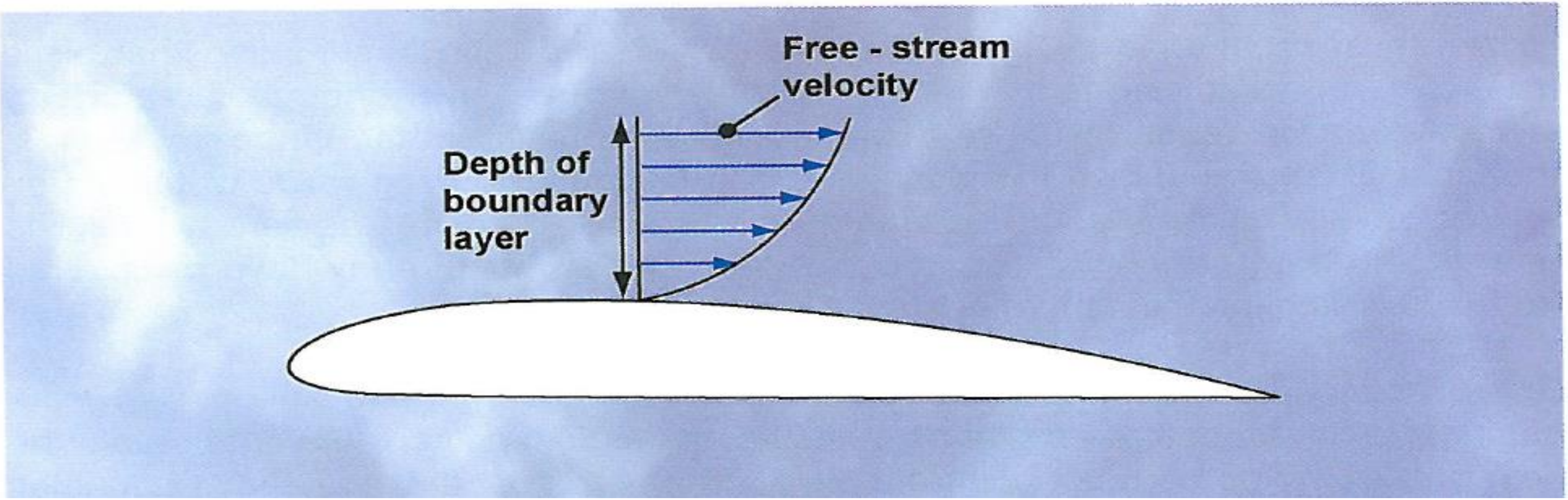
The remaining lift is provided by the wing's lower surface as air striking the underside is deflected downward. According to Newton's Third Law of Motion, "for every action there is an equal and opposite reaction." The air that is deflected downward also produces an upward (lifting) reaction.

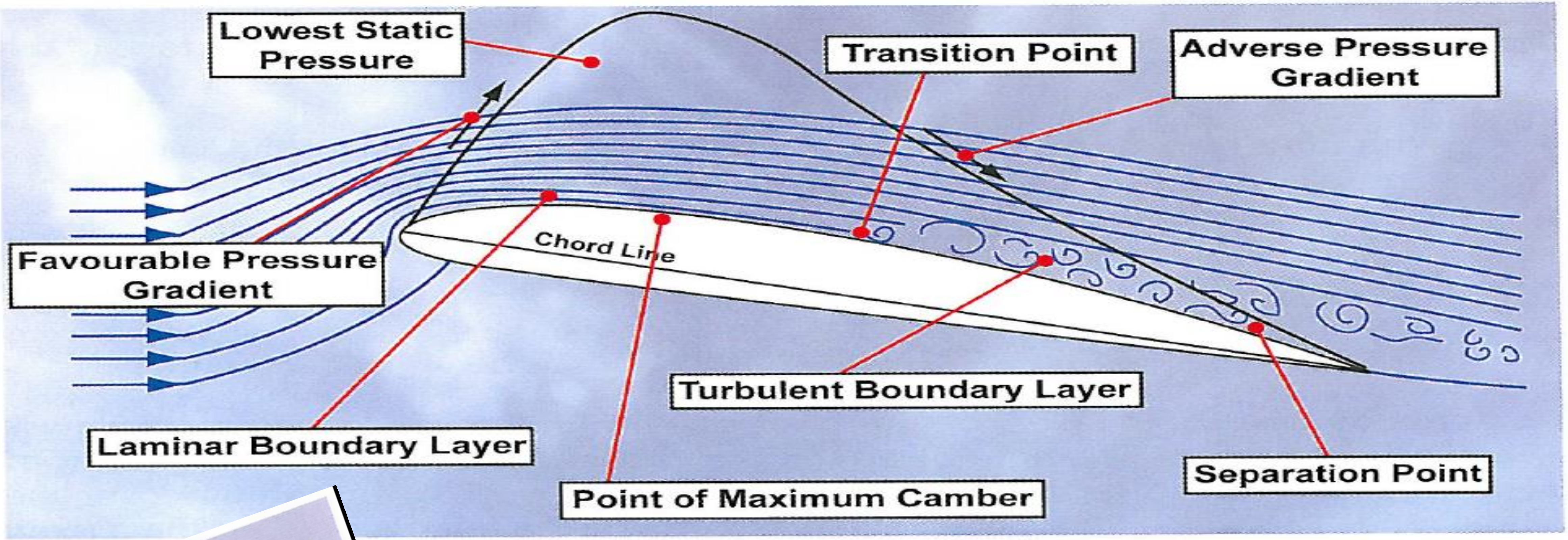
Since air is much like water, the explanation for this source of lift may be compared to the planing effect of skis on water. The lift which supports the water skis (and the skier) is the force caused by the impact pressure and the deflection of water from the lower surfaces of the skis.

Under most flying conditions, the impact pressure and the deflection of air from the lower surface of the wing provide a comparatively small percentage of the total lift. The majority of lift is the result of the decreased pressure above the wing rather than the increased pressure below it.


Increase in Airflow Velocity
Upwash
Lift
Total Reaction
Drag
Chord Line
Decrease in Airflow Velocity
Downwash

The **depth of airflow** within which the **frictional forces** generated by the viscosity of air cause the airflow's relative velocity to reduce from its free-stream value to zero on the aerofoil's upper surface constitutes what aerodynamicists call the **boundary layer**. The most common way of representing the changing velocity of the airflow within a boundary layer is to use the velocity profile shown in *Figure 4.1*. The depth of the **boundary layer** depicted in *Figure 4.1* is greatly exaggerated.





Figur[illegible] the Boundary Layer and Separation (NB: the depth of boundary layer is greatly exaggerated) .

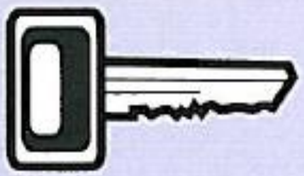
The point at which the pressure gradient becomes so adverse that the boundary layer separates from the wing's surface is called the separation point.

The transition point is the point where the airflow within the boundary layer changes from laminar to turbulent.

The Centre of Pressure.

Note that the **total reaction**, and the two components of the **total reaction: lift** and **drag**, are all shown originating at a point called the **Centre of Pressure.** *(See Figure 3.11 and 3.12).* **The Centre of Pressure** is defined as the point on a body through which the **total reaction** of all the aerodynamic forces affecting that body acts. When an aircraft is in cruising flight, the angle of attack is small, about 4°, and the **Centre of Pressure** lies approximately 1/3 of the way back from the wing's leading edge.

Do not confuse the **Centre of Pressure** with the aircraft's **Centre of Gravity** which is the point through which the **total weight** of the aircraft acts.



Lift can be considered as acting through the Centre of Pressure.

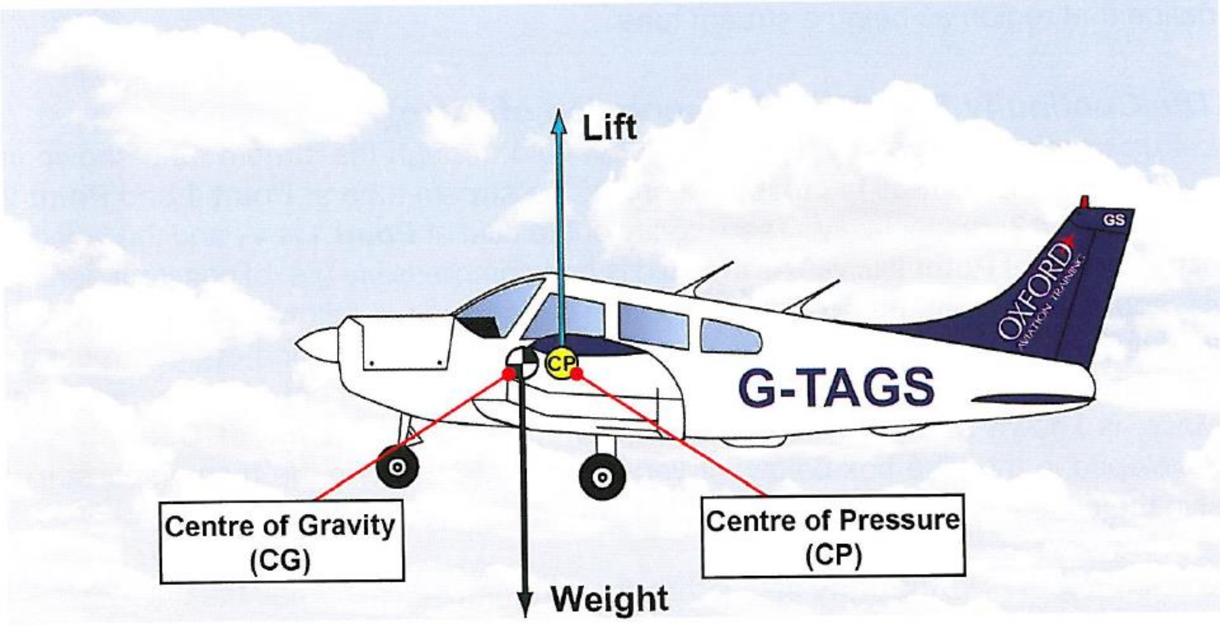
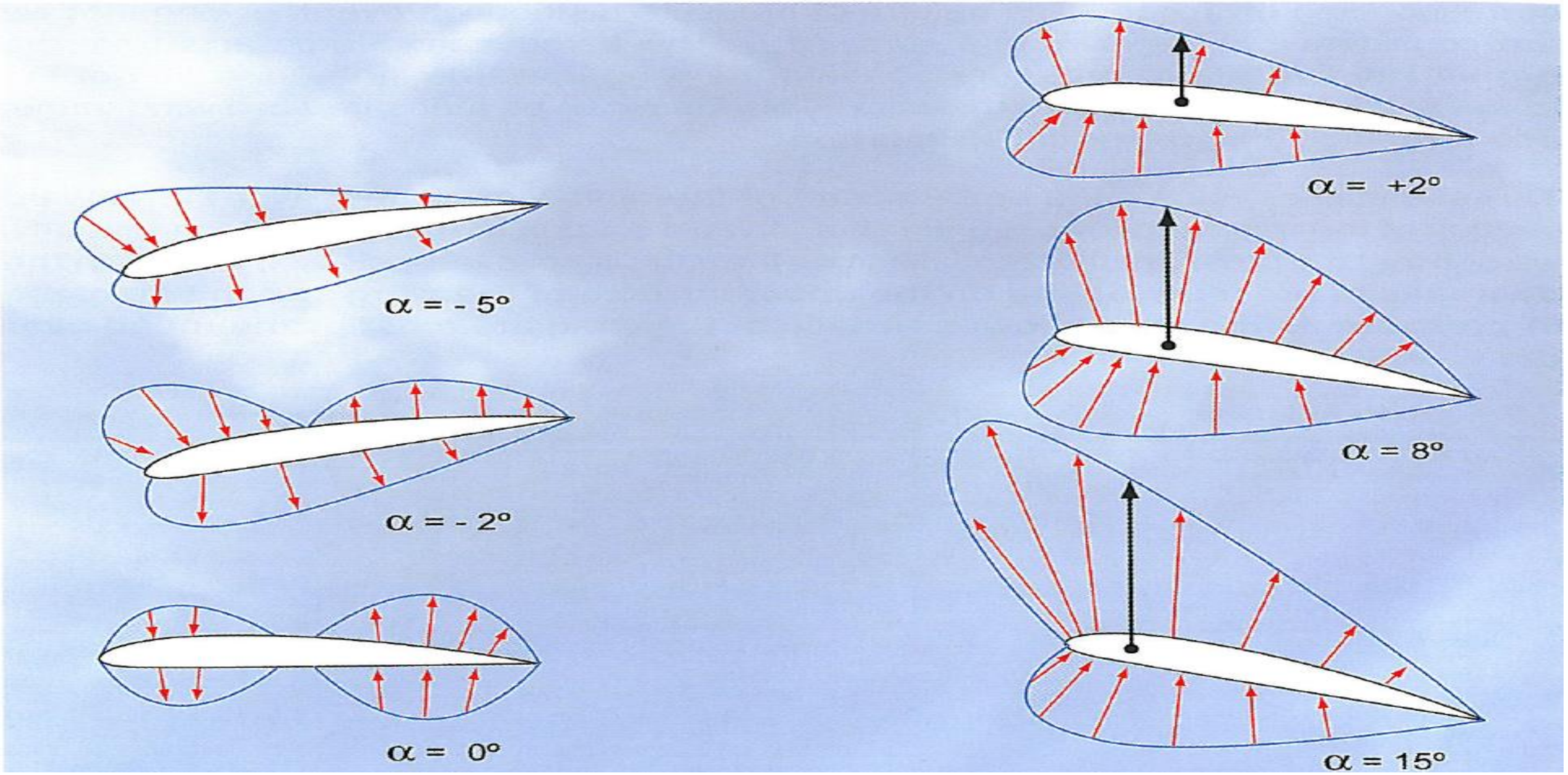


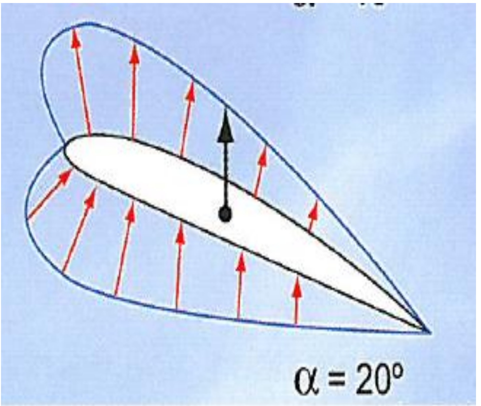
Figure 3.12 The Centre of Gravity and Centre of Pressure.

VARIATION OF LIFT AND PRESSURE DISTRIBUTION WITH ANGLE OF ATTACK.



As the angle of attack increases from 2° to 15° the **Centre of Pressure** gradually moves forwards and the resultant lift force increases in magnitude, until reaching about 16° (this is a typical stalling angle of attack for many light training aircraft). Beyond this lift force decreases abruptly and the **Centre of Pressure** moves rearwards again. This abrupt decrease in lift and rearwards movement of the **Centre of Pressure** is due to the separation of the airflow from the wing's upper surface. You will learn about separation in the Chapter on Stalling.

Lift increases with increasing angle of attack until reaching the stalling angle of attack of around 16°, at which point lift decreases abruptly.



Angle of Attack.

As we defined earlier, the **angle of attack** is the angle between the aerofoil's chord line and the relative (free stream) airflow. See *Figure 3.21*. Do not confuse the **angle of attack** with the **pitch attitude** of the aircraft. Your flying instructor will have a lot to say to you about **pitch attitude** and will define **attitude** for you precisely. As an approximate definition, we may say that **pitch attitude** is the angle of the aircraft's nose relative to the horizon.

Angle of attack is the angle between an aerofoil's chord line and the relative airflow.

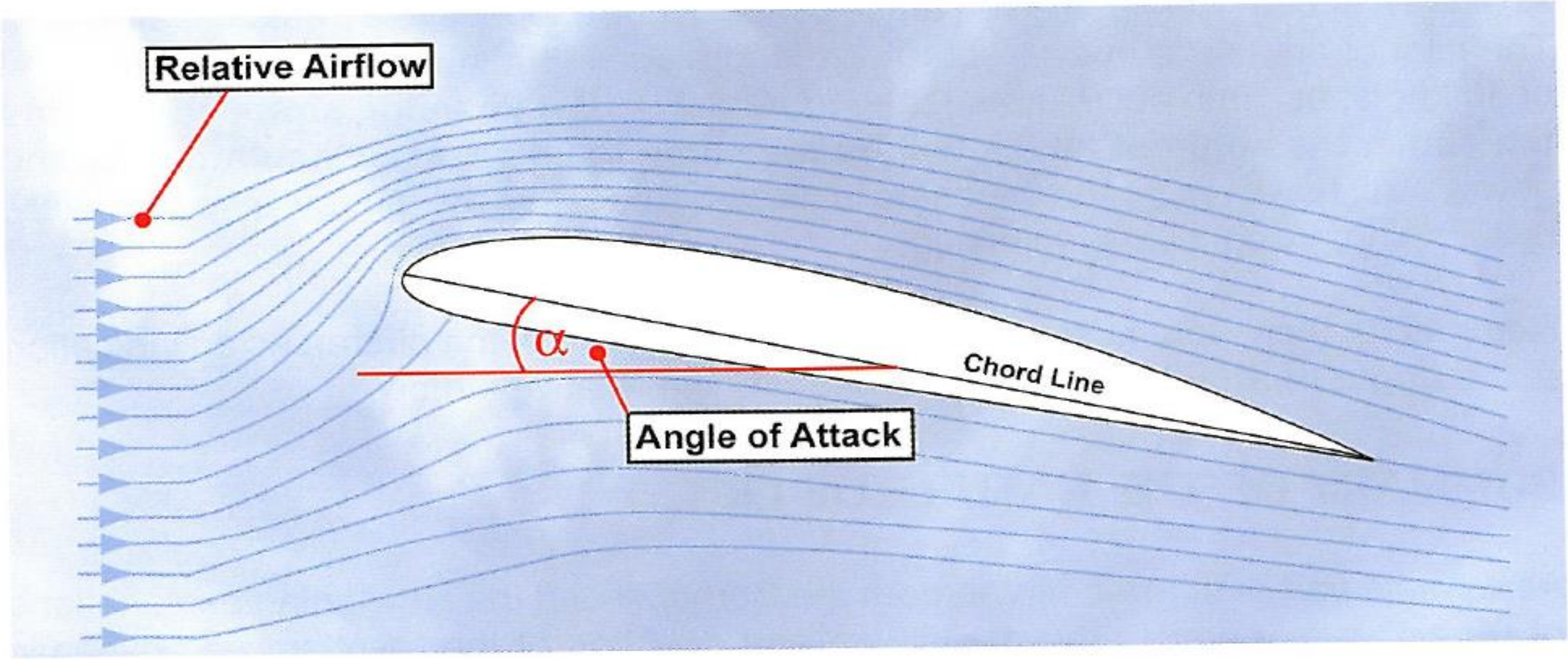
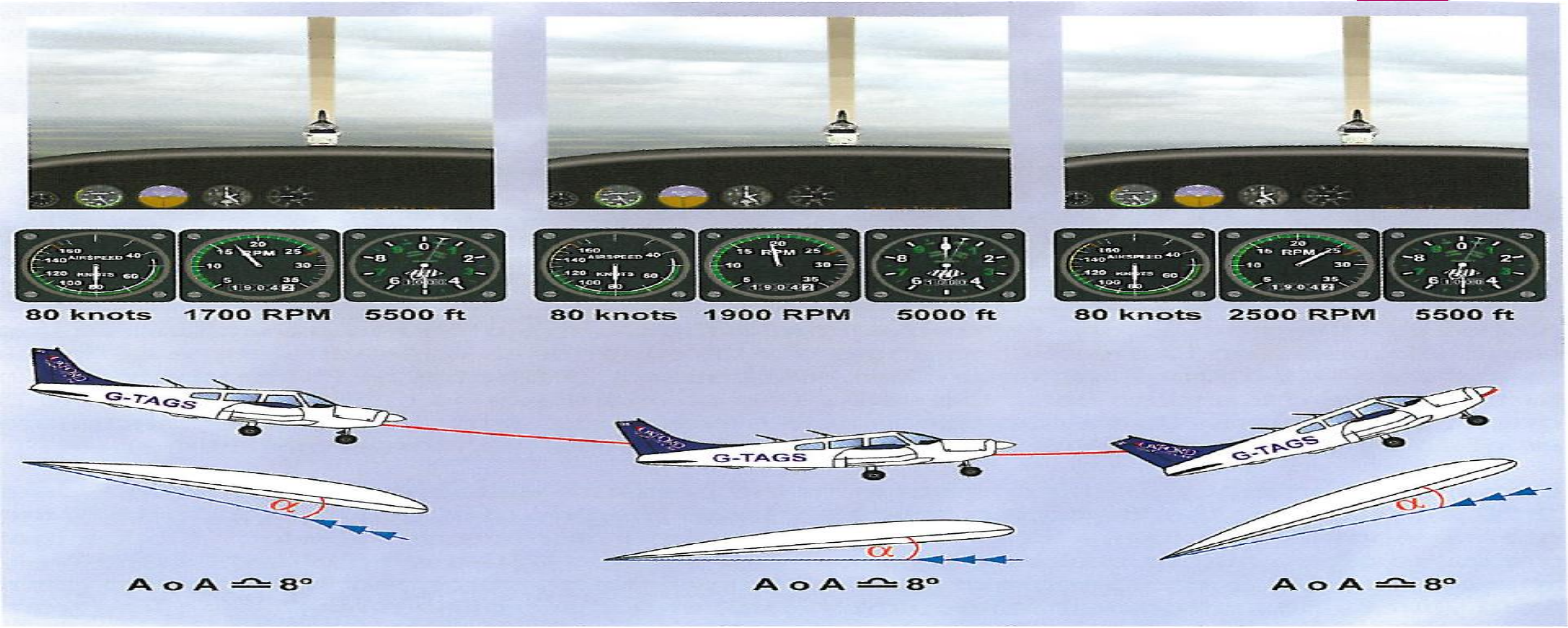


Figure 3.21 Angle of Attack.



At a given aircraft weight, a given angle of attack corresponds to a particular airspeed. The pilot of an aircraft may elect to descend at, say, 80 knots, fly straight and level at 80 knots, or climb at 80 knots *(see Figure 3.21)*. **Because the airspeed remains the same, the angle of attack will be the same in all cases. Pitch attitude** (and power) will, however, <u>not</u> be the same in all cases because the aircraft is, respectively, descending, flying level or climbing.

Remember, then, you must <u>not</u> treat the **pitch attitude** of the aircraft as an indication of the **angle of attack** between the wing and the relative airflow.

THE GENERAL LIFT EQUATION AND THE COEFFICIENT OF LIFT.

$$\textbf{Lift} = C_L \tfrac{1}{2} \rho v^2 S$$

C_L is the **coefficient of lift** which takes account of the **shape** of the aerofoil and the aerofoil's **angle of attack** with the relative airflow. C_L has no units

½ is a constant which is arrived at by experiment.

ρ is a Greek letter (pronounced "roe") which represents the density of the air. ρ has the units **kg/m³**

v is the **velocity** of the free-stream relative airflow which is the same as the **true airspeed** of the aircraft. Notice that lift varies according to the **square** of the velocity; **v** has the units **m/sec**

S is the surface area of the wing. **S** has the units **m²**.

Lift = $C_L \frac{1}{2} \rho v^2 S$

- **Lift is directly proportional to air density**. This information is not very useful because a pilot can do nothing about **air density**, although he might deduce that the higher he flies, the lower will be the **air density**, and he might suspect that this fact might somehow affect the aircraft's performance.

- **Lift is directly proportional to wing area.** That can be useful knowledge if an aircraft is fitted with Fowler Flaps which extend from the wing, and so increase area. The pilot might deduce, for instance, that with Fowler Flaps extended, he can generate the same lift at lower airspeeds.

- **Lift is directly proportional to the square of the airspeed;** so, if the aircraft flies twice as fast, the lift generated by the wings will increase fourfold. This is very useful information, because the pilot will see immediately that his ability to control the aircraft's speed gives him direct control over the lift produced by the wings.

- **Lift is directly proportional to the Coefficient of Lift, C_L**. This is also very useful information. We have learnt that C_L includes both the **shape** of the wing and the **angle of attack** of the wing with the free-stream relative airflow. By increasing the **angle of attack**, the pilot can increase C_L and so increase the lift produced by the wing, **but not beyond the angle of attack for maximum lift**. By selecting flap, the pilot can also modify the **shape** of his aircraft's wing and, therefore also modify the value of C_L. He will understand, therefore, that the selection or deselection of flap will affect the lift generated by the wing.

Variation of Coefficient of Lift with Angle of Attack

To bring this chapter on **lift** to a close, let us examine a graph illustrating how the Coefficient of Lift, $\mathbf{C_L}$, and so (because **lift** is directly proportional to $\mathbf{C_L}$) the **total lift** produced by any given wing, varies with **angle of attack**.

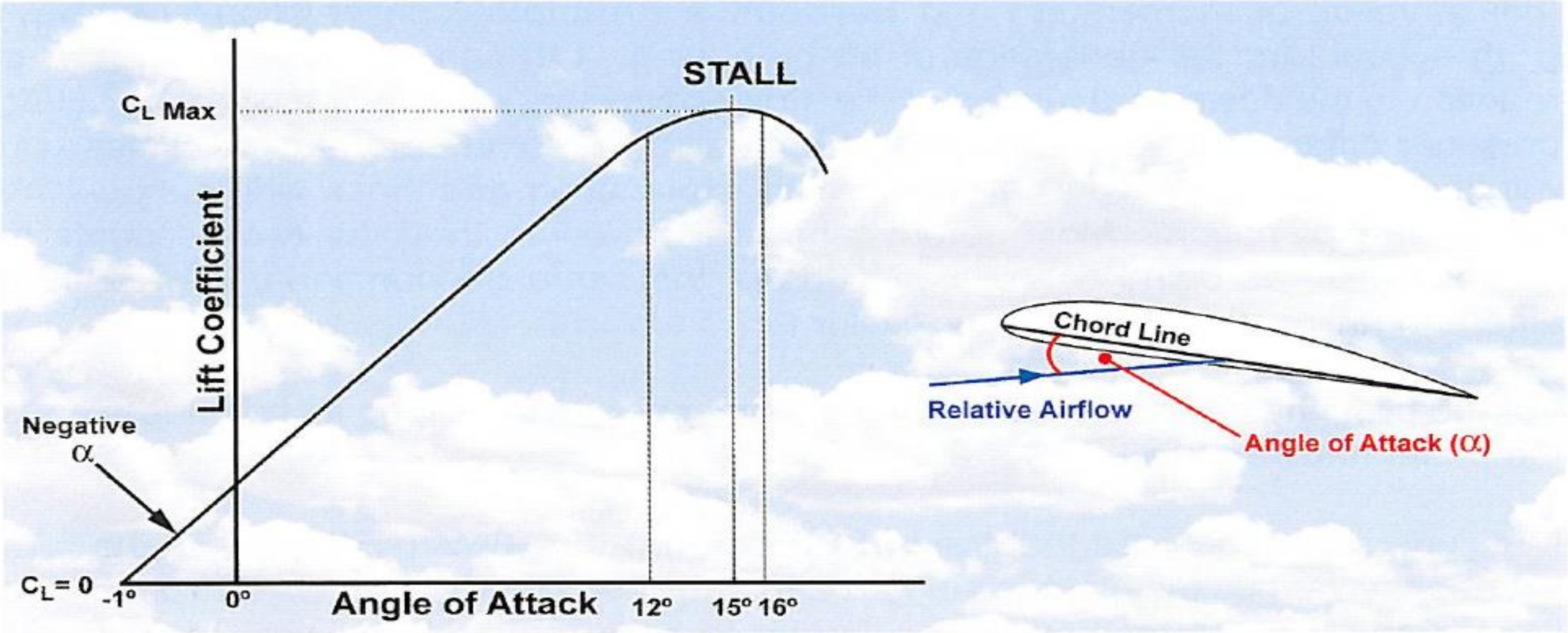


Figure 3.22 The variation of C_L with Angle of Attack.

AIRFOIL DESIGN FACTORS

Wing design is based on the anticipated use of the airplane, cost, and other factors. The main design considerations are wing planform, camber, aspect ratio, and total wing area.

Planform refers to the shape of the airplane's wing when viewed from above or below. Each planform design has advantages and disadvantages. (Figure 1-19)

Camber, as noted earlier, affects the difference in the velocity of the airflow between the upper and lower surfaces of the wing. If the upper camber increases and the lower camber remains the same, the velocity differential increases.

There is, of course, a limit to the amount of camber that can be used. After a certain point, air will no longer flow smoothly over the airfoil. Once this happens, the lifting capacity diminishes. The ideal camber varies with the airplane's performance specifications, especially the speed range and the load-carrying requirements.

Aspect ratio is the relationship between the length and width of a wing. It is one of the primary factors in determining lift/drag characteristics. At a given angle of attack, a higher aspect ratio produces less drag for the same amount of lift. (Figure 1-20)

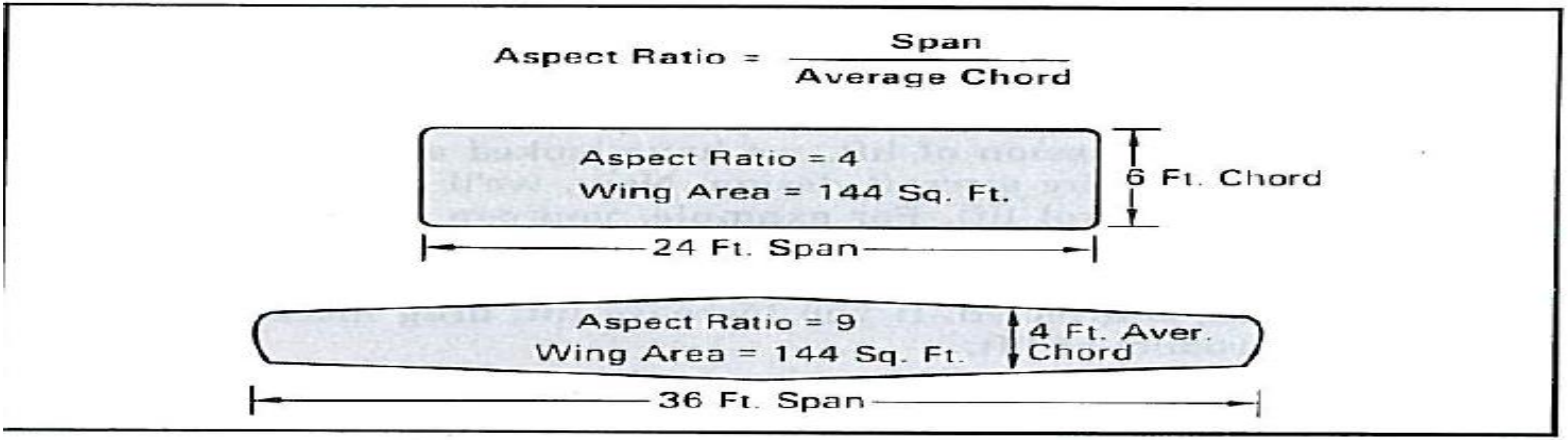


Figure 1-20. Aspect ratio is the span of the wing, wingtip to wingtip, divided by its average chord. In general, the higher the aspect ratio, the higher the lifting efficiency of the wing. For example, gliders may have an aspect ratio of 20 to 30, while typical training aircraft have an aspect ratio of about seven to nine.

Wing area is the total surface area of the wings. Most wings don't produce a great amount of lift per square foot, so wing area must be sufficient to support the weight of the airplane. For example, in a training aircraft at normal operating speed, the wings produce only about 10.5 pounds of lift for each square foot of wing area. This means a wing area of 200 square feet is required to support an airplane weight of 2,100 pounds during straight-and-level flight.

Once the design of the wing is determined, the wing must be mounted on the airplane. Usually it is attached to the fuselage with the chord line inclined upward at a slight angle, which is called the **angle of incidence**. (Figure 1-21)

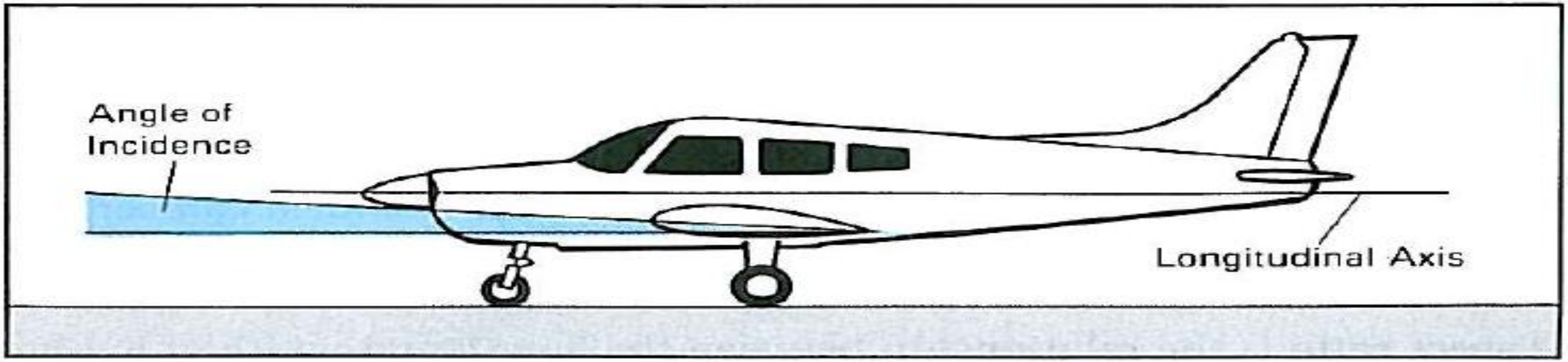


Figure 1-21. Angle of incidence refers to the angle between the wing chord line and a line parallel to the longitudinal axis of the airplane. A slight positive angle of incidence provides a positive angle of attack while the airplane is in level flight at normal cruising speed. It also improves over-the-nose visibility when the airplane is in a level flight attitude.

PILOT CONTROL OF LIFT

CHANGING ANGLE OF ATTACK

CHANGING AIRSPEED

USING FLAPS

١٢. To generate the same amount of lift as altitude is increased, an airplane must be flown at

A. The same true airspeed regardless of angle of attack.
B. A lower true airspeed and a greater angle of attack.
C. A higher true airspeed for any given angle of attack.

١٢٠. Drag is acting in the direction of ………; lift is perpendicular to the… …..

A. Chord line.
B. Relative wind (airflow).
C. Horizon.

٢٢. Lift on a wing is most properly define as the

A. Force acting perpendicular to the relative wind.
B. Differential pressure acting perpendicular to the chord of the wing.
C. Reduce pressure resulting from a laminar flow over the upper chamber of an airfoil which acts perpendicular to the mean camber.

١٤٩. Of the total lift produced by the wing:

A. The lower surface produces the greater proportion.
B. The upper and lower surfaces always give equal proportions of the lift.
C. The upper surface produces the greater proportion at at all speeds.

١٥٠.Downwsh is:

A. The decreases in the angle of incidence from root to tip of the wing.
B. The higher speed airspeed behind the propeller.
C. The downward deflection of the airflow behind the wing.

١٥٣. At zero angle of attack in flight, a symmetrical wing section will produce:

A. Some lift and drag.
B. Zero lift with some induced and profile drag.
C. Zero lift with some drag.

١٥٦. Lift of a wing is increased by:

A. An increase in the temperature of the atmosphere.
B. An increase in the pressure of the atmosphere.
C. An increase in the humidity of the atmosphere.

CHAPTER 5
DRAG

A body moving through a viscous fluid such as air will, because it displaces the air, experience a resistance to its motion which is given the name **drag**.

Total drag is divided into two main sub categories: **parasite drag** and **induced drag**.

Parasite drag is the **drag** which is generated as the air flows around the aircraft, by virtue of such things as the aircraft's **shape**, **speed** (dynamic pressure), **frontal area**, and the **texture and condition** of the aircraft's **surface**. You will sometimes hear **parasite drag** referred to as **profile drag** or **zero-lift drag**. **Zero-lift drag** is a good descriptive term for **parasite drag** because it emphasises that this type of **drag** is unconnected to **lift**.

Induced drag is the **drag** which is produced as a <u>by-product</u> of **lift**. **Parasite drag** will be present even if the aircraft is flying at an angle of attack at which the wings are producing no **lift**. When the wings are producing **lift**, some **drag** will be generated which is additional to the **parasite drag**. The <u>additional</u>, <u>lift-dependent</u> drag is called **induced drag**. You may often hear **induced drag** <u>called</u> **lift-dependent drag**.

PARASITE DRAG.

Parasite drag may be further sub-divided into **skin-friction drag**, **form drag** (sometimes called **profile drag** or **pressure drag**) and **interference drag**. *(See Figure 5.2.)*

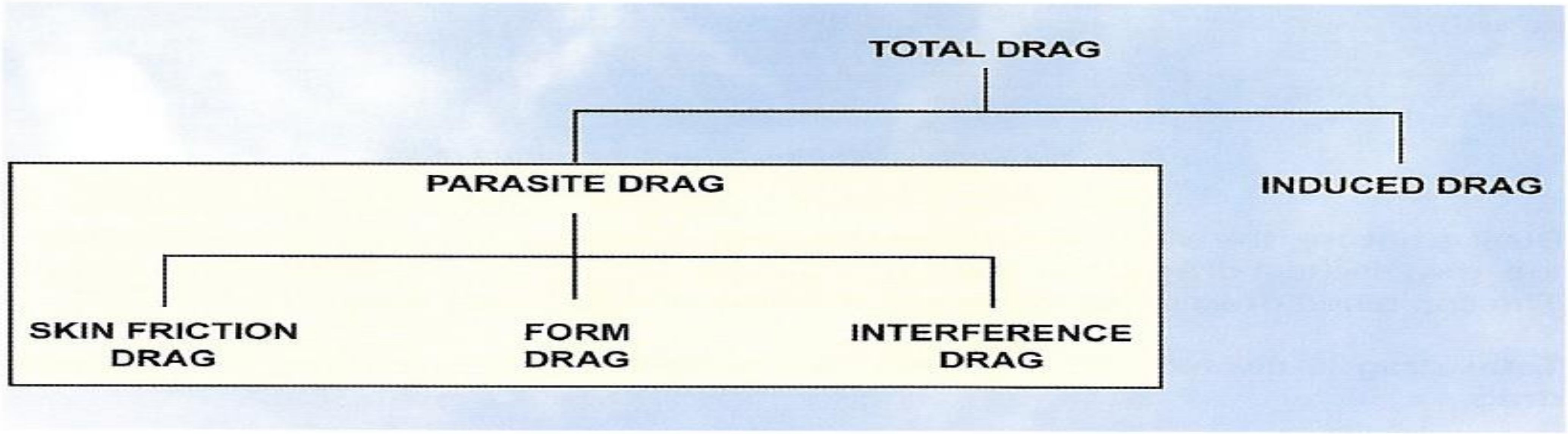


Figure 5.2 The components of Parasite Drag.

Skin-Friction Drag.

If the airflow within the boundary layer remains laminar over as much of the aerofoil as possible, so that the layers of air are kept sliding smoothly over each other, **skin-friction drag** is reduced. The turbulent section of the boundary layer is much thicker than the laminar boundary layer. Because of the energy expended in the change of the airflow from laminar to turbulent, it is estimated that a turbulent boundary layer causes in the region of five times as much **skin-friction drag** as a laminar boundary layer.

Any roughness on the skin of a leading portion of an aircraft's airframe will induce a turbulent flow and increase skin-friction drag.

A polished aircraft not only looks good, but will fly more efficiently since **skin-friction drag** is reduced. Construction methods can greatly affect skin friction. Flush riveted or bonded metal aircraft will have less skin friction than aircraft with rivet heads that stand proud, or fabric aircraft with pronounced stitching. *(See Figure 5.3.)*

Figure 5.3 The surface area and the surface finish affect skin friction drag.

Many aircraft today are constructed from composite materials, which produce continuous smooth structures with low skin friction values. *(See Figure 5.4.)*

The manufacturer will determine the type of construction of the aircraft, and its inherent skin friction values. In service, the aircraft's surface can become contaminated with dirt, water, ice, frost or snow, which will affect not only the **skin-friction drag** but also the **lift** that can be produced.

Figure 5.4 Composites materials produce continuous smooth structures which have low skin-friction drag.

Figure 5.5 The surface area and the surface finish affect skin friction drag.

Tests have shown that wing contamination of a thickness and surface roughness similar to medium or coarse sandpaper will reduce **lift** by as much as 30%. *(See Figure 5.5.)*

Any contaminants on the aircraft's surface, especially on the wing, will increase **skin-friction drag**, as well as adversely affecting the aerofoil profile, adding to the weight and, thus, increasing stalling speed. A pilot must always remove such contaminants as ice, snow, or squashed insects from the wings before flight, especially from the leading edge and the area around it.

Form Drag.

The **form drag** (sometimes called **profile drag** or **pressure drag**) acting on a body moving through a viscous fluid is the name given to the type of drag generated principally by the shape of the body. An aircraft's shape will influence the extent to which the air through which it is moving is disturbed. All aircraft, whatever their shape, cause a very significant disturbance to the air.

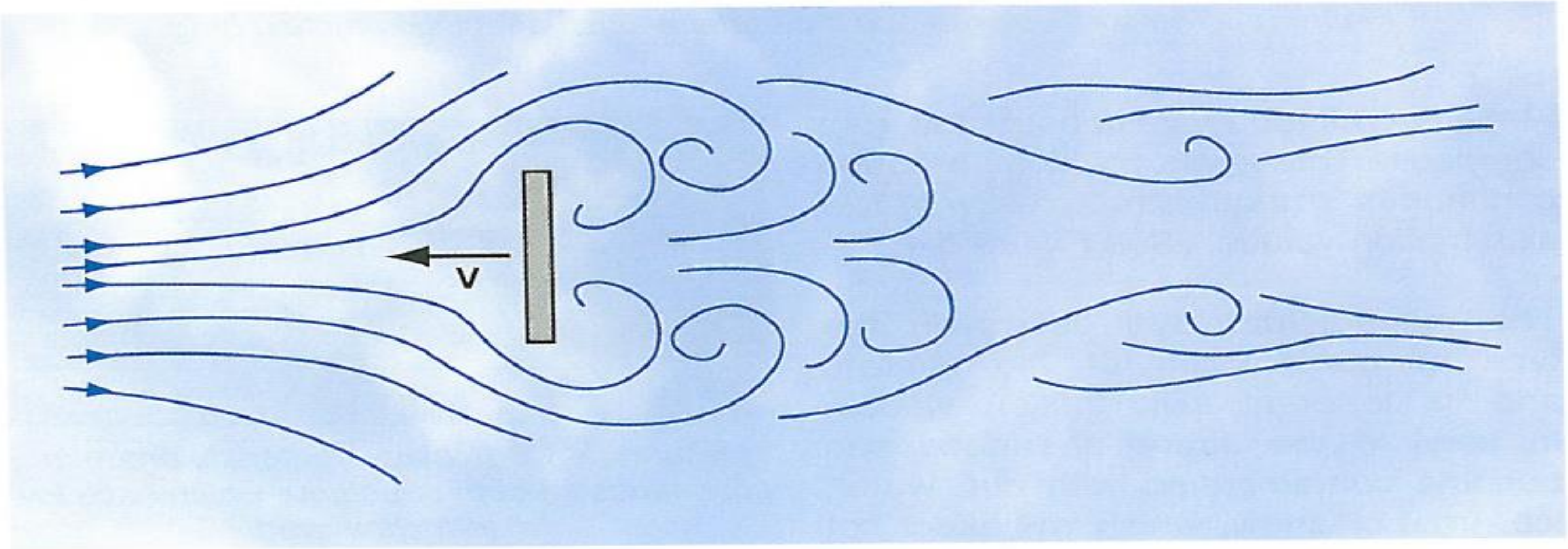


Figure 5.6 A flat plate moving through the air, at a right angle to the airflow, generates a very large amount of form drag.

Reducing Form Drag through Streamlining.

In the chapter on **lift** you learned that lines which show the direction of flow of a fluid at any particular moment are called **streamlines**. A body so shaped as to produce the least possible turbulence in the air flowing around it is said to be a **streamlined** shape. A **streamlined** shape will, consequently, generate far less **form drag** that a shape of large, flat, frontal cross-sectional area.

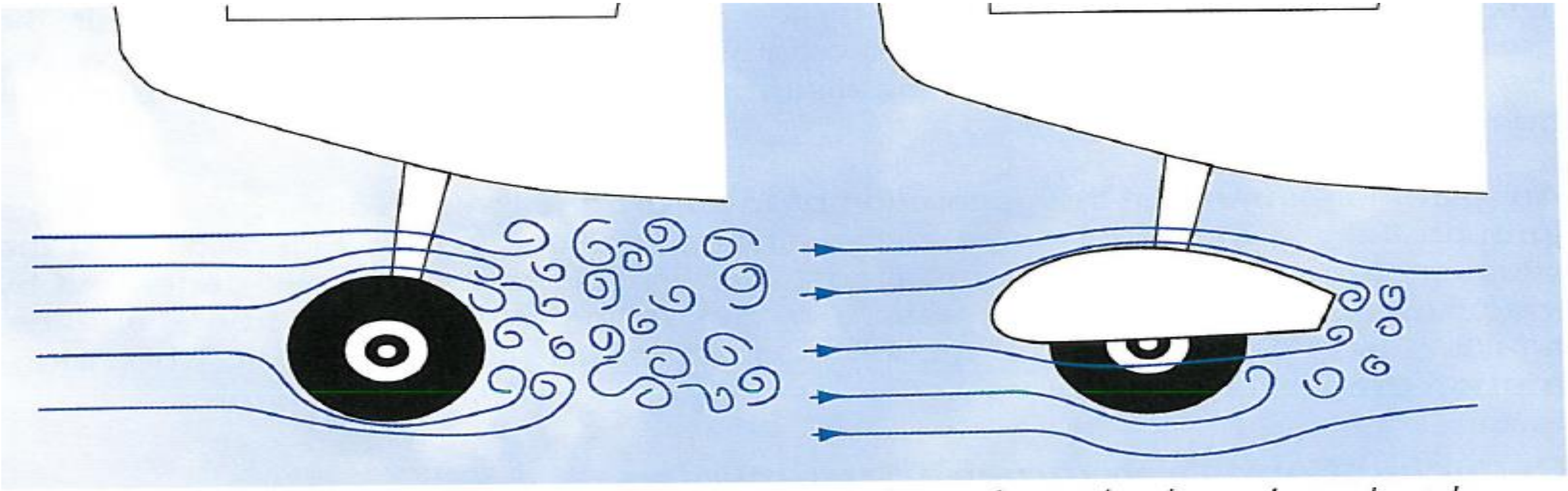


Figure 5.8 The form drag generated by an undercarriage wheel may be reduced by fitting spats.

Increase in Form Drag with Increasing Angle of Attack.

We have established, then, that the **form drag** generated by an aircraft increases in proportion as the air is disturbed by the aircraft's passage. You will not be surprised to learn, therefore, that **form drag** increases as a wing's **angle of attack** increases. You may remember that, as **angle of attack** increases, the **separation point**, at which the boundary layer breaks away from the wing, moves forward towards the wing's leading edge, creating an increasing area of erratic and haphazard airflow, aft of the wing. As the **angle of attack** approaches the **stalling angle** (typically 16° for a light training aircraft without sophisticated lift augmentation devices), the erratic, haphazard wake, behind the wing, thickens, causing **form drag** to increase rapidly. *Figure 5.9* illustrates this phenomenon. In order to keep things simple, we depict only the airflow above the wing. The increase in **form drag** with increasing angle of attack explains why **drag** increases markedly at the **point of stall**, to accompany the abrupt decrease in **lift**.

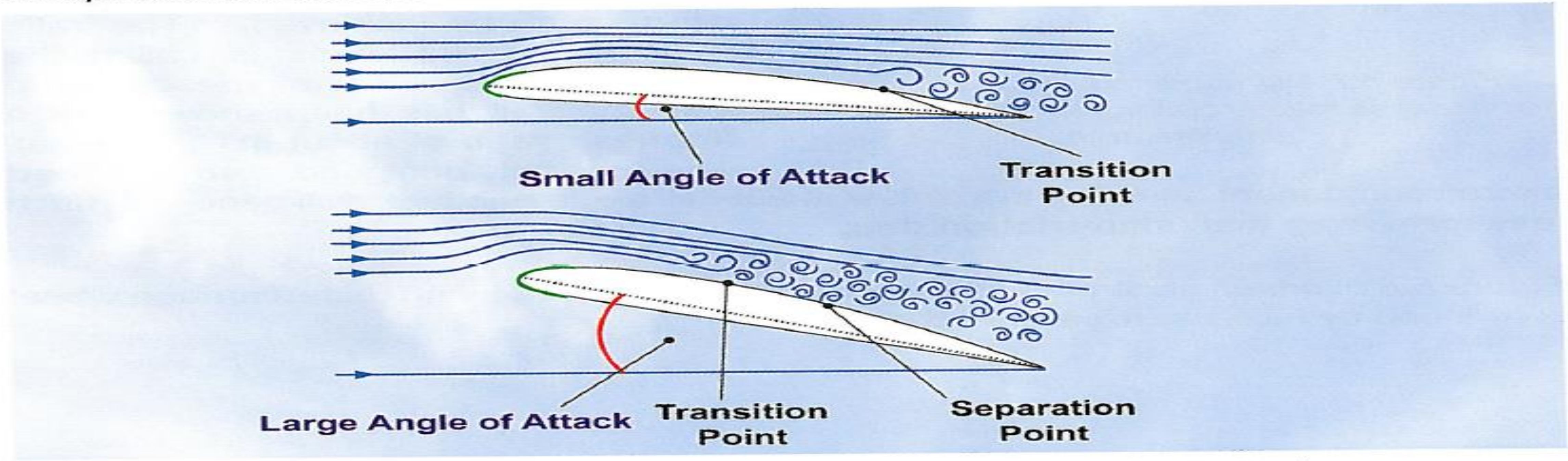


Figure 5.9 Form drag increases with increasing angle of attack.

Interference Drag.

Although the **form drag** of any aircraft component may be minimised by **streamlining**, it is not always the case that two **streamlined** components will generate minimum **form drag**, if those components are joined together. It can be demonstrated by experiment that the **form drag** generated by a complete aircraft is greater than the sum of the separate elements of **form drag** generated by each individual component.

This additional **increment in form drag** is called **interference drag**. **Interference drag** is caused, primarily, by the joining of the wings to the fuselage.

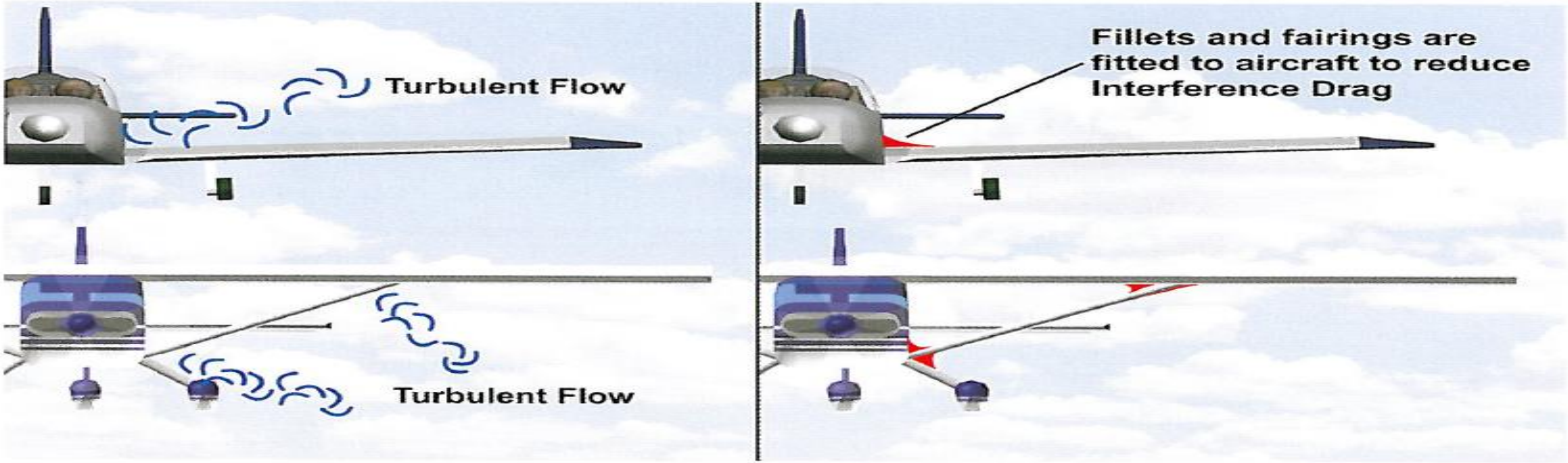


Figure 5.10 Interference drag occurs, primarily, at the junction between wing and fuselage, and may be reduced by fitting fairings of fillets.

Interference drag can be reduced at the junctions where components meet by ensuring that no sharp angles are formed by the junctions. This is achieved by fitting **fairings** or **fillets** *(see Figure 5.10)*.

The Variation of Parasite Drag with Aircraft Speed.

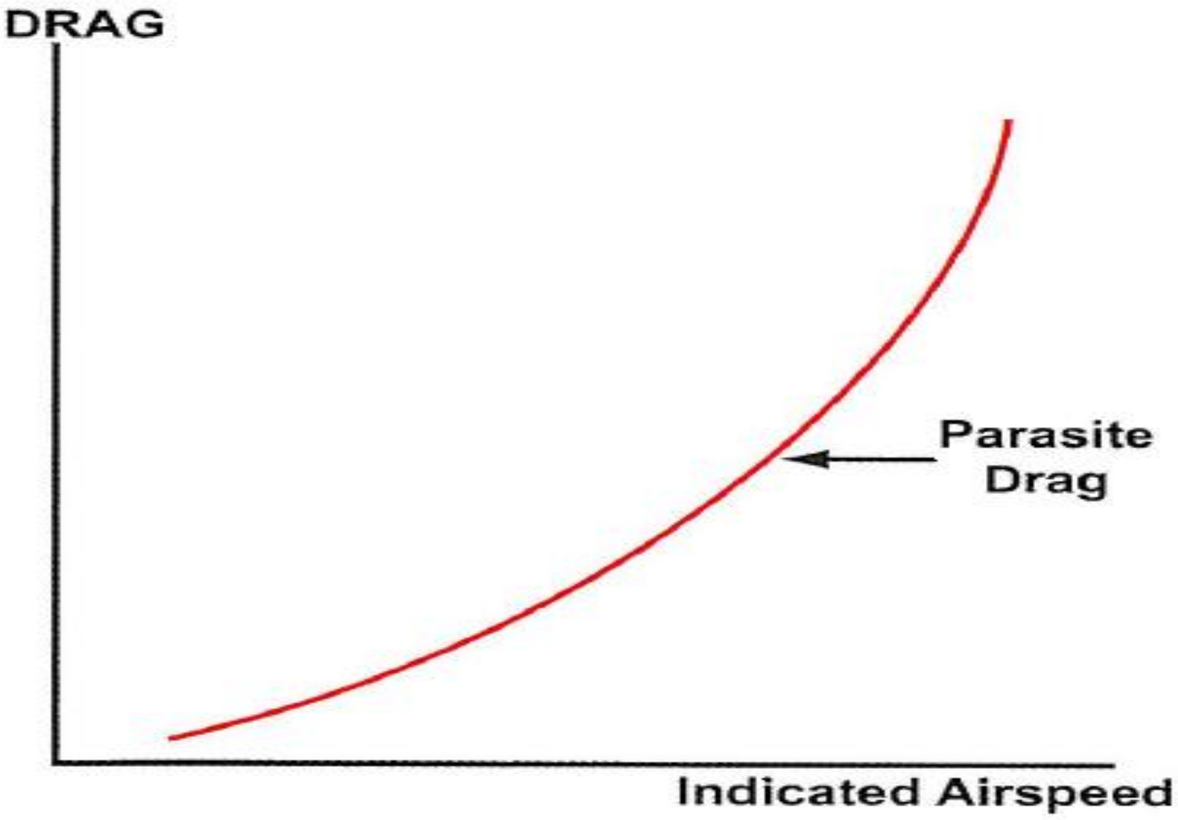


Figure 5.11 Parasite drag increases as the square of the indicated airspeed.

Analysis of the **total drag** acting on an aircraft is complex. However, it is fairly accurate to say that **parasite drag increases as the square of the indicated airspeed**.

So if, at 90 knots, the **parasite drag** acting on an aircraft is 200 pounds (lbs) force, (91 kilograms force or 892 Newtons), the **parasite drag** at 180 knots would be four times that value: 800 lbs force, (324 kilograms force or 3 568 Newtons). *Figure 5.11* illustrates graphically how **parasite drag** increases with indicated airspeed. The graph is a curve, because, as we have learnt, the increase in **parasite drag** varies as the **square** of the indicated airspeed.

INDUCED (OR LIFT-DEPENDENT) DRAG.

All parts of an aircraft generate **parasite drag**, but the wings, as the producers of **lift**, generate an additional form of **drag** which is **inextricably bound to their lift-producing function**, and which is called **induced drag**. This type of **drag** bears the name **induced drag** because, in producing **lift**, the regions of differing pressure, above and below the wings, **induce** vortices, which vary in strength, dimension and **drag effect** with varying **angle of attack**. Because it is inseparable from **lift, induced drag** is also known as **lift-dependent drag**. (See *Figure 5.12.)*

Figure 5.12 The regions of differing pressure, above and below the wings, induce vortices which vary in drag effect with varying angle of attack.

Trailing Edge and Wingtip Vortices.

Where the **spanwise** deflections in the airflow combine with the main longitudinal airflow, at the wing's trailing edge, they meet at an angle to each other to form **vortices** at the trailing edge, as depicted by *Figure 5.16*. When viewed from behind, these **vortices** will be rotating clockwise from the port (left) wing and anti-clockwise from the starboard (right) wing. The **vortex at each wingtip** is particularly large and strong. *(See Figure 5.17.)*

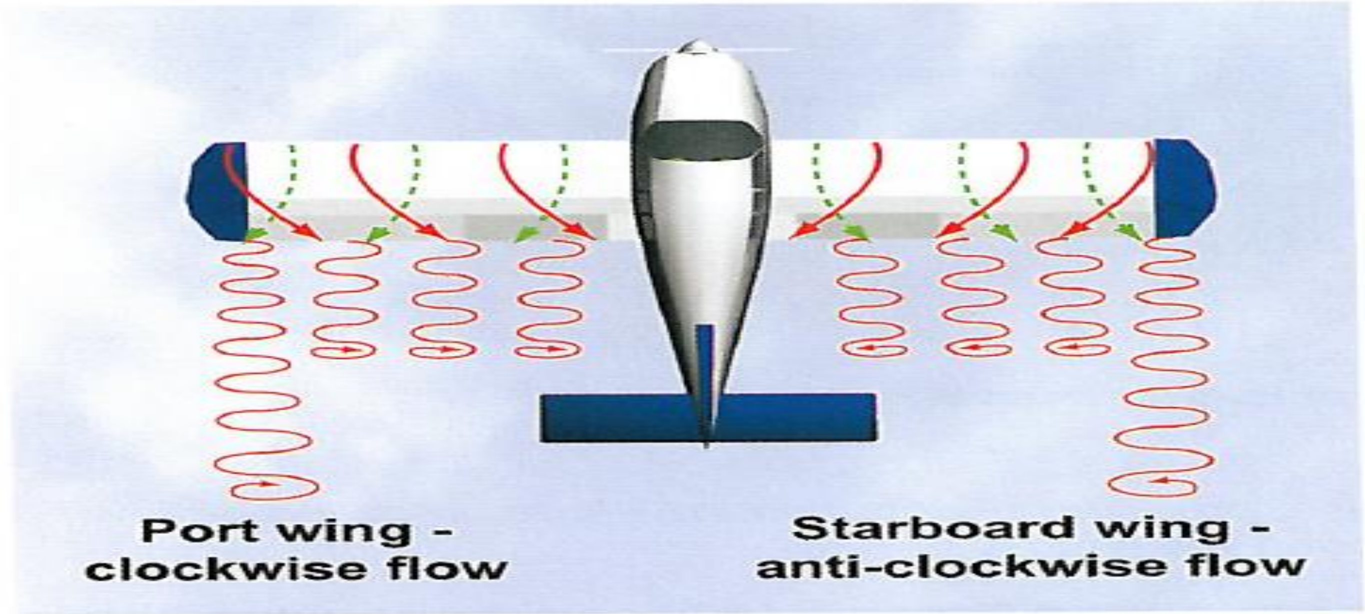


Figure 5.16 When spanwise deflection meets the main airflow, vortices are formed at the trailing edge.

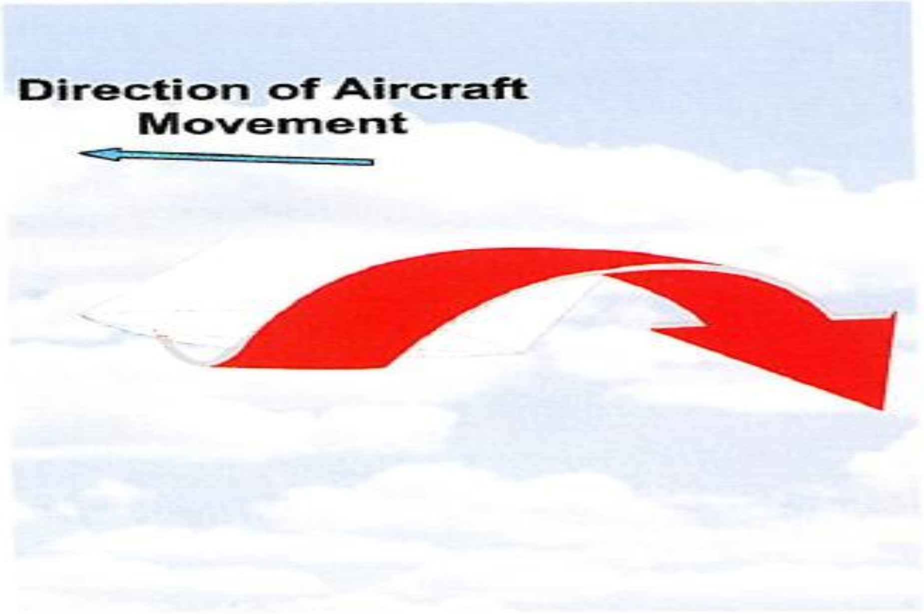


Figure 5.17 The wingtip vortex is particularly large and strong.

It is the combination of trailing-edge and wingtip vortices which are the cause of induced drag.

So whenever the wings are producing lift, they are also generating **induced drag**. In particular, in straight flight, the lower the aircraft's speed (greater angle of attack) the greater is the **induced drag**, and the higher the aircraft's speed, the lower is the **induced drag**.

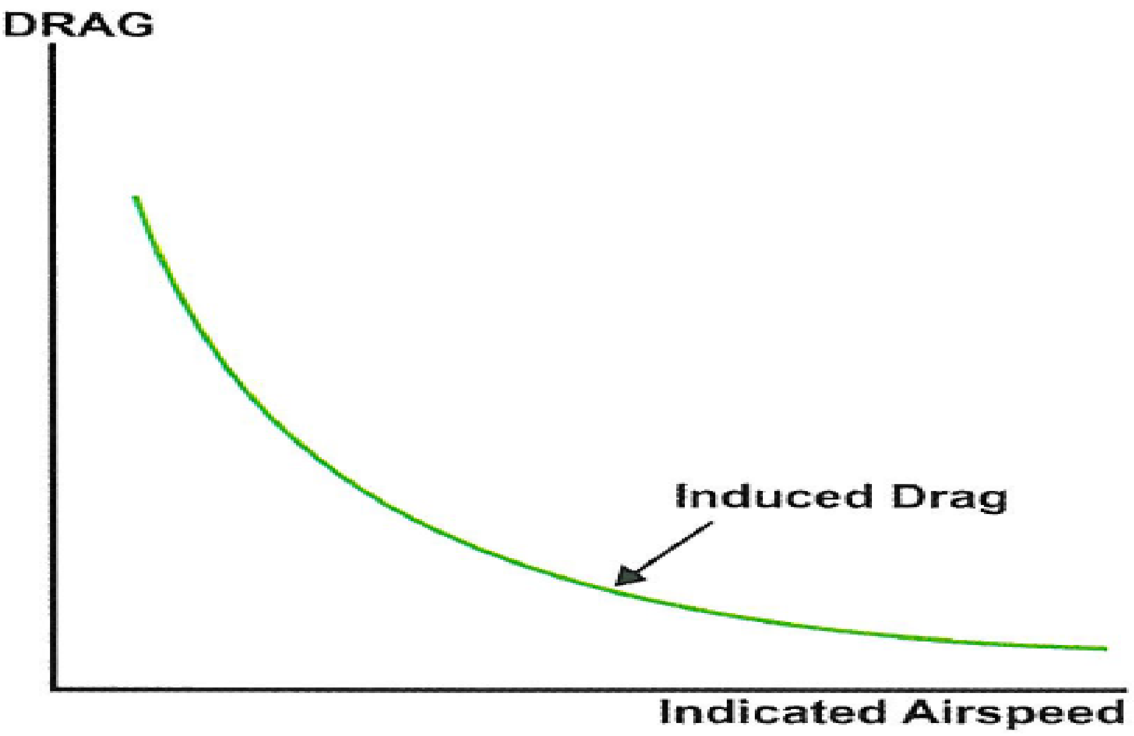


Figure 5.19 Induced drag is inversely proportional to the square of the airspeed.

In fact, induced drag is inversely proportional to the square of the aircraft's velocity, in straight flight. This relationship is shown in *Figure 5.19*.

This is a totally opposite situation to the case of **parasite drag** which increases as the aircraft's speed increases. (**Parasite drag**, you will remember, is directly proportional to the square of the aircraft's velocity.)

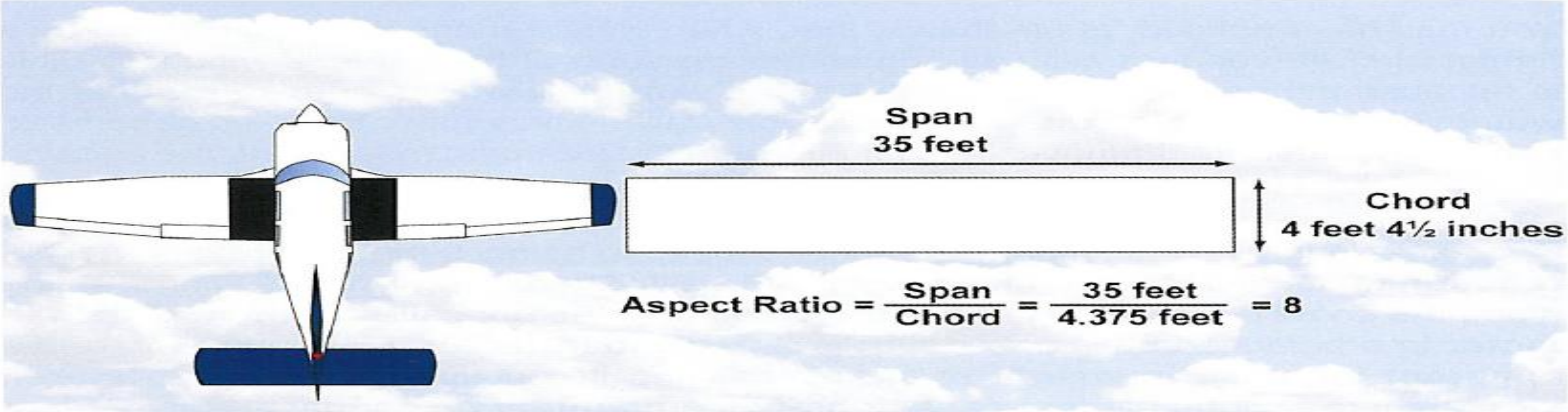
The **wing tip vortices** and, therefore, the **induced drag**, are largest and most powerful at high angles of attack, and disappear altogether at the zero-lift angle of attack; that is, at about -2° for a typical light-aircraft wing.

Methods of Reducing Induced Drag.

A wing of infinite length would, of course, have no wingtips, so there would be no wingtip vortices, no spanwise flow and no **induced drag**. This hypothetical situation is the situation we were considering when we examined parasite drag. An infinitely long, wingtipless wing is obviously an impossibility. In practice, the best methods of minimising **induced drag** involve reducing the vortex-generating effects of wings and wingtips. There are several methods of achieving this aim.

Reducing Induced Drag - Aspect Ratio.

An infinitely long wing, without wingtips, generates no **induced drag**. The best practical approximation to a wing of infinite length is a wing of high **aspect ratio**; that is a wing whose **span** is great relative to its **mean chord**. The notion of **aspect ratio** is illustrated in *Figure 5.21*.



Both the schematics of simple wing plan-forms in *Figures 5.21* and *5.22* have approximately equal wing areas. But the shorter, stubbier wing has a l**ow aspect ratio** of 8 whereas the longer, more slender wing has a **high aspect ratio** of 25. The aircraft illustrated alongside each plan-form may not have these exact **aspect ratios** in reality, but the illustrations <u>do</u> show how aircraft can have either low or high **aspect ratio** wings.

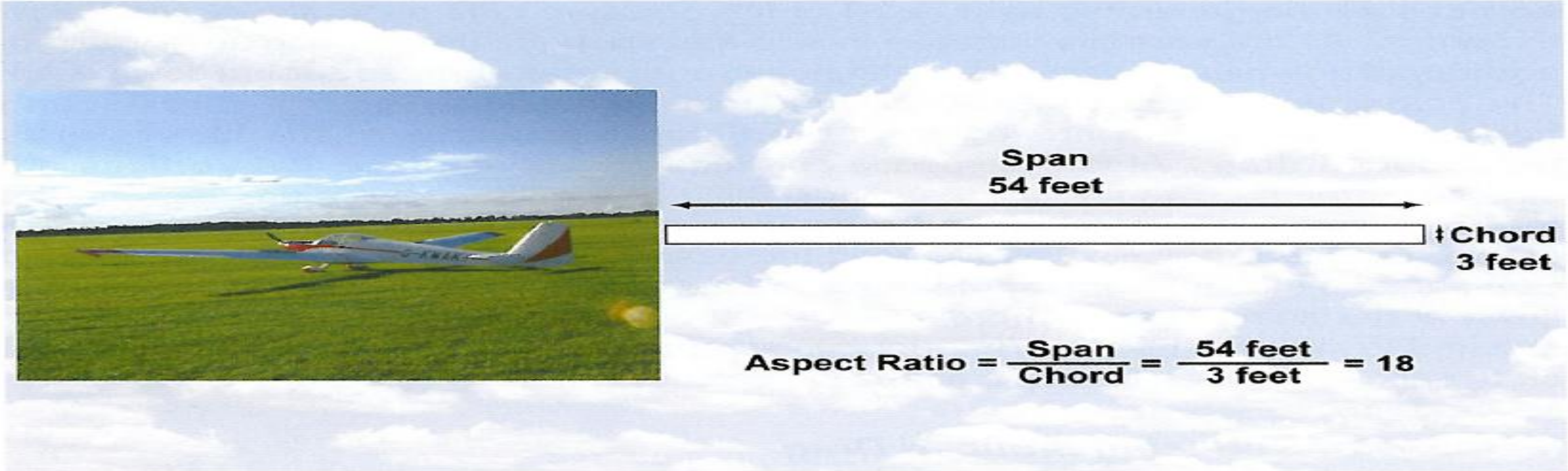


Figure 5.22 A wing of high aspect ratio.

A **light training aircraft**, for instance, might have an **aspect ratio** of 7 or 8, whereas a **touring motor glider** could have an **aspect ratio** of around 14 to 18.

Now, in the design of a wing, area is an important factor in determining what lift the wing can develop **(Lift = C_L ½ ρ v^2 S)**. But a wing of **high aspect ratio** will generate much **less induced drag** than a wing of **low aspect ratio** of equal area.

The Shape of the Wing's Plan-form.

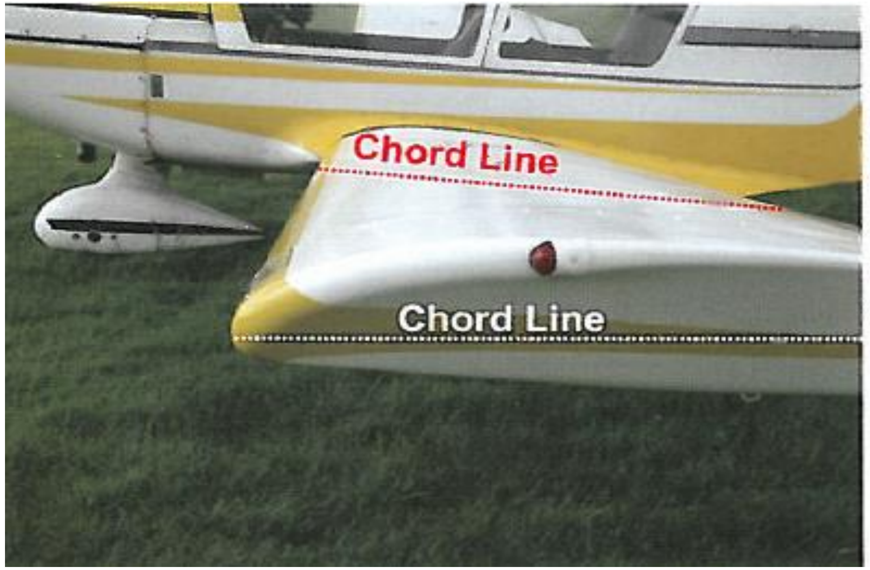
We have established that **induced drag** is greatest when the **wingtip vortices** are greatest, so any method of reducing **wingtip vortices** will reduce **induced drag**, too. **High aspect ratio** wings will achieve this reduction in **induced drag**, as we have just seen. Wings of **elliptical plan-form** will achieve the same objective of keeping the wingtip small compared to wing span. The Spitfire is, doubtless, the most famous aircraft to be fitted with wings of **elliptical plan-form**.

Figure 5.23 Spitfires showing elliptical wing plan form.

Elliptical wings are expensive to produce because of the manufacturing processes required to create the wing. It is more common for aircraft designers to consider **tapered wings** which also reduce wingtip size, and, thus, vortex strength. **Tapered wings** are, however, less effective that **elliptical wings** at reducing **induced drag**.

Washout.

You should now be totally at ease with the explanation that **induced drag** is greatest at high **angles of attack**, because of the increased pressure difference between the airflow above and below the wings, and that the **vortices** which cause **induced drag** are strongest at the **wingtips**. Now, the **wingtip angle of attack** can be kept lower than the **mean angle of attack** for the whole wing by constructing the wing with **washout**. On a wing with **washout**, the **angle of incidence** between the wing and the aircraft's longitudinal axis reduces gradually along the length of the wing, as the wingtip is approached. In other words, the wing is slightly twisted along its span, as illustrated in *Figure 5.24, overleaf.*



Winglets and Other Wingtip Modifications.

Modifications to wingtips, designed to minimise spillage from the high to low pressure regions, can also reduce **wingtip vortex** strength and, thus, **induced drag**.

Common wingtip modifications, some of which are illustrated in *Figure 5.25*, are: **winglets, shaped wingtips, wing end-plates**, or **wing fences**, and **wingtip tanks**.

Figure 5.25 Wingtip shapes designed to reduce wingtip vortex strength.

TOTAL DRAG.

Total drag as you learnt at the beginning of this chapter is made up of **parasite drag** and **induced drag**. You have also learnt that **parasite drag** increases with the square of the airspeed, whereas **induced drag** decreases with the square of the airspeed. When we consider an aircraft in any phase of flight: take-off, climb, cruise, descent, or landing, the **total drag** acting on the aircraft, at any time, will be made up partly of **parasite drag** and partly of **induced drag**. *Figure 5.26* combines the graphs for the variation of both **parasite** and **induced drag** with speed.

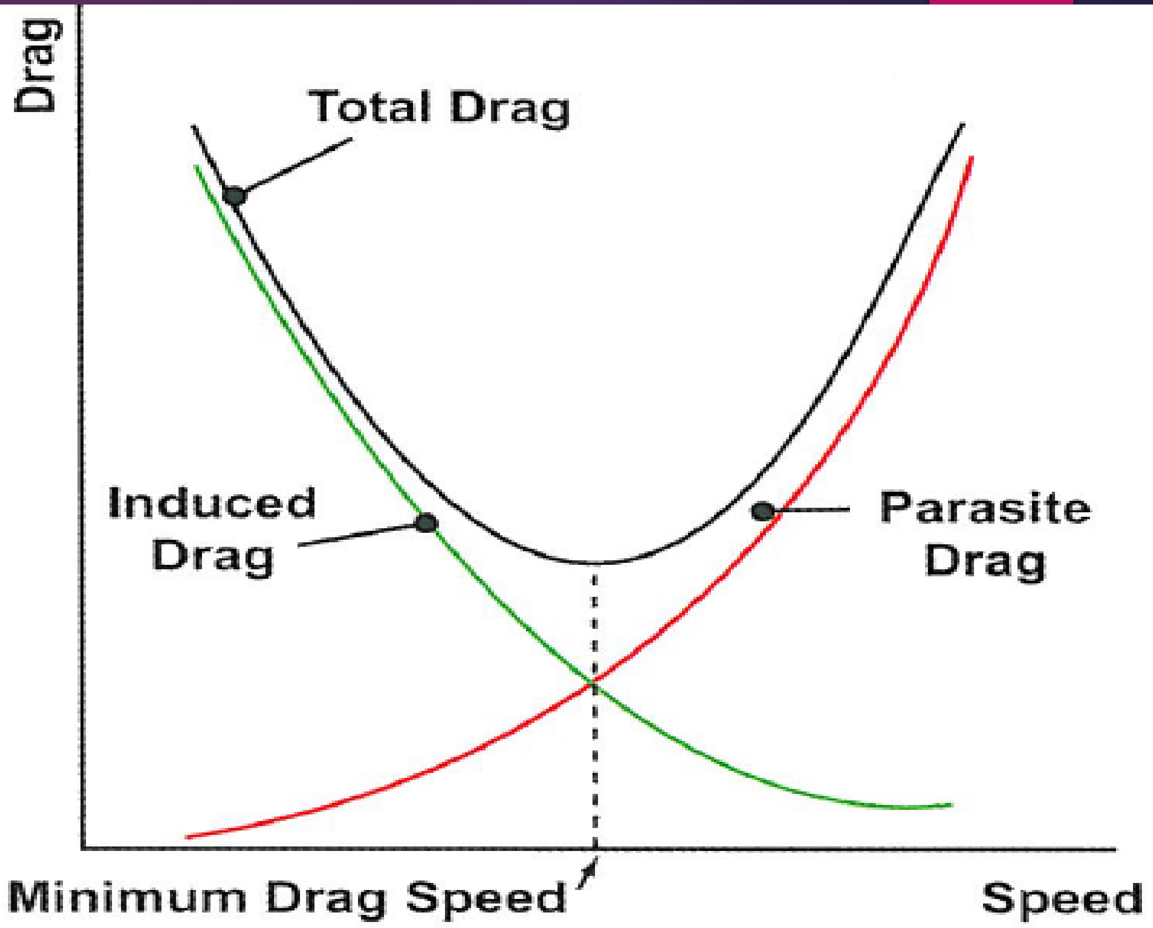


Figure 5.26 Graph showing total drag against speed.

The Drag Equation.

Having derived a graph showing how **total drag varies with airspeed**, we can see from the graph *(Figure 5.26)* that **total drag** is high at both low and high speeds. In order to relate **total drag** to general aircraft parameters such as **aircraft surface area**, **air density**, **wing shape**, **angle of attack** and, of course, **speed**, aerodynamicists have derived the following **drag equation**:

$$\text{Drag} = C_D \tfrac{1}{2} \rho v^2 S$$

Ground Effect.

When an aircraft is taking off or landing, the closeness of the wing to the ground prevents full development of the **wingtip vortices**, thus making them much weaker. This **reduction in vortex strength** is called **ground effect**. (*Figure 5.32.*)

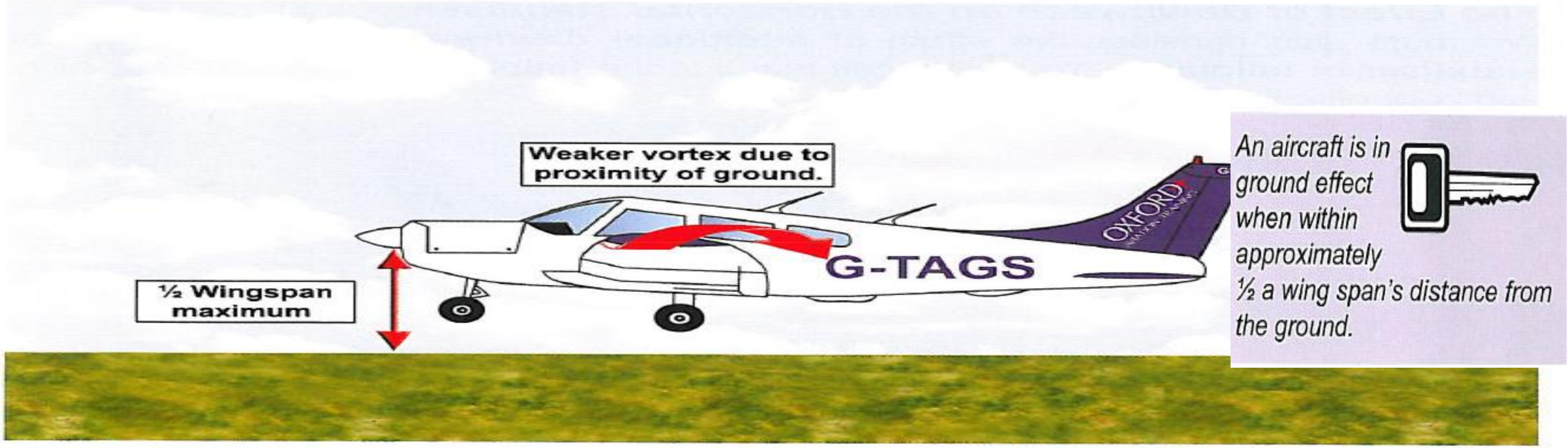


Figure 5.32 Ground effect prevents full development of the wing tip vortices.

An aircraft is subject to **ground effect** when it is within approximately half wingspan distance from the ground.

The **reduction in vortex strength** near the ground causes a **decrease in the additional downwash angle** and, consequently, an increase in the effective angle of attack, and an **increase in lift**.

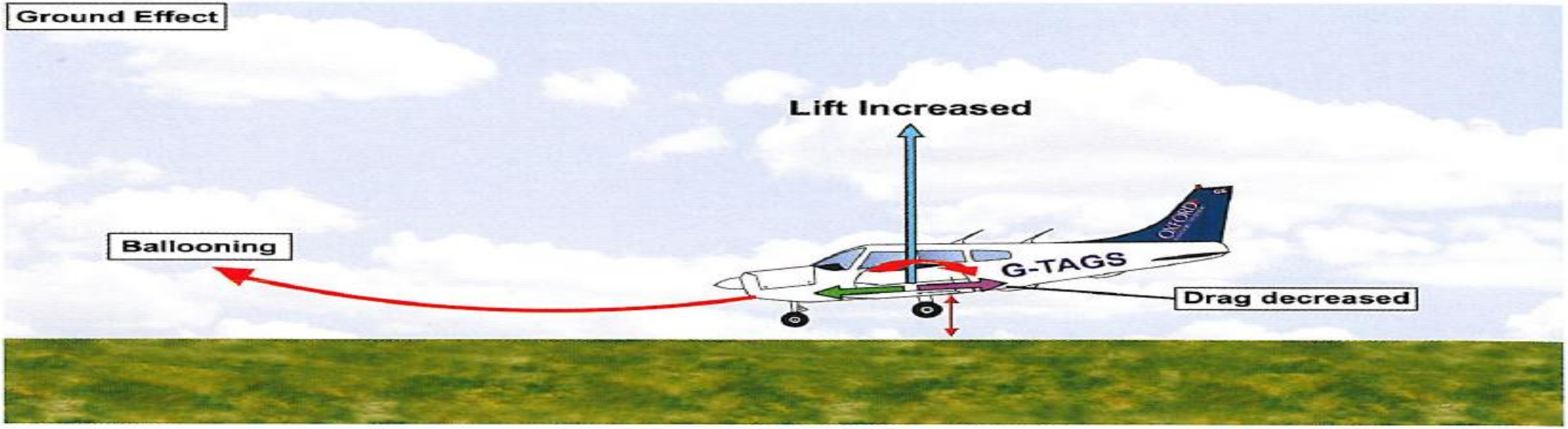


Figure 5.33 Ground effect reduces the wingtip vortices and increases the effective angle of attack, thus increasing lift.

Furthermore, even though the effective angle of attack has increased, the **induced drag** will decrease in **ground effect** due to the **reduced wingtip vortices**. This **reduction in drag** will cause the aircraft to tend to accelerate, and further **increase lift**.

The combination of **ground effect** and an approach flown at too high an airspeed, especially with a small flap angle selected, may lead to a balloon landing; a common trait of the student pilot. *(See Figure 5.33.)* For this reason, it is necessary for the pilot to demonstrate good speed control on the approach.

١٢. Which statement is true relative to changing angle of attack ?

A. A decrease in angle of attack will increase pressure below the wing, and decrease drag.
B. An increase in angle of attack will increase drag.
C. An increase in angle of attack will decrease. pressure below the wing, and increase drag.

٢٦. On a wing, the force of lift acts perpendicular to and the force of drag acts parallel to the

A. Chord line.
B. Flight path
C. longitudinal axis

٣٠. If the same angle of attack is maintained in ground effect as when out of ground effect, lift will

A. Increase, and induced drag will decrease.
B. Decrease, and parasite drag will increase.
C. Increase, and induced drag will increase.

١٨. In theory, if the airspeed of an airplane is double while in level flight, parasite drag will become

A. Twice as great.
B. Half as great
C. Four times great

٢٨. An airplane leaving ground effect will

A. Experience a reduction in ground friction and require a slight power reduction.
B. Experience an increase in induced drag and require more thrust.
C. Require a lower angle of attack to maintain the same lift coefficient.

٥٦. What causes an airplane (except a T-tail) to pitch nose-down when power is reduced and controls are not adjusted?

A. The CG shift forward when thrust and drag are reduced.
B. The downwash on the elevators from the propeller slipstream is reduced and elevator effectiveness is reduced.
C. When thrust is reduced to less than weight, lift is also reduced and the wings can no longer support the weight.

٧٢. What must a pilot be aware of as a result of ground effect ?

A. Wingtip vortices increase creating wake turbulence problems for arriving and departing aircraft
B. Induced drag decreases; therefore, any excess speed at the point of flare many cause considerable floating.
C. A full stall landing will require less up elevator deflection than would a full stall when done free of ground effect.

٧٣. Ground effect is most likely to result in which problem ?

A. Setting to the surface abruptly during landing.
B. Becoming airborne before reaching recommended Take-off speed.
C. Inability to get airborne even through airspeed is sufficient for normal take-off needs.

٧٤. What is ground effect ?

A. The result of the interference of the surface of the earth with airflow patterns about an airplane
B. The result of an alteration in airflow patterns increasing induced drag about the wings of an airplane
C. The result of the disruption of the airflow patterns about the wings of an airplane to the point where the wings will no longer support the airplane in flight.

٧٦. When landing behind a large aircraft, which procedure should be followed for vortex avoidance ?

A. Stay above its final approach flight path all the way to touch down.
B. Stay below and to one side of its final approach Flight path.
C. Stay well below its final approach flight path and land at least ٢,٠٠٠ feet behind.

١١٢. A high aspect ratio wing produces:

A. A decrease in induced drag.
B. Less sensitivity to gust effects.
C. A decrease in stall speed.

٧٥. Floating caused by the phenomenon of ground effect will be most realized during an approach to land when at

A. Less than the length of the wingspan above the surface
B. Twice than length of the wingspan above the surface.
C. A higher-than-normal angle of attack.

٧٧. How does the wake turbulence vortex circulate around each wingtip.

A. Inward, upward, and around each tip.
B. Inward, upward, and counter clockwise.
C. Outward, upward, and around each tip.

١٠٦. What must a pilot be aware of as a result of ground effect ?

A. Wingtip vortices increase creating wake turbulence problems for arriving and departing aircraft.
B. Induced drag decreases; therefore any excess speed at the point of flare may cause considerable floating.
C. A full stall landing will require less up elevator deflection than would a full stall when done free of ground effect.

١١٨. Induced drag of an aircraft would be increased with:

A. Increased speed.
B. Increased weight.
C. Increased aspect ratio.

١٣٣.Which of the following statements are correct?

A. Drag acts in the same direction as the relative airflow and lift perpendicular to it.
B. Lift acts at right angles to the top surface of the wing and drag acts at right angles to lift.
C. Drag acts parallel to the chord and opposite to the direction of motion of the aircraft and lift acts perpendicular to the chord.

١١٦. Induced drag is greatest:

A. At the wingtip.
B. At the wings root.
C. At high speeds.

١٢٢. Which location on the aeroplane has the largest effect on the induced drag.

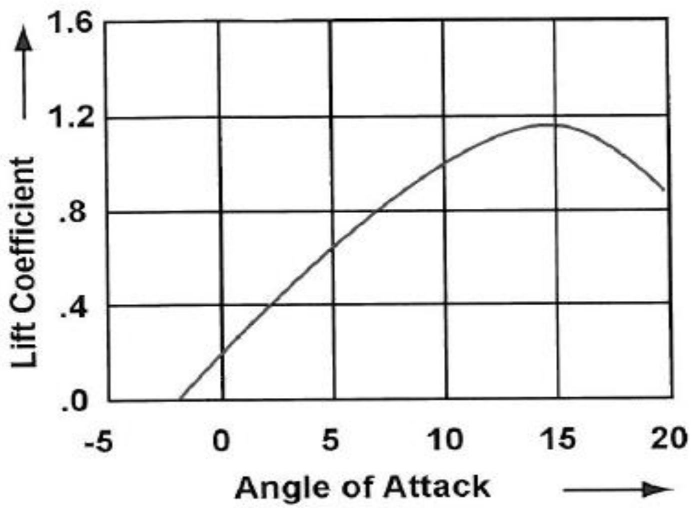
A. Wing root junction.
B. Engine cowling.
C. Wing tip.

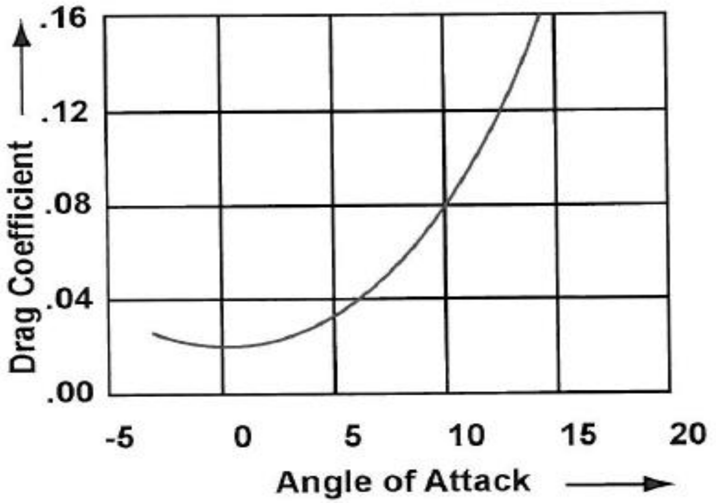
CHAPTER 6
THE LIFT/DRAG RATIO

THE RELATIONSHIP BETWEEN LIFT AND DRAG.

Introduction.

Figure 6.1 depicts graphs of the **coefficient of lift**, C_L, and the **coefficient of drag**, C_D, against **angle of attack**, for a particular aerofoil. These graphs are similar to the ones you have already met.





$$\text{Lift} = C_L \tfrac{1}{2} \rho v^2 S$$

$$\text{Drag} = C_D \tfrac{1}{2} \rho v^2 S$$

The Lift-Drag Ratio.

In most (but not all) phases of flight, the generation of **lift** by the wing is a distinct benefit, while the generation of **drag** is a distinct disadvantage. When the aircraft is flying very fast at low angles of attack (low C_D), we have seen that **parasite drag** is high, and when the aircraft is flying at low speeds and high angles of attack (high C_D), the **induced drag** is high. *(See Figure 6.2)*. So at neither of these two extremes of **high drag** is the wing working at its most efficient. The wing will be working **most efficiently** when it is generating **maximum lift for minimum drag**.

Consequently, a factor of greater significance to aircraft performance issues than lift and drag considered separately, is the **lift-drag ratio**. The **lift-drag ratio** is commonly expressed, using initial letters, as the **L/D ratio**.

The lift-drag ratio varies with angle of attack and, therefore, also with airspeed.

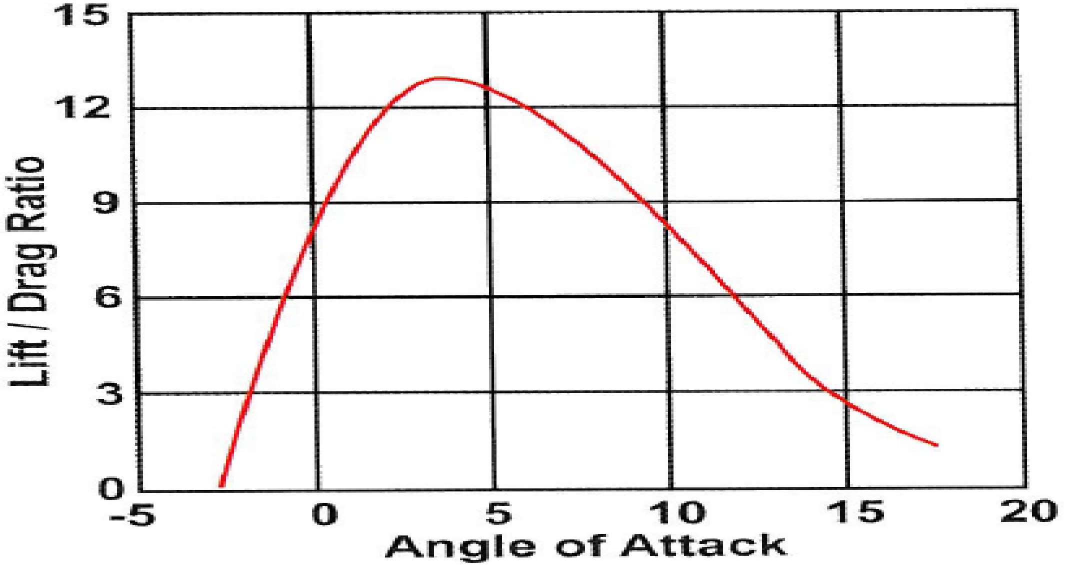


Figure 6.3 Graph showing Lift-Drag (L/D) ratio against Angle of Attack.

Maximum lift for **minimum drag** occurs at the highest **lift-drag ratio**; that is at the highest value of the **L/D ratio**. From the values available from the two individual graphs of C_L and C_D against **AoA**, we can plot a further graph which shows how the **lift-drag ratio** (**L/D ratio**) varies with **AoA**. Such a graph is depicted in *Figure 6.3*.

You have already learnt that the values of **lift** and **drag** are not the same as the values of C_L and C_D because the actual **lift** and **drag** forces depend on other parameters such as **airspeed**, **air density** and **wing area**. But to obtain information on the **lift to drag ratio**, we may plot either **Lift/Drag** against **AoA** or C_L/C_D against **AoA**. The following mathematical relationship illustrates why this is so.

$$\frac{\textbf{Lift}}{\textbf{Drag}} = \frac{C_L \frac{1}{2} \rho v^2 S}{C_D \frac{1}{2} \rho v^2 S} = \frac{C_L \cancel{\frac{1}{2} \rho v^2 S}}{C_D \cancel{\frac{1}{2} \rho v^2 S}} = \frac{C_L}{C_D}$$

From *Figure 6.3*, then, you can see that the **L/D ratio** increases rapidly to a maximum value, at an **AoA** of around **4°** and then falls away as **AoA** is increased further. Be aware that this does not mean that lift is greatest at **4° AoA**. As the C_L graph shows, **lift** carries on increasing well beyond an **AoA** of **4°**. But, of course, from the C_D graph you see that the **drag** goes on increasing beyond **4° AoA**, too. Therefore, when we combine the data from the C_L and C_D curves, we see that the **best L/D ratio** (**L/D**$_{MAX}$) occurs at **4° AoA**.

Performance Criteria Related to Maximum Lift-Drag Ratio (L/D_{MAX}).

In steady, level, cruising flight, the **thrust** developed by the propeller must equal **drag**; so, for flight at **L/D_{MAX}** (that is, at minimum drag), the thrust required to maintain level flight is also a minimum.

Several important aspects of aircraft performance are related to an aircraft's **maximum achievable Lift-Drag ratio**. The most relevant of these are: **maximum power-off gliding range**, **maximum cruising range**, and **best rate of climb**.

As you have learnt, **L/D_{MAX}** corresponds to flight at **4° AoA**, for a conventional aircraft. Whilst light aircraft are not fitted with angle of attack indicators, you learnt in the Chapter on **lift** that, **at a given aircraft weight, a given angle of attack corresponds to a particular airspeed**. Therefore, for a given aircraft, at an assumed normal operating weight, a speed will be published in the **Pilot's Operating Handbook (POH)** for (amongst other performance criteria) **best glide range**, **maximum cruising range** and **best rate of climb**.

Lift-Drag Ratio and Glide Performance.

One final point to note is that an aircraft's power-off glide performance expressed as the ratio of **ground distance covered** to **height lost** is the same as the **ratio of Lift to Drag**, assuming zero wind. This situation is depicted in *Figure 6.4*. So, in still air, if an aircraft is gliding at a **Lift-Drag ratio** of, say, **10:1**, it will cover **10 000 feet** (1.65 nautical miles), horizontally, for every **1 000 feet** of height lost.

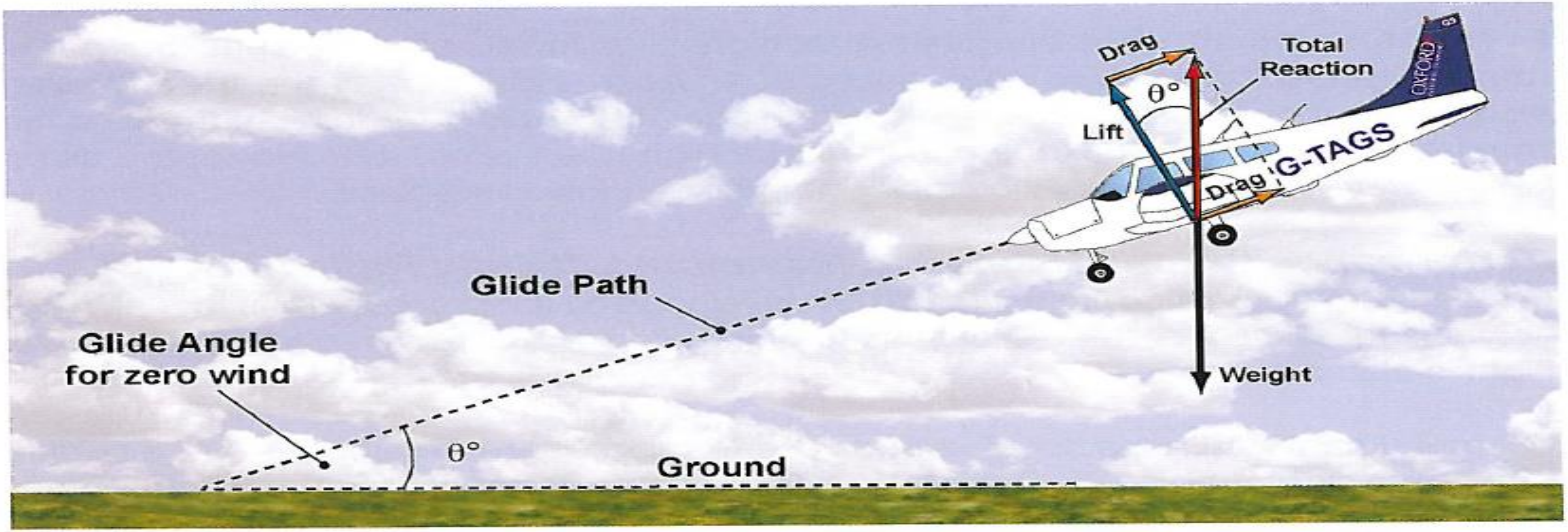


Figure 6.4 In still air, an aircraft's glide performance (distance covered/height lost) is equal to the Lift-Drag ratio.

١٩. As airspeed decreases in level flight below that speed for maximum lift/drag ratio total drag of an airplane

A. Decreases because of lower parasite drag.
B. Increases because increased induced drag.
C. Increases because of increased parasite drag.

١٥٨. If the weight of the aircraft is increased, the maximum lift/drag ratio will:

A. Decrease.
B. Increase.
C. Remain the same but occur at a higher speed.

١٥٤. Which of the following statements about the lift to drag ratio in straight and level flight is correct?

A. At the highest value of the lift/drag ratio the total drag is lowest.
B. The highest value of the lift/drag ratio is reached when the lift is zero.
C. The lift/drag ratio always increases as the lift decreases.

١٥٧. The effect of increasing aspect ratio is to:

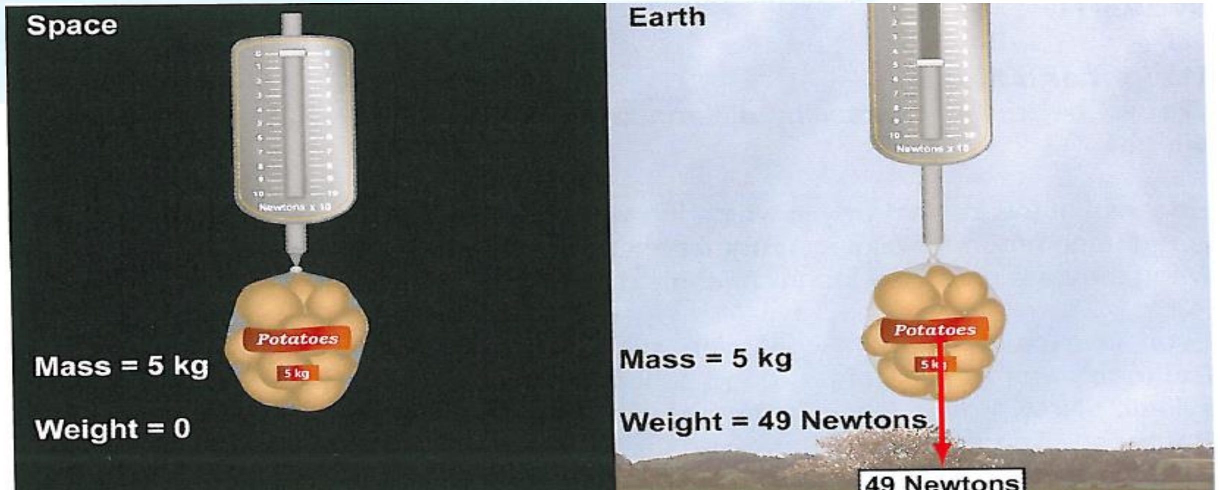
A. Increase the maximum lift/drag ratio.
B. Decrease the maximum lift/drag ratio.
C. Not affect the maximum lift/drag ratio.

CHAPTER 7
WEIGHT

What is the difference between weight and mass?

Put simply, **mass is a measure of the amount of matter in a body**. **Mass** can be measured in **imperial units such pounds (lbs)** or **metric units such as kilograms (kg).** The standard unit of **mass** is the **kg**.

Weight, on the other hand, **is a force**. To be exact, it is the **force** which results from a body of a given **mass**, situated within a **gravitational field**, being subjected to a **gravitational acceleration** as it is attracted to another **mass**. The standard unit of **weight** is the **Newton (N)**.



Weight is Different from Mass.

The 1000 kg vehicle, **having the same mass everywhere,** requires the same force to accelerate it horizontally, if we ignore issues like air resistance and friction, whether it is located on the Earth or on the Moon. But, if we wish to **lift** the vehicle, we have to apply a **force** to overcome the **weight** that the vehicle possesses by virtue of its presence within a particular **gravitational field**. The **lifting force** required to counterbalance the **weight** of the vehicle needs to be **6 times greater on the Earth than on the Moon.**

Weight – One of the Forces Acting on an Aircraft in Flight.

Now, having learnt the difference between **weight** and **mass**, and understood why some people sometimes confuse the two, and why **weight** is commonly and unscientifically measured in **kilograms**, we may now look at **weight** as one of the forces which act on an aircraft in flight.

The **weight** of an aircraft is the **force**, exerted by the Earth's gravity, which, acting on the aircraft's mass, acts vertically downwards, through the aircraft's **centre of gravity**, tending to pull the aircraft towards the Earth's centre.

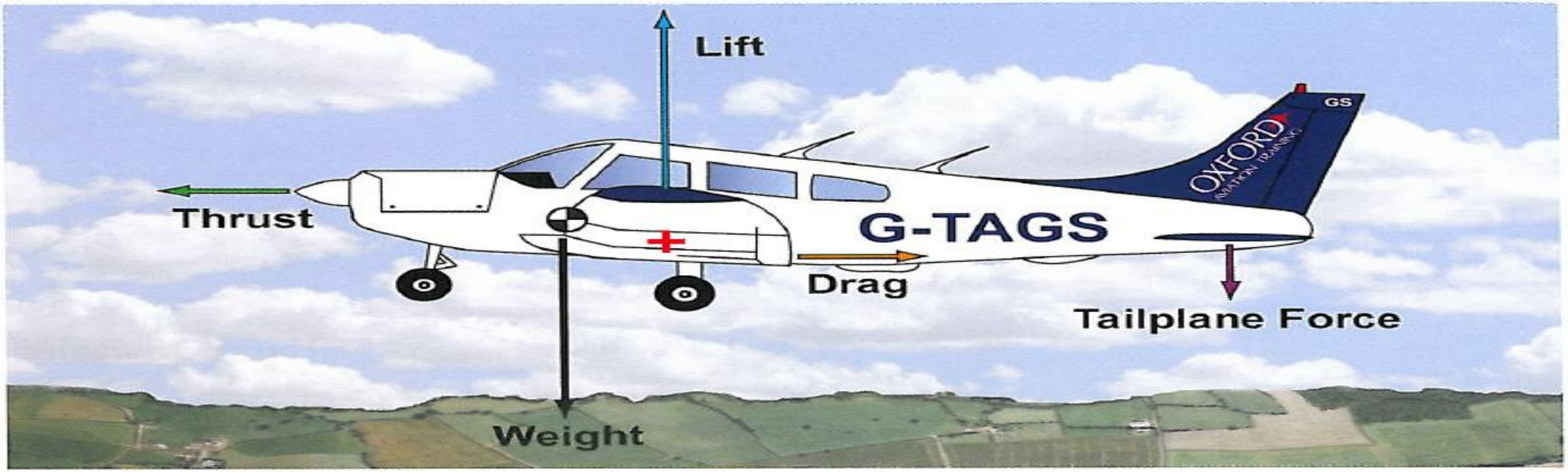


Figure 7.6 The aircraft's weight acts vertically downwards. The total weight of the aircraft is considered as acting through the aircraft's centre of gravity.

Of course, as we perceive **weight**, we should simply say that **weight** is the **force pulling the aircraft towards the ground**. Although each aircraft component will have its own weight, the **total weight** of the aircraft is considered as acting through the aircraft's **centre of gravity**. *(See Figure 7.6.)*

If the aircraft is to fly, the force of **weight** must be opposed by the force of **lift**. In steady, straight and level flight (**level** means **at constant altitude**), **lift**, then, must equal **weight** and must act in the opposite direction to **weight**. If **lift** is greater than **weight**, the aircraft will begin to accelerate upwards; if **weight** is greater than **lift**, the aircraft will begin to accelerate downwards. But that is another story.

The Centre of Gravity.

The **centre of gravity**, is the point within a body through which all of a body's **weight** is considered to act. If an aircraft were to be suspended by a single force, say a rope, attached to the aircraft's **centre of gravity**, we could place the aircraft with its longitudinal axis horizontal, and the aircraft would remain horizontal in perfect balance, as depicted in *Figure 7.7*.

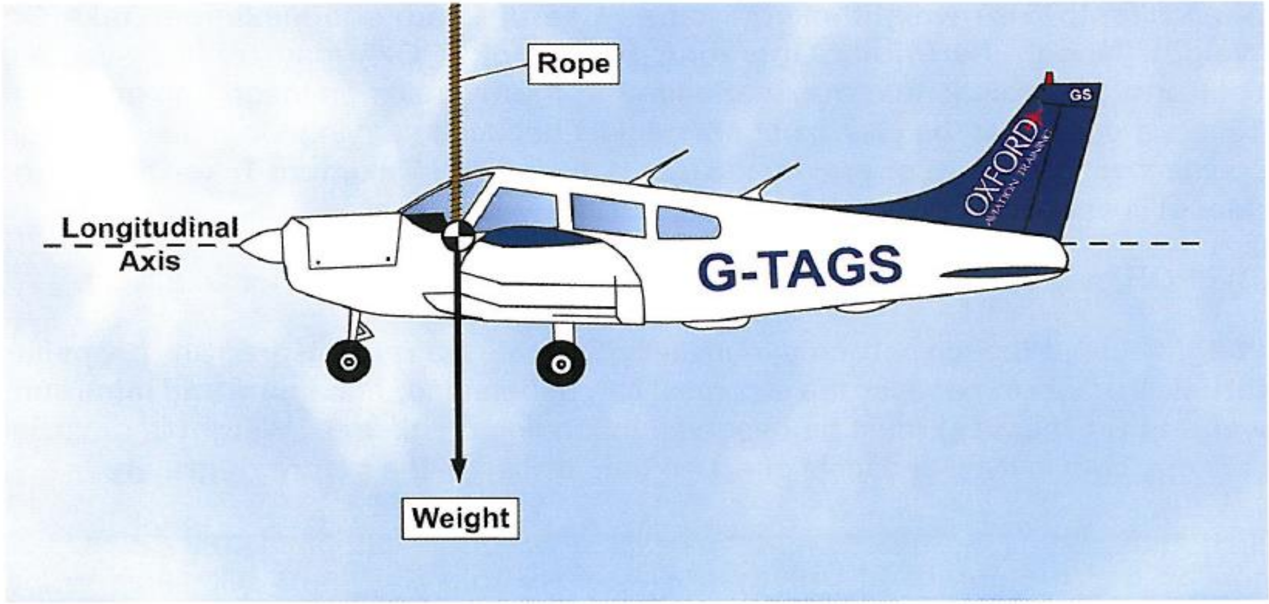


Figure 7.7 If the aircraft were to be suspended through its Centre of Gravity, the aircraft would hang in perfect balance.

As you will learn in the **Mass & Balance** section of this series, because **weight** acts through the **centre of gravity**, the position of the **centre of gravity** along the aircraft's longitudinal axis affects the **stability** of the aircraft. Therefore, there are **forward** and **aft limits** *(See Figure 7.8)*, calculated by the aircraft designer, within which the **centre of gravity** must remain throughout a flight. These **centre of gravity limits** are established in order that the pilot may have sufficient elevator authority, in all phases of flight, to control the aircraft in pitch, as he requires. If the **centre of gravity** exceeds the **forward limit**, the aircraft is said to be **nose heavy**. If the **centre of gravity limit** is too far **aft**, the aircraft is said to be **tail heavy**. An aircraft which has its **centre of gravity** outside the **aft limit** may be dangerously **unstable in pitch** and display unfavourable stall and spin characteristics.

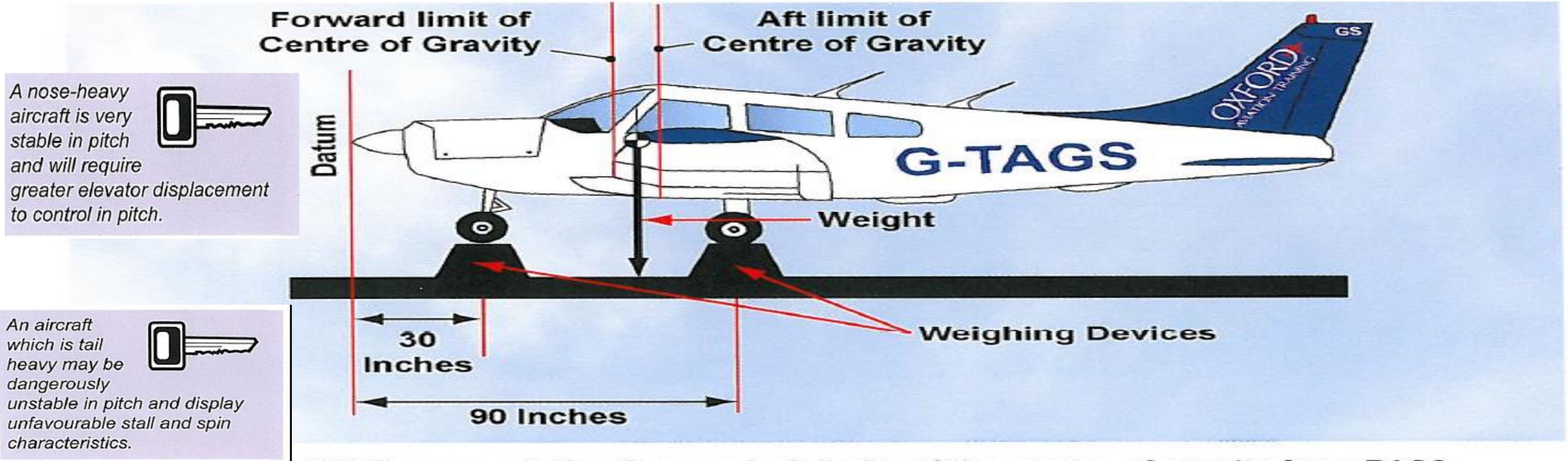


Figure 7.8 Representative fore and aft limits of the centre of gravity for a PA28.

CHAPTER 8
PROPELLER THRUST

THRUST.

The force which propels an aircraft through the air is known as **thrust**. As you have learnt, **thrust**, together with **lift**, **drag** and **weight**, is one of the four principal forces which act on an aircraft in flight, *(Figure 8.2)*. At any constant airspeed, **thrust** is equal and opposite to the force of **drag**. If **thrust** is greater than **drag**, for instance, because the pilot, in level flight, has opened the throttle further, the aircraft will accelerate. If **thrust** is less than **drag** the aircraft will decelerate.

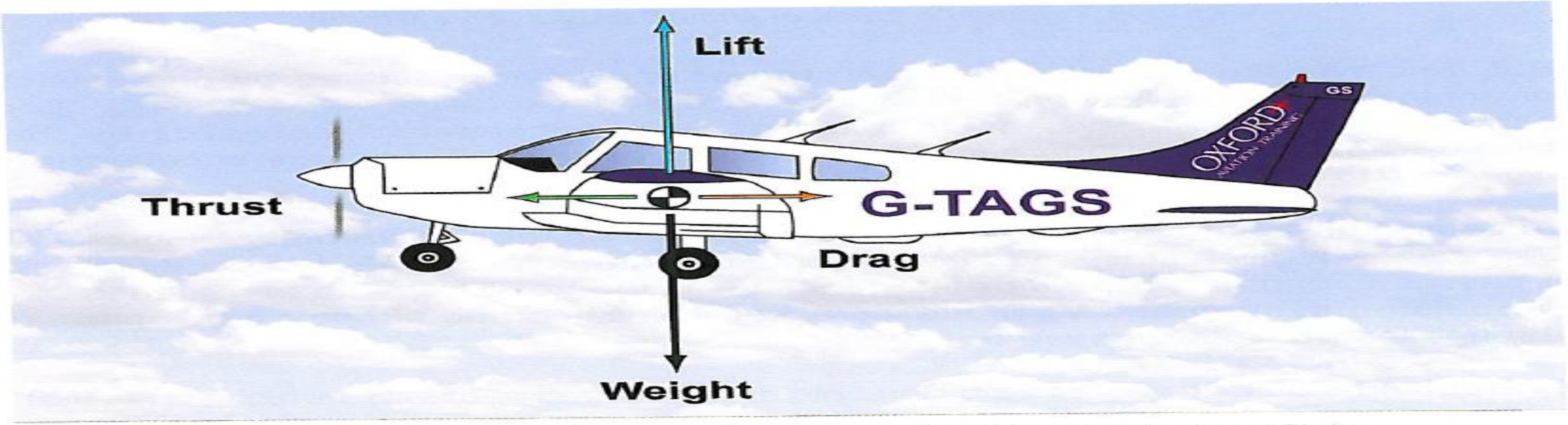


Figure 8.2 The Four forces acting on an aircraft in steady, level flight.

The exact way in which **thrust** is developed by an aircraft's powerplant depends on the type of **propulsion system** fitted to the aircraft. Common types of aircraft **propulsion systems** are: the **Piston Engine/Propeller combination**, the **Pure Turbojet**, the **By-pass Turbojet** and the **Turboprop** *(Figure 8.3)*.

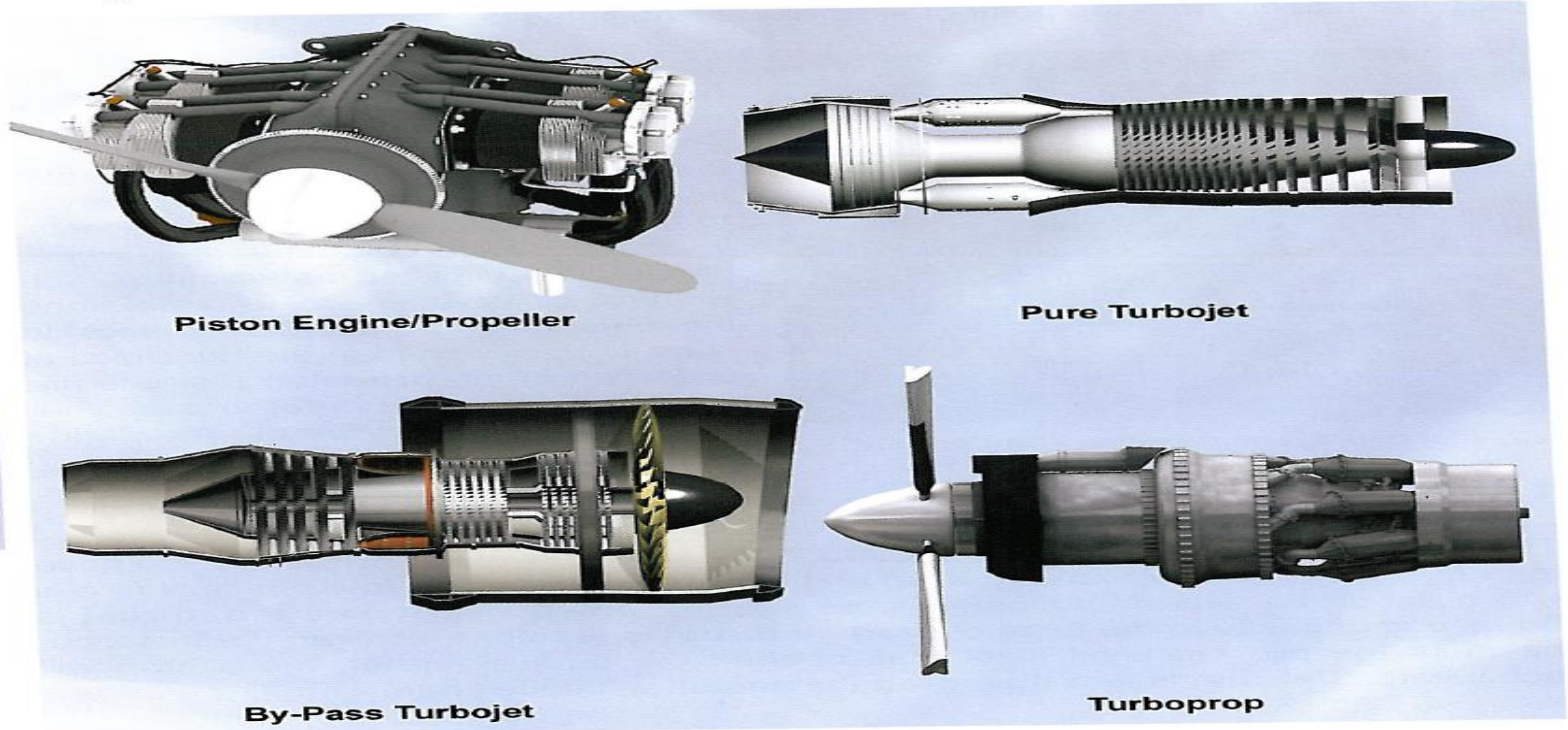


Figure 8.3 Common types of aircraft propulsion systems.

PROPELLERS.

The propulsion system which powers most light aircraft is the **piston engine/ propeller combination***. The **piston engine** causes the **propeller** to rotate, and, by producing **thrust**, the **propeller** acts is such a way as to convert the power developed by the engine into **propulsive power**. As you will discover, the exact nature of the **thrust force** developed by a **propeller** is very complex. As well as accelerating air rearwards, **propeller blades** are also **aerofoils**, and are, therefore, as you learnt in the Chapter on **Lift**, also able to develop **thrust** in the form of a "horizontal lift" force because of the favourable pressure distribution over the blades created by the relative airflow when the propeller is rotating. So do not be surprised if your flying instructors sometimes disagree on what scientific explanation best accounts for the **thrust** developed by a **propeller**.

* *"engine" from Latin **ingenum** meaning "genius"; "propeller" from Latin **pro** + **pellere** "to drive" meaning "to drive forward."*

DEFINITION OF TERMS.

Before we begin our discussion of the **Principles of Flight** aspects of **propeller theory**, here are some basic illustrations and definitions of **propeller components**, and technical terms describing the function of **propellers**, without which any discussion of propeller theory would be extremely difficult.

Blade Shank (Root).

The **Blade Shank** or **Root** is the section of the blade nearest the **hub** to which the blade is attached. The hub forms the end of the propeller shaft which is turned by the engine.

Blade Tip.

The **Blade Tip** is the outer end of the blade farthest from the **hub**.

Plane of Rotation.

The **Plane of Rotation** is an imaginary plane perpendicular to the propeller shaft. It is the plane which is described when the blades rotate *(see Figure 8.6)*.

Spinner.

The **spinner** is the fairing fitted over the **hub** of the propeller, in order to reduce drag.

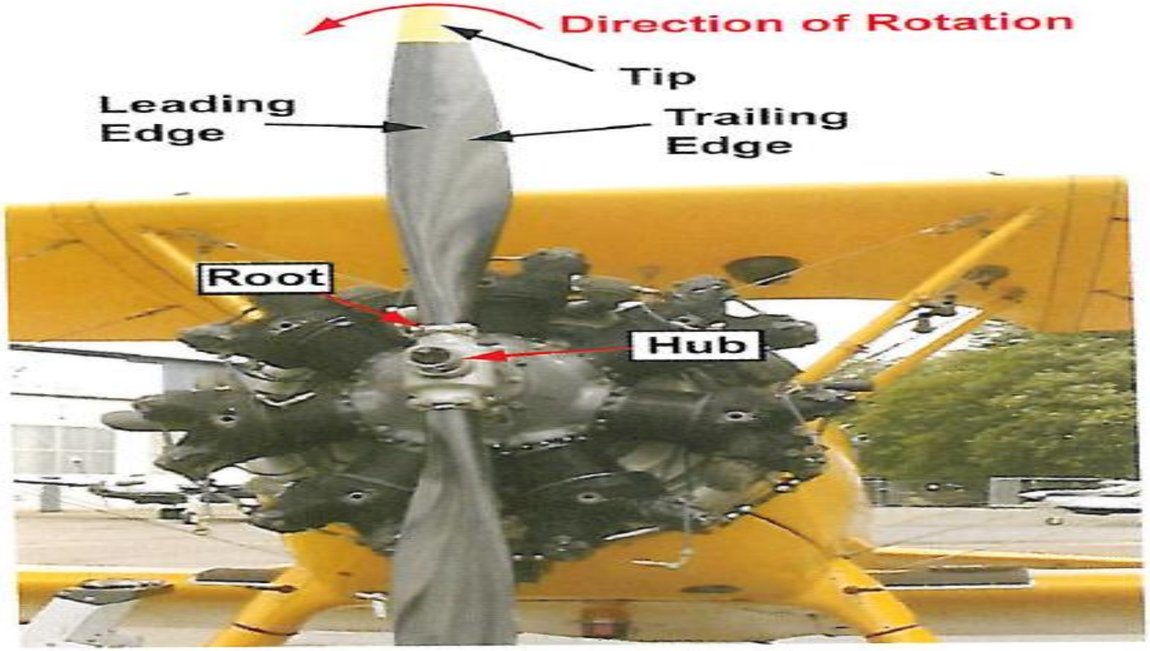
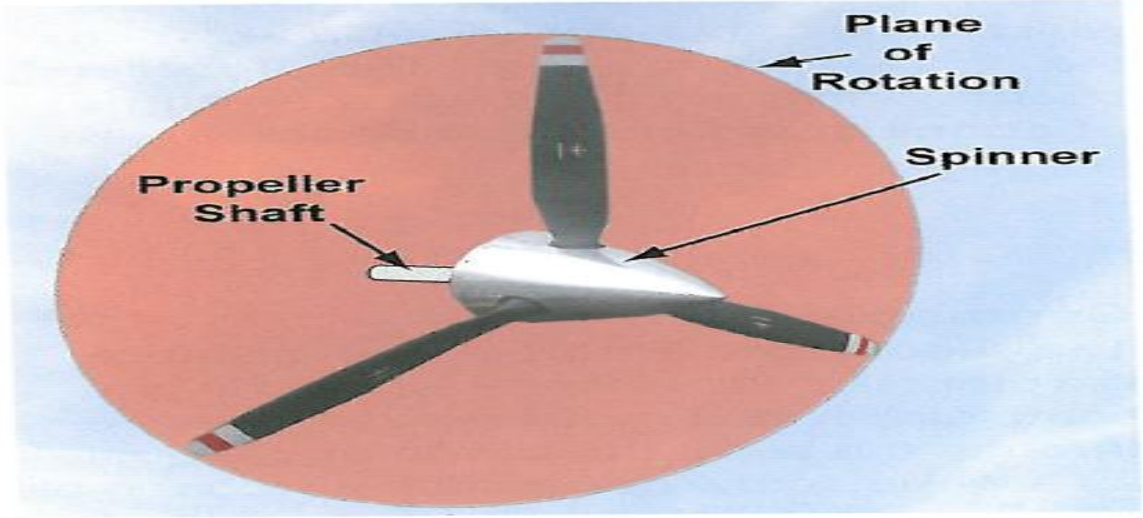


Figure 8.5 Propeller nomenclature.



Blade Chord Line.

If the propeller blade is viewed end-on, from tip to root, and a cross-section is taken across the blade, it can be seen that the blade is of aerofoil shape. This means that the blade's section has a chord line, just as a wing cross-section does. The **Blade Chord Line** is an imaginary straight line joining the centre of curvature of the leading edge of the propeller blade to the blade's trailing edge.

Figure 8.6 Plane of rotation.

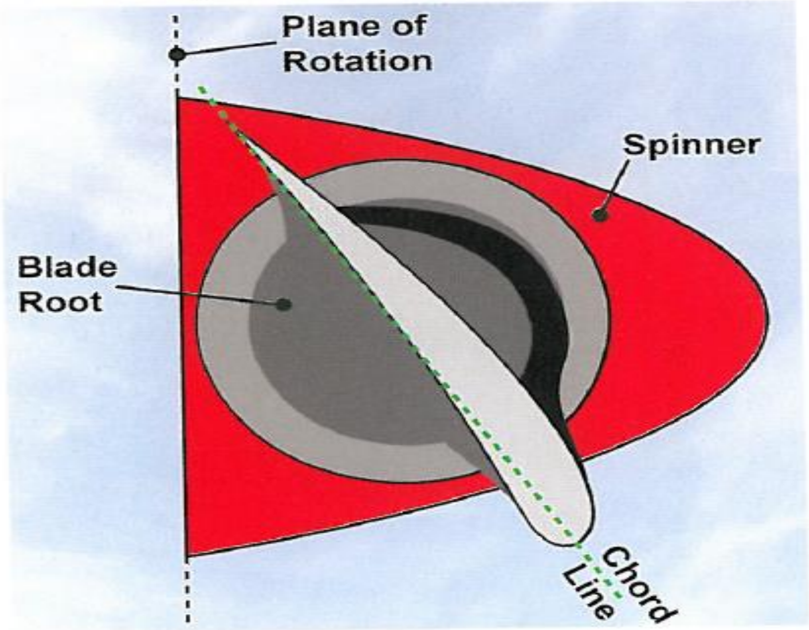


Figure 8.7 Blade cross-section and chord line.

Blade Angle or Blade Pitch.

The **Blade Angle** or **Blade Pitch** is the angle between the **blade chord line** and the **plane of rotation**. The **blade angle** changes along the length of the propeller blade, decreasing from root to tip. This twist in the propeller blade can be seen in *Figure 8.5,* and will be dealt with later in the chapter. The **"mean blade angle"** of a propeller is the blade angle at the **three-quarters blade length position**, measured from **blade root** to **tip**. **Fine-pitch propellers** have a small mean **blade angle.** Propellers with larger mean **blade angles** are called **coarse-pitch propellers.**

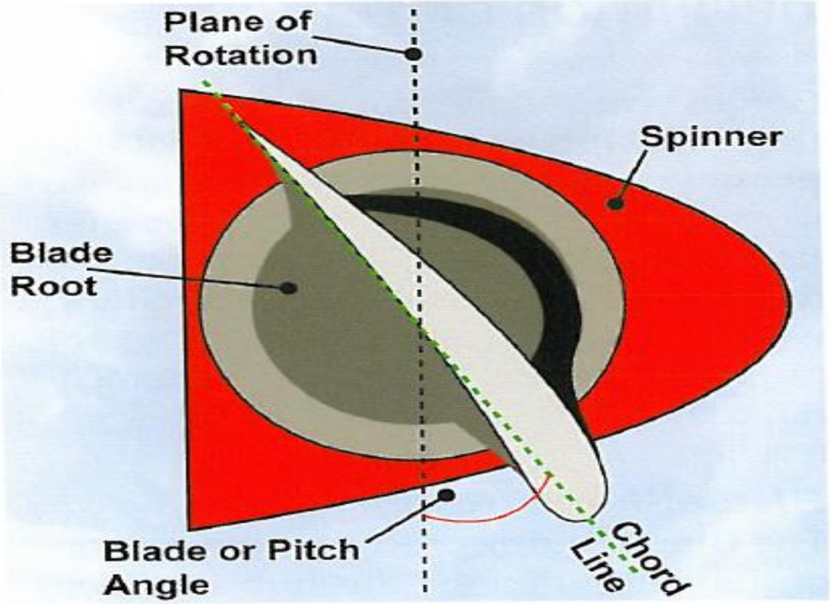


Figure 8.8 Mean blade pitch angle.

Blade Angle of Attack.

The **Blade Angle of Attack** is the angle between the **chord line** of any given blade element and the **relative airflow** which meets the propeller blade when the propeller is rotating. The propeller operates at its most efficient at an **angle of attack** of around **2** to **4 degrees**.

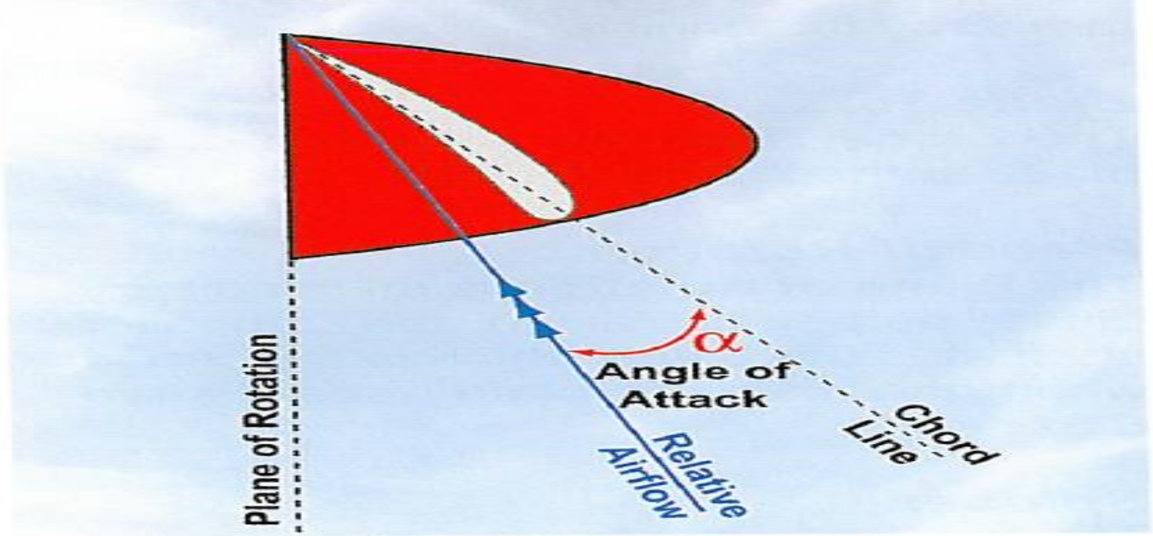


Figure 8.9 Angle of Attack.

Geometric Pitch.

The **Geometric Pitch** is the distance the propeller would travel forward in one complete revolution, if it were to advance through the air at the **blade angle**, just as a wood screw penetrates a wooden block with one turn of the screwdriver.

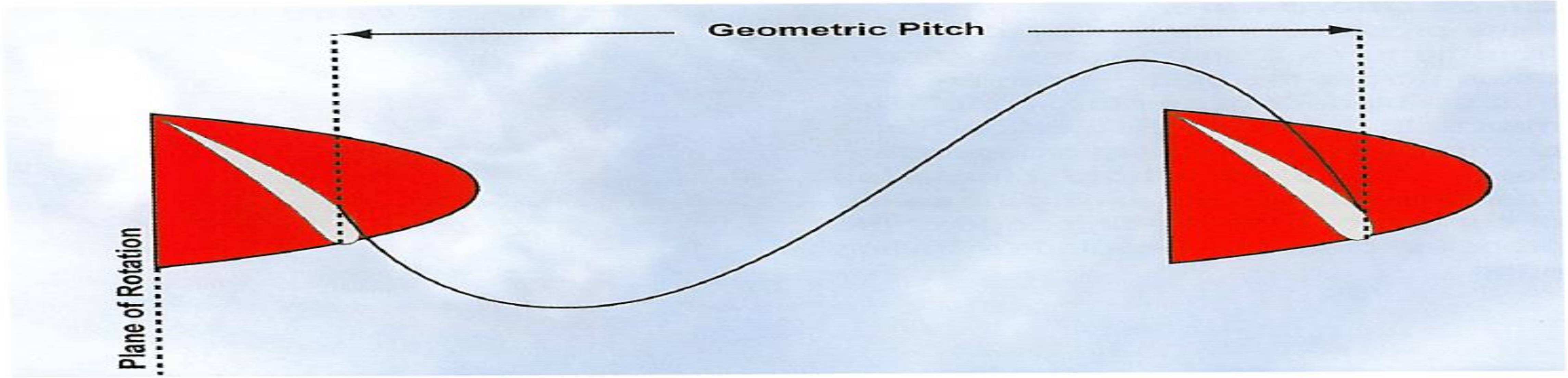


Figure 8.10 Geometric pitch.

Effective Pitch.
In flight, the propeller will hardly ever advance through the air at the **Geometric Pitch**. Air is a fluid, not a solid medium like wood. **Propeller Slip** will almost always be present. The distance that the propeller actually moves forward with one revolution is called the **Effective Pitch.**

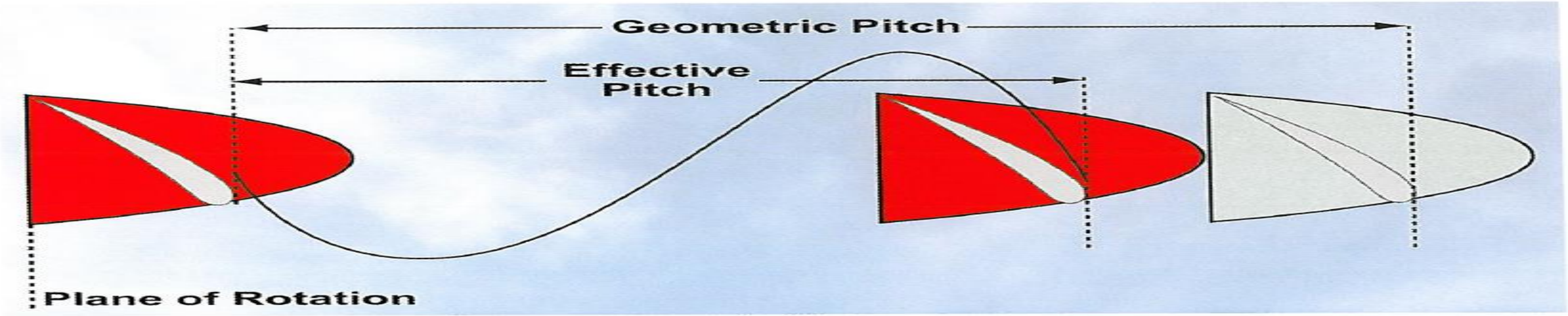


Figure 8.11 Effective pitch.

Propeller Slip.
The difference between **Geometric Pitch** and **Effective Pitch** is called **Propeller Slip**.

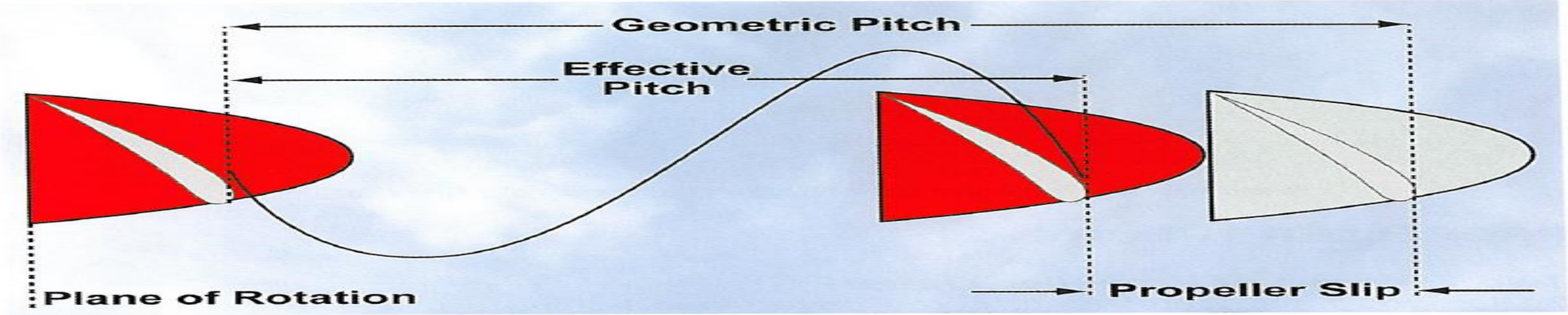


Figure 8.12 Propeller slip.

Helix Angle.

As the propeller rotates and advances through the air (following the line of **Effective Pitch**), the actual path that the blades follow describes a **helix**. The **Helix Angle** is the angle between the **Plane of Rotation** of the propeller and the path of the **Effective Pitch**.

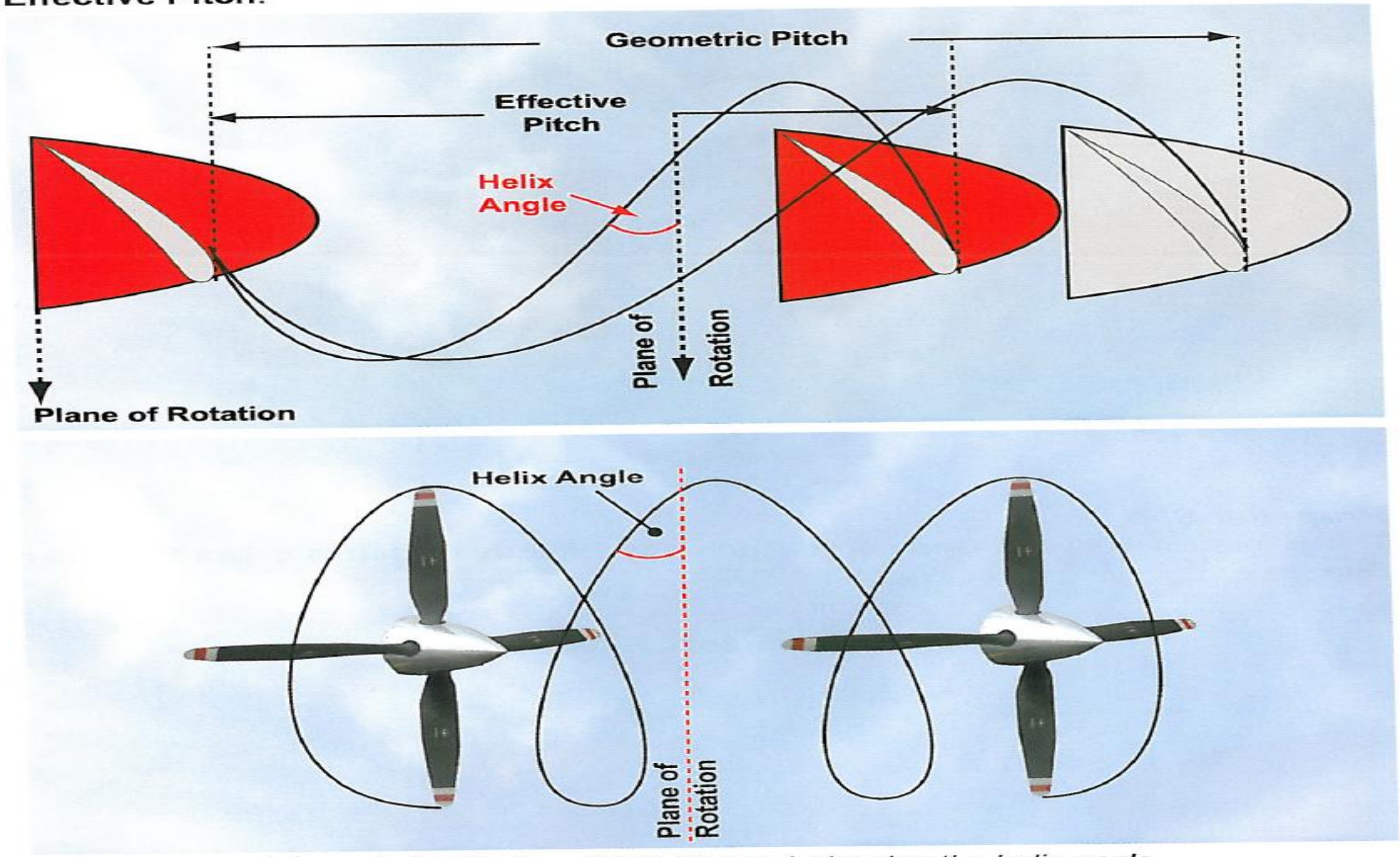


Figure 8.13 (Top) and 8.14 (Bottom) showing the helix angle.

PROPELLER THEORY.

Two Theories of Propeller Thrust?

So far, you have learnt (and, if you have stood behind a propeller-driven aircraft with its engine running, have doubtless experienced) that **a propeller accelerates a large mass of air rearwards**, thus generating **thrust** in accordance with **Newton's 2nd and 3rd Laws**. You have also read in the definitions above that propeller blades are **aerofoils** and are set at a given angle to the plane of rotation and so meet the air at an **angle of attack**. Furthermore, you will recall from an earlier chapter, in this Principles of Flight book, that aerofoils which meet the relative airflow at certain angles of attack generate an aerodynamic force called **lift** by virtue of the **pressure distribution** above and below the **aerofoil**. Rotating propeller blades, then, would seem to be able to generate **thrust** in the form of a **"horizontal lift force"** in accordance with the theories of the Swiss scientist **Bernoulli**, and as illustrated in *Figure 8.16*.

The equation: $\textbf{Thrust} = \dfrac{m(V_e - V_o)}{t}$ ..

$\textbf{Thrust} = C_L \tfrac{1}{2} \rho v^2 S$

Acceleration is, of course, just another name for **change in velocity**. *Figure 8.4* depicts how a given mass **m** of air is accelerated from velocity $\mathbf{V_o}$ to velocity $\mathbf{V_e}$, as it passes through a **propulsion system**. $\mathbf{V_o}$ is the velocity of the air entering the **propulsion system** and $\mathbf{V_e}$ is the increased velocity of the air after it has passed through the **propulsion system**.

The Variation of Thrust with Speed for a Fixed-Pitch Propeller.

Having established that **propeller thrust** is greatest when the aircraft is stationary under full power, let us see how the **thrust from a fixed-pitch propeller varies with the aircraft's forward velocity**. As aircraft speed increases, V_o increases, too, being equal to the aircraft's forward speed, plus a small value of induced velocity caused by the propeller's rotation. V_e, on the other hand, increases by a much smaller amount with increasing airspeed, because, as we shall see, **increasing airspeed causes the blade's angle of attack to decrease.**

Therefore, with V_o increasing more rapidly than V_e, as the aircraft gathers speed, the value $V_e - V_o$ must decrease, causing the propeller to impart a progressively diminishing acceleration, or velocity increase, to the air passing through its disk.

PROPELLER POWER AND PROPELLER EFFICIENCY.

You may remember from your Physics lessons at school that **Power** is defined as the **Rate of Doing Work**, and that **Power** may be expressed using the formulae:

$$\textbf{Power} = \frac{\textbf{Work Done}}{\textbf{time taken}}$$

or, because **Work Done = Force × Distance** through which the Force moves,

$$\textbf{Power} = \frac{\textbf{Force} \times \textbf{Distance}}{\textbf{time taken}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\textbf{(5)}$$

Let us apply Equation **(5)** to the case of an aircraft in flight. You know that the **Force** which drives an aircraft forward is called **Thrust**. You may also have learned that the term $\frac{\textbf{Distance}}{\textbf{Time}}$ is an expression of **"velocity"**.

Therefore, the power required to drive an aircraft forward at a given velocity is expressed by:

$$\textbf{Power} = \textbf{Thrust} \times \textbf{Aircraft Velocity} \quad \ldots\ldots\ldots\ldots(6)$$

In the specific case of the propeller,

Let us now examine **propeller power** and **propeller efficiency**. **Propeller power**, or **propulsive power,** obviously comes ultimately from the engine, and, in order to help it fly efficiently, an aircraft should develop maximum possible **propulsive power** at the expense of the smallest possible power output from the engine. **Propeller efficiency, then, is an expression of what proportion of engine power output is converted into propulsive power.**

$$\textbf{Propeller Efficiency} = \frac{\textbf{Propeller Power}}{\textbf{Engine Power}} \quad \ldots\ldots\ldots\ldots(8)$$

THE PROPELLER AS A ROTATING WING.

Up to now, we have considered, principally, the Newtonian, or simplified momentum theory of **thrust**. But, propeller blades are **aerofoils**. A propeller blade, then, acts like a **rotating wing**, and, like a wing, the propeller blade, in its normal operating range, meets the relative airflow at a certain **angle of attack**.

These **wing-like properties** of the propeller, especially the fact that it cuts through the air at a certain angle of attack, can of course help to explain how air is accelerated rearwards when the propeller rotates, just as a wing induces a downwash to the air flowing over it *(see Figure 8.19)*. But the **propeller blade's aerofoil cross section** also gives us another view on how thrust is produced.

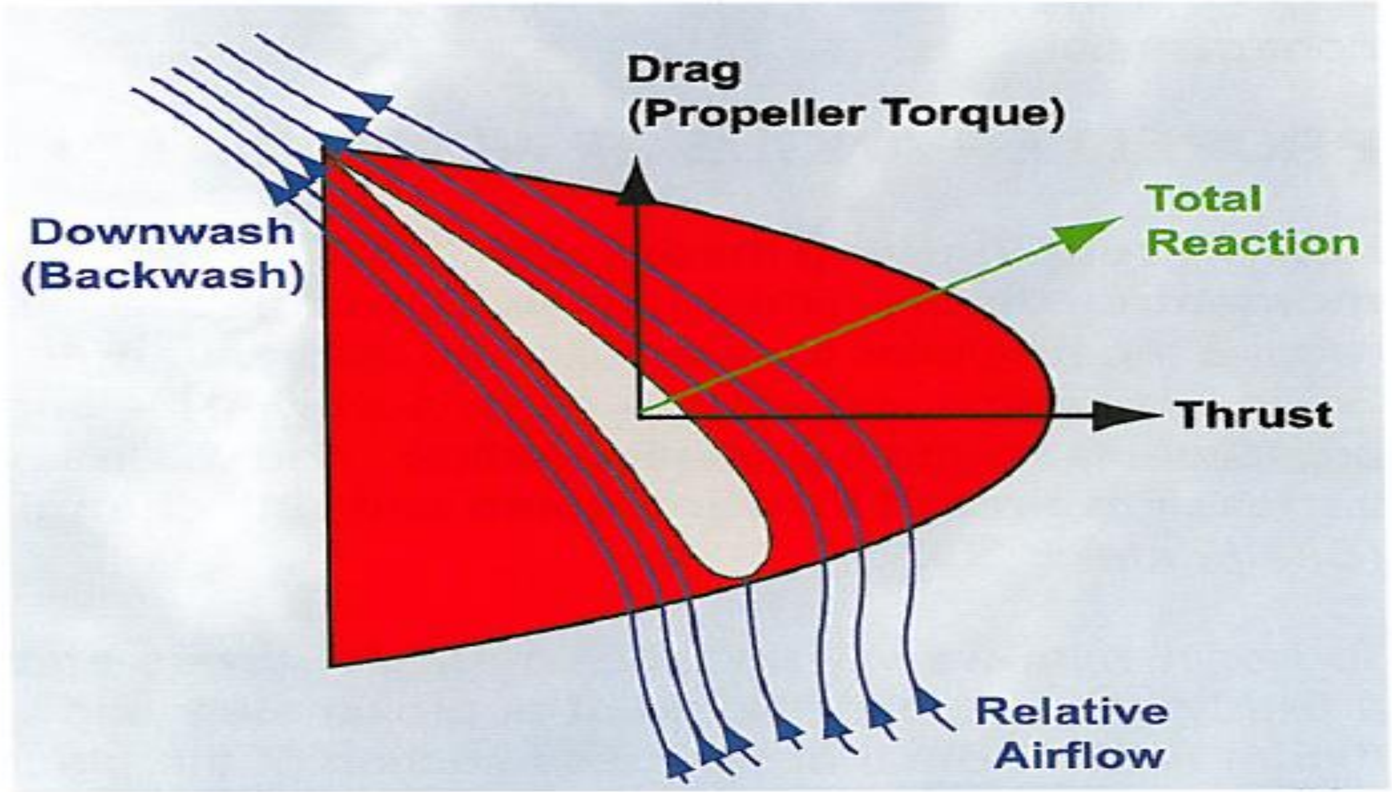


Figure 8.19 The rotating-wing analogy of propeller thrust.

It is, therefore, in order to maintain optimal propeller efficiency (that is, to maintain the most efficient angle of attack) along the whole length of the propeller blade the propeller is twisted such that the blade angle is progressively reduced from root to tip *(see Figure 8.21)*.

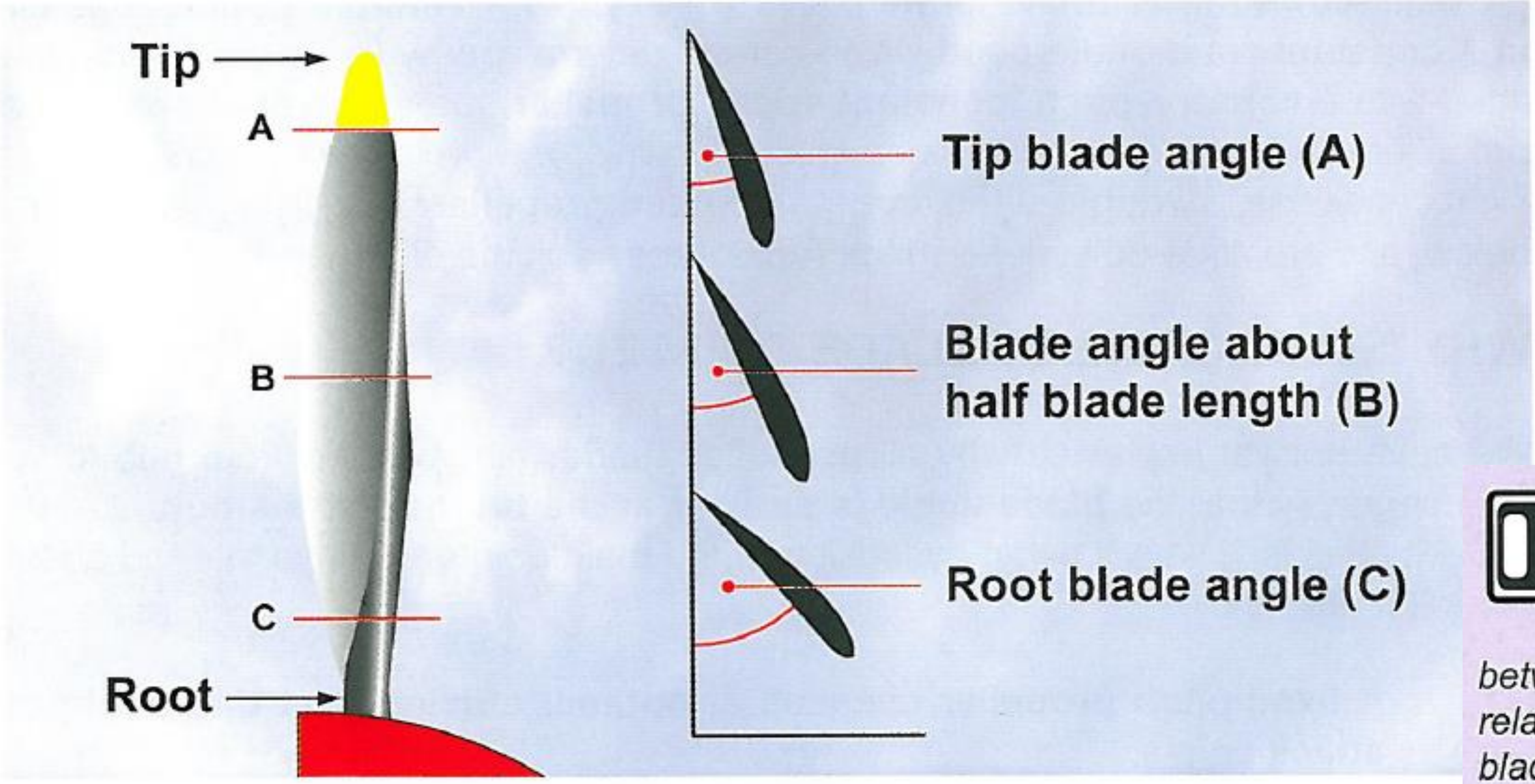
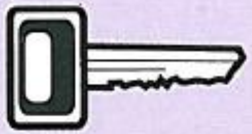


Figure 8.21 Blade angle reduces from root to tip.



In order to maintain the optimal angle of attack between the blade and the relative airflow, a propeller blade is twisted along its length, decreasing in blade angle from root to tip.

VARIABLE-PITCH CONSTANT-SPEED PROPELLERS.

The significant limitations of the fixed-pitch propeller can be partially overcome by fitting an aircraft with a powerplant which drives a **variable pitch propeller**, at a **constant rotational speed** which can be determined by the pilot.

With a **variable pitch, constant-speed propeller**, a desired propeller rotational speed can be selected by the pilot, and the propeller **blade-angle** will then adjust itself to different flight speeds in order to maintain the **selected rotational speed**. **In this way, optimal propeller efficiency is maintained over a range of aircraft speeds**.

Torque.

You should note, too, at this point, that, as well as accelerating air rearwards, the **propeller blades** also give rise to a **drag force** (whose magnitude varies with blade angle of attack and blade velocity), acting in the opposite direction to propeller rotation, **which balances the turning force of the engine** as depicted in *Figure 8.16*. The propeller's **drag force** is often called **"propeller torque"** while the **engine's turning force**, or, more accurately expressed, turning moment, is called **"engine torque"**. The magnitude of the **torque** produced by the propeller enables the propeller to absorb the power of the engine. **Torque is a by-product of thrust**. Without **torque**, there could be no **thrust**, and the propeller would overspeed to the destruction of both it and the engine.

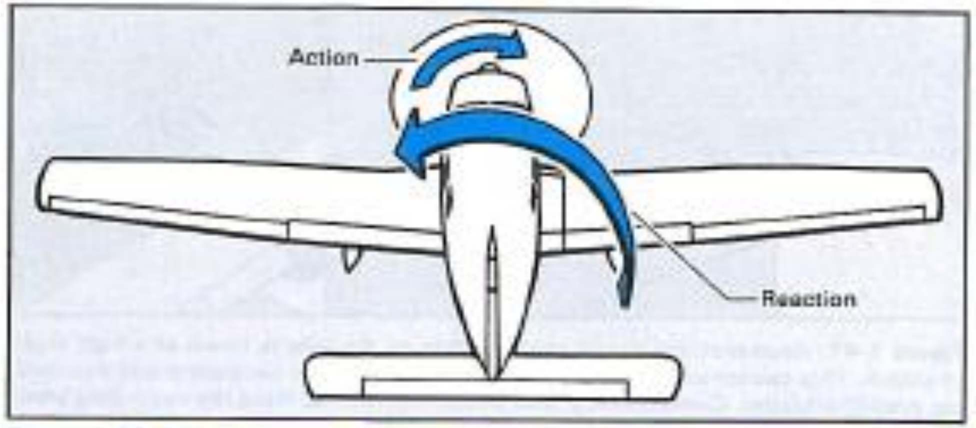


Figure 1-39. In a single-engine airplane, you will experience the greatest effect of torque during takeoff or climb when you are in a low-airspeed, high-power, high angle of attack flight condition.

Propeller Torque Effect.

Propeller torque is the propeller's reaction to engine torque. **Propeller torque** enables the propeller to absorb engine power, but it also causes a reaction in the aircraft, itself, causing the aircraft to attempt to rotate about the propeller shaft in the opposite direction to propeller rotation. This aircraft reaction is, of course, resisted by, amongst other things, the undercarriage, which is in contact with the ground.

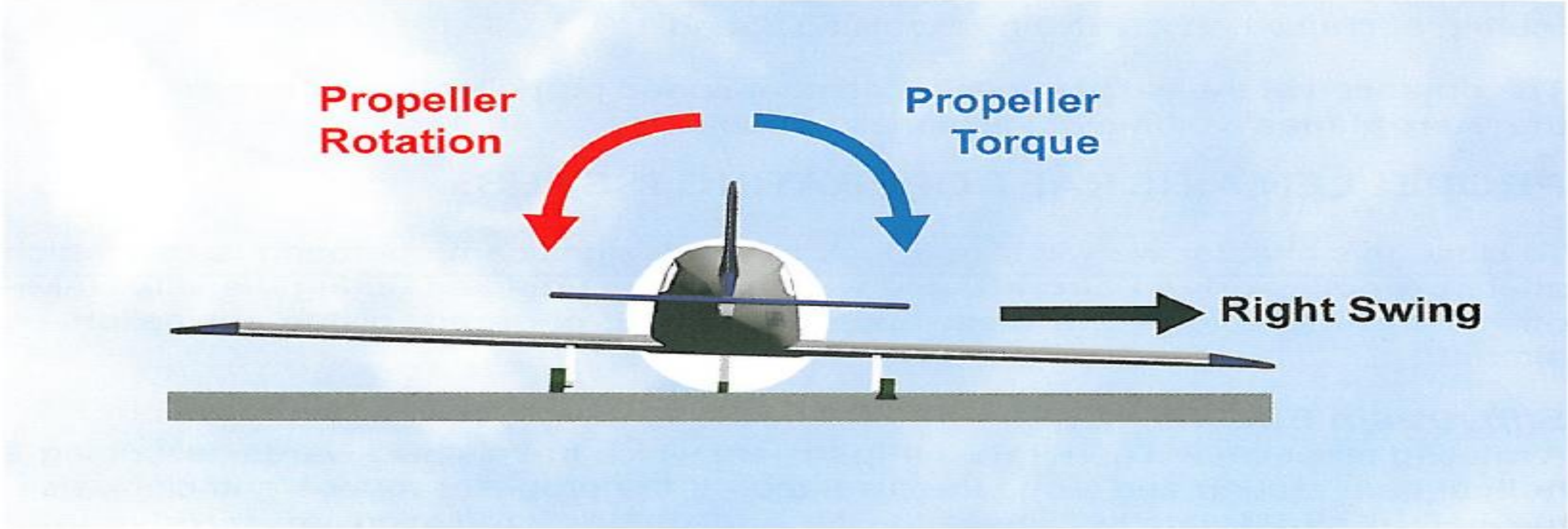


Figure 8.25 Propeller torque effect.

The **slipstream effect,** however, can cause a marked yaw when full power is applied to begin the take-off roll. In flight, the **slipstream effect** will cause the aircraft to yaw in one direction when power is applied in order, for instance, to make the transition from level flight to the climb, and in the opposite direction when power is reduced prior to levelling-off or descending. When power is applied, the aircraft will yaw against the direction of propeller rotation, and when power is reduced, it will yaw in the direction of propeller rotation. In all these situations, the pilot must prevent yaw by making an appropriate rudder input.

LEFT-TURNING TENDENCIES

Slipstream Effect.

A rotating propeller will generate a **slipstream** which travels backwards describing a **helical** path around and along the fuselage. If the propeller rotates anti-clockwise, the helical **slipstream** will meet the fin and rudder, producing an **aerodynamic force** at the tail assembly acting to the left, causing the aircraft to yaw to the right. Obviously, if the propeller rotates in the opposite direction, the yaw will also be in the opposite direction. For straight and level flight at the aircraft's cruise speed, any yaw resulting from slip-stream effect is normally eliminated by the manufacturer's rudder trim setting.

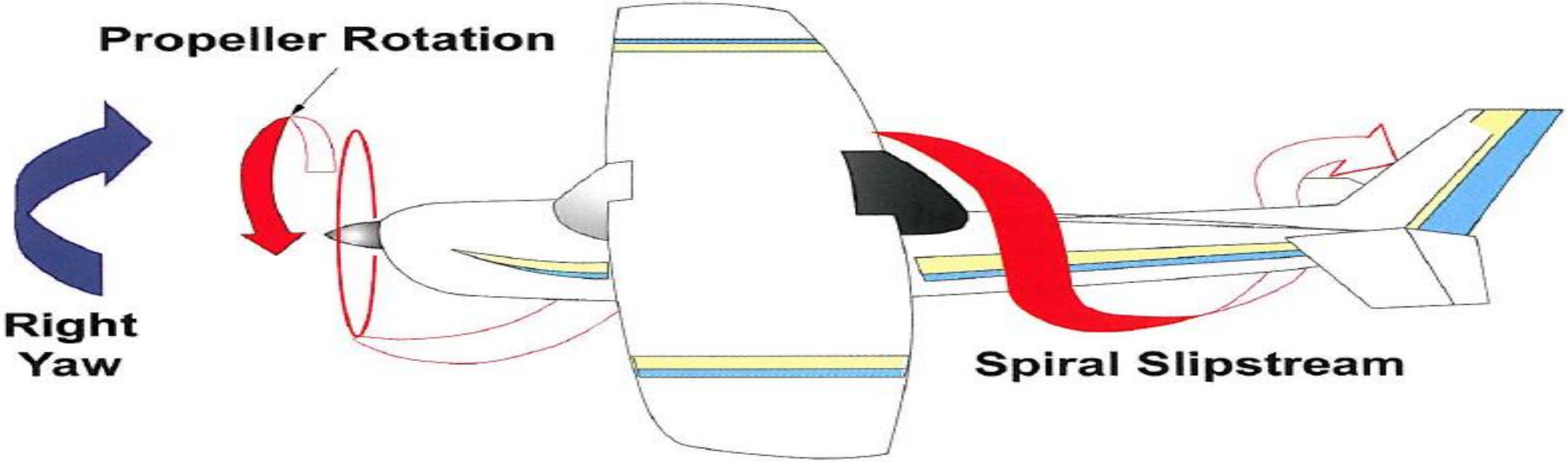


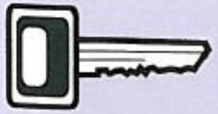
Figure 8.24 The slipstream effect.

If the propeller is rotating anti-clockwise, as seen by the pilot, the aircraft will, in reaction, attempt to roll to the right. *(See Figure 8.25)* This will apply a downward force on the starboard main wheel thereby increasing its rolling resistance. This situation will cause the aircraft to swing to the right until downward force is removed from the wheels altogether, at lift-off. If the propeller is rotating in a clockwise direction, the tendency to swing will be to the left. Note that swing induced by **propeller torque effect** is in the same direction as swing caused by the slipstream effect. **Propeller torque effect** is most apparent in the early stages of take-off.

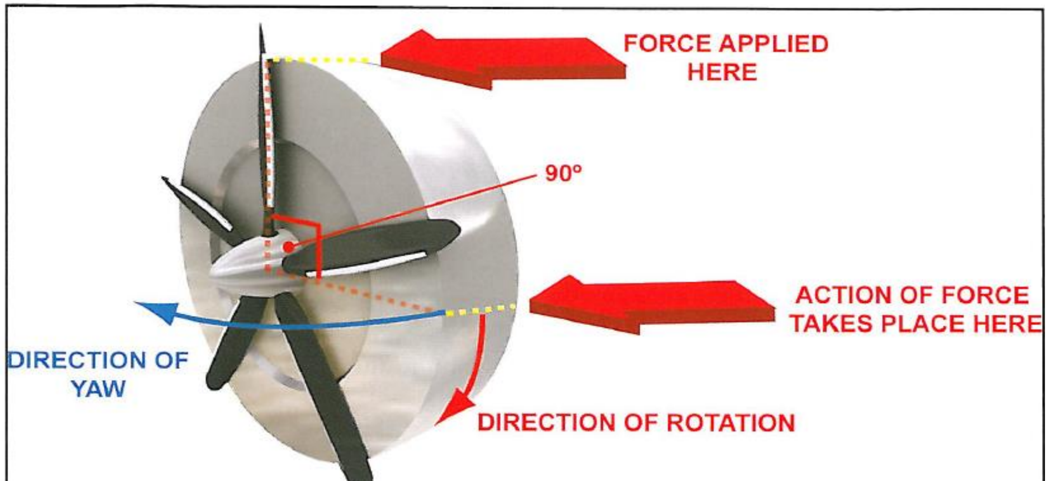
The Gyroscopic Effect - Gyroscopic Precession.

Any spinning body, or **gyroscope**, will resist movement when a force is applied to it. If you were to hold the two ends of the axis of a wheel spinning towards you (when viewed from above), you would notice that if you attempted to tilt the axis, by lowering one end, the axis would not move very far in the direction you wished it to, but would instead move in the horizontal plane as if you had tried to push the end of the axis away from you. This phenomenon is known as **gyroscopic precession**. The result of **gyroscopic precession** is that the line of action of any force applied to the spin axis moves through 90° in the direction of spin, before taking effect.

A rotating propeller acts like a **gyroscope**. Therefore, if the pilot of an aircraft pitches the nose downwards, he is, in effect, tilting the axis of rotation of the propeller forwards. **Gyroscopic precession** will cause the effect of the tilting force to take place along a line of action displaced by 90°, in the direction of spin. So, if the propeller is rotating anticlockwise as seen from the pilot's seat, and the pilot pitches the nose downwards, **gyroscopic precession** will cause the aircraft to tend to yaw to starboard (to the right as seen by the pilot). This tendency is especially marked in tail-wheel aircraft, on the take-off run when, under full power (maximum rpm), the pilot lifts the aircraft's tail. **Gyroscopic precession** in a propeller is illustrated in *Figure 8.26*



An anticlockwise rotating propeller, as viewed from the pilot's seat, will cause a powerful piston-engine driven, tail-wheel propeller aircraft to swing to the right when the tail is lifted on the take-off run.



Direction of Swing.

In the case of a propeller rotating **anti-clockwise** as seen by the pilot, **Slipstream Effect**, **Torque Effect**, **Gyroscopic Effect** and **Asymmetric Blade Effect** all induce a **swing to the right**, and **all effects reinforce one another.**

For an aircraft with the propeller rotating **clockwise** when viewed from the pilot's seat, these effects would combine to induce a swing to the left.

So, as a final illustration, imagine you are commencing a take-off in a **tailwheel aircraft** with an **anticlockwise rotating propeller** (as seen from your pilot's seat). You should, then, be prepared for **a possible swing to the right** when you start to roll. If your aircraft has a powerful engine, yaw to the right during the take-off roll, as the tail is lifted into the flying position, will almost certainly be significant.

Consider, then, in this situation, to what extent this **swing to starboard** might be exacerbated by a **cross-wind from the right** which acts on the tail, pushing it even more to the left. The increase in right swing could be considerable. Of course, a cross wind from the left will tend to negate the right swing on take-off. If your aircraft had a **clockwise rotating propeller**, viewed from your seat, it would, of course, tend to **swing to the left on take-off**. A left swing will be amplified by a cross-wind from the left and diminished by a cross-wind from the right.

٢٧. Which statement is true regarding the opposing forces acting on an airplane in steady-state level flight?

A. These forces are equal.
B. Thrust is greater than drag and weight and lift are equal
C. Thrust is greater than drag and lift is greater than weight.

٨٥. What is the relationship of lift, drag, thrust, and weight when the airplane is in straight-and-level-flight?

A. Lift equals weight and thrust equals drag.
B. Lift, drag, and weight equal thrust.
C. Lift and weight equal thrust and drag.

٨٧. An advantage of a constant-speed propeller is that it:

A. Allows the pilot to select a high blade angle and high RPM setting for takeoffs.
B. Allows the pilot to select and maintain a desired cruising speed.
C. Allows the pilot to select the blade angle that provides the most efficient performance.
D. Allows the airplane to operate smoother with stable RPM and eliminates vibrations.

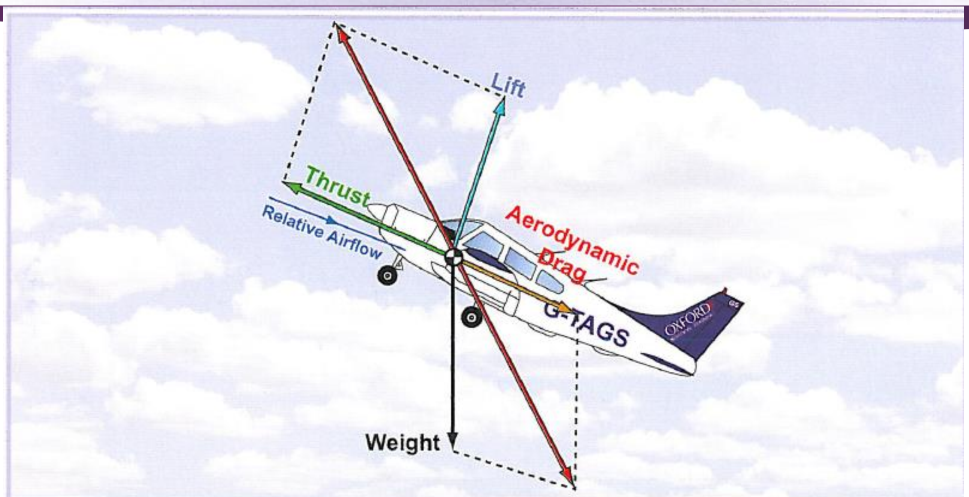
٨٤. The four forces acting on an airplane in flight are

A. Lift, weight, thrust, and drag.
B. Lift, weight, gravity, and thrust.
C. Lift, gravity, power, and friction

٩٢. When does P-factor cause the airplane to yaw to the left ?

A. When at low angles of attack.
B. When at high angles of attack.
C. When at high airspeeds.

CHAPTER 9
THE FOUR FORCES AND TURNING FLIGHT



Before your airplane turns, however, it must overcome inertia, or its tendency to continue in a straight line. You create the necessary turning force by banking the airplane so that the direction of lift is inclined. Now, one component of lift still acts vertically to oppose weight, just as it did in straight-and-level flight, while another acts horizontally. To maintain altitude, you will need to increase lift by increasing back pressure and, therefore, the angle of attack until the vertical component of lift equals weight. The horizontal component of lift, called **centripetal force**, is directed inward, toward the center of rotation. It is this center-seeking force which causes the airplane to turn. Centripetal force is opposed by **centrifugal force**, which acts outward from the center of rotation. When the opposing forces are balanced, the airplane maintains a constant rate of turn, without gaining or losing altitude. [Figure 1-35]

Lift acts at 90° to the relative airflow, and is considered as acting though the **centre of pressure**. If angle of attack is increased, but remains below the stalling angle, the centre of pressure will move forwards along the wing chord. With decreasing angle of attack, the centre of pressure will move rearwards.

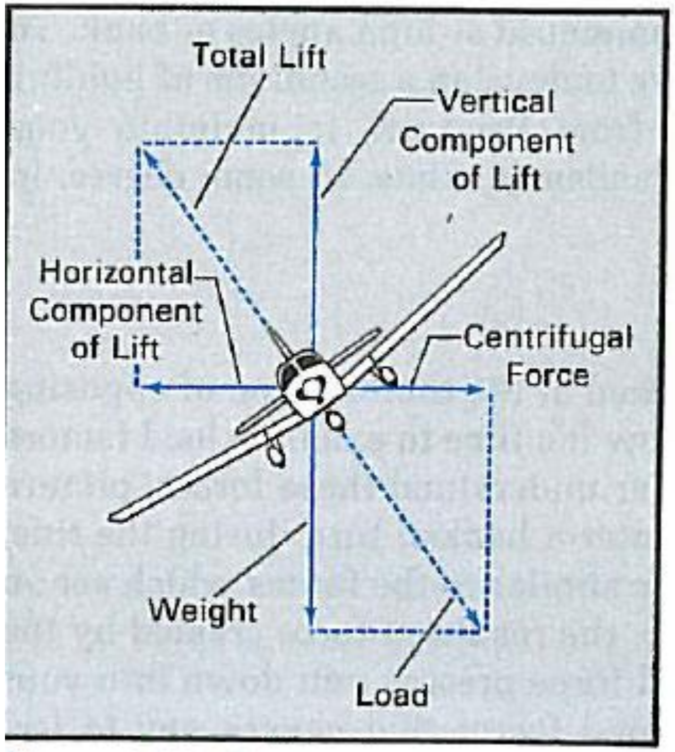
Weight always acts vertically downwards through the aircraft's **centre of gravity**. During flight, the aircraft consumes fuel, and so the weight of the aircraft constantly changes. As individual fuel tanks empty, the position of the aircraft's **centre of gravity**, may change. Its position must, however, remain within prescribed limits. When the aircraft manoeuvres in pitch, roll and yaw, the aircraft rotates about its **centre of gravity**.

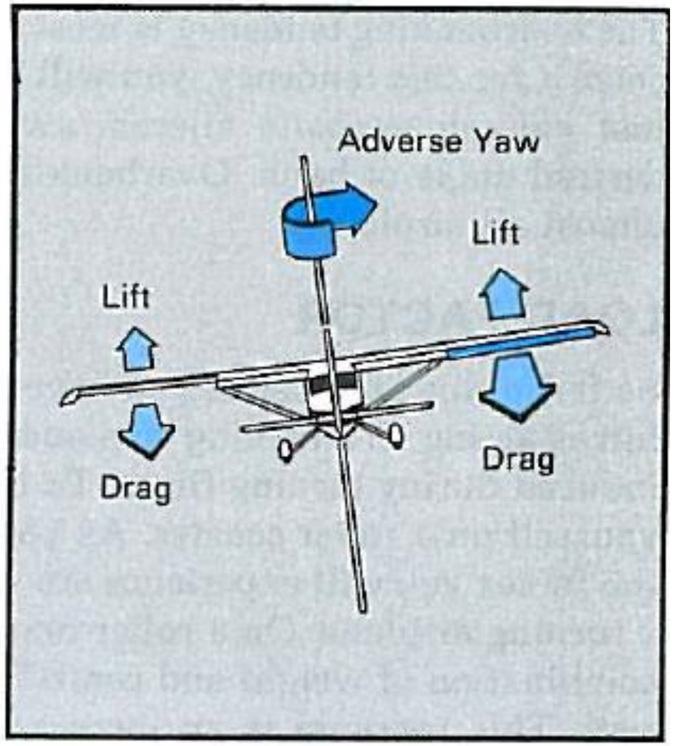
Thrust may be considered to act along the line of the propeller shaft.

Drag may be considered to act parallel to the relative airflow so as to resist the motion of the aircraft. The actual line of action of the total drag is difficult to determine except by experiment, and will vary with changing angle of attack.

ADVERSE YAW

When you roll into a turn, the aileron on the inside of the turn is raised, and the aileron on the outside of the turn is lowered. The lowered aileron on the outside increases the angle of attack and produces more lift for that wing. Since induced drag is a by-product of lift, you can see that the outside wing also produces more drag than the inside wing. This causes a yawing tendency toward the outside of the turn, which is called **adverse yaw.** [Figure 1-36]





OVERBANKING TENDENCY

During your initial flight training, you will learn how to maneuver the airplane through coordinated use of the controls. As you enter a turn and increase the angle of bank, you may notice the tendency of the airplane to continue rolling into an even steeper bank, even though you neutralize the ailerons. This **overbanking tendency** is caused by the additional lift on the outside, or raised, wing. The outside wing is traveling faster than the inside wing. This adds to the lift, and the combined effects tend to roll the airplane beyond the desired bank angle.

STRAIGHT FLIGHT AT CONSTANT SPEED.

Equilibrium.

In steady, straight flight, at constant speed, the four forces will be in **equilibrium**. With the four forces all **in equilibrium**, the forces balance each other exactly, either one against one, or two together against the other two together. With the forces in **equilibrium**, the aircraft continues flying in its steady state without any change in attitude or speed. This state of **equilibrium** may be achieved in straight and level flight, a straight climb or a straight descent.

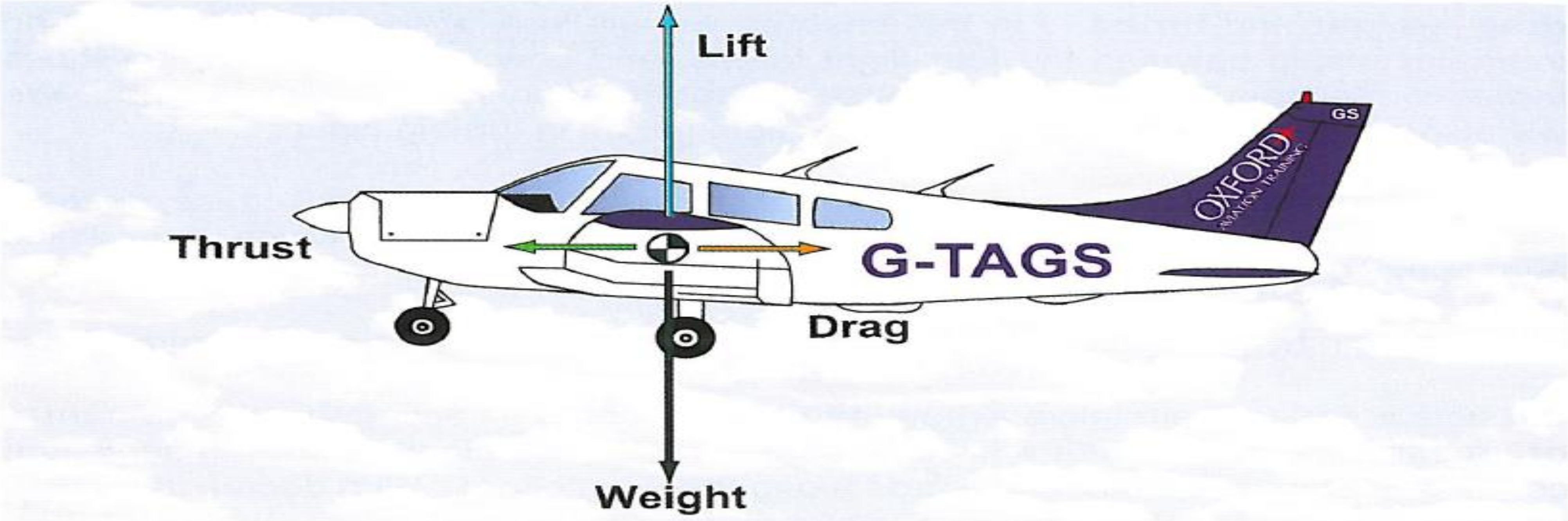


Figure 9.1 An idealistic state of equilibrium of the four main flight forces in straight and level flight.

You should note that, in reality, there is a considerable difference in the magnitude of the two pairs of forces: lift-weight, and thrust-drag. For a light aircraft the lift will typically be in the order of 10 times as great as the drag, giving a **lift-drag ratio** of 10. You have already learnt about the importance of **lift-drag ratio**.

TURNING FLIGHT.

Centripetal Force.

It will be clear to you that when a body is turning in a circular path, it is constantly changing direction. **Consequently, the forces acting on a body which is following a circular path are not in equilibrium.** In circular motion, there must be an out-of-balance resultant force acting towards the centre of the circle, or else the body would be moving in a straight line in accordance with **Newton's 1st Law**. This out-of-balance force is called by scientists a **centripetal force**. *(See Figure 9.10)* **Centripetal** is derived from Latin and means **centre-seeking**.

For an aircraft in turning flight, the **centripetal force** has to be supplied by

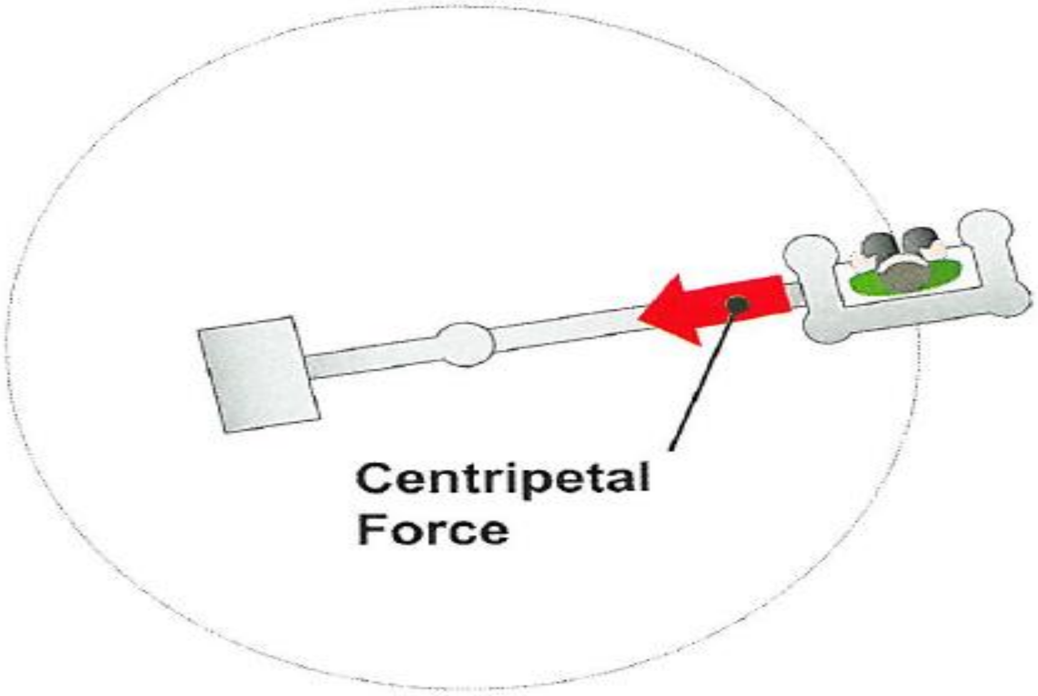


Figure 9.10 For a body to travel in a circular path, it must constantly change direction under the influence of an out-of-balance force called "centripetal force".

the **lift** force being directed towards the centre of the turn. That is why, in order to turn, a pilot must apply bank in the direction of turn. That part of the **lift** force which then provides the **centripetal force** constantly changes the direction of flight of the aircraft, and, because **centripetal force** is an out-of-balance, resultant force, the pilot feels it as an apparent increase in weight. What is actually happening is that the **centripetal force** is accelerating the mass of the aircraft towards the centre of the circle, but because the aircraft's linear velocity (its airspeed) is superimposed on the acceleration towards the centre of the circle, the aircraft does not move towards the centre of the circle but instead describes a circular path at a constant distance, or radius, from the centre. This acceleration, not surprisingly called **centripetal acceleration**, acts on all the individual masses of components, equipment and crew which are part of the aircraft.

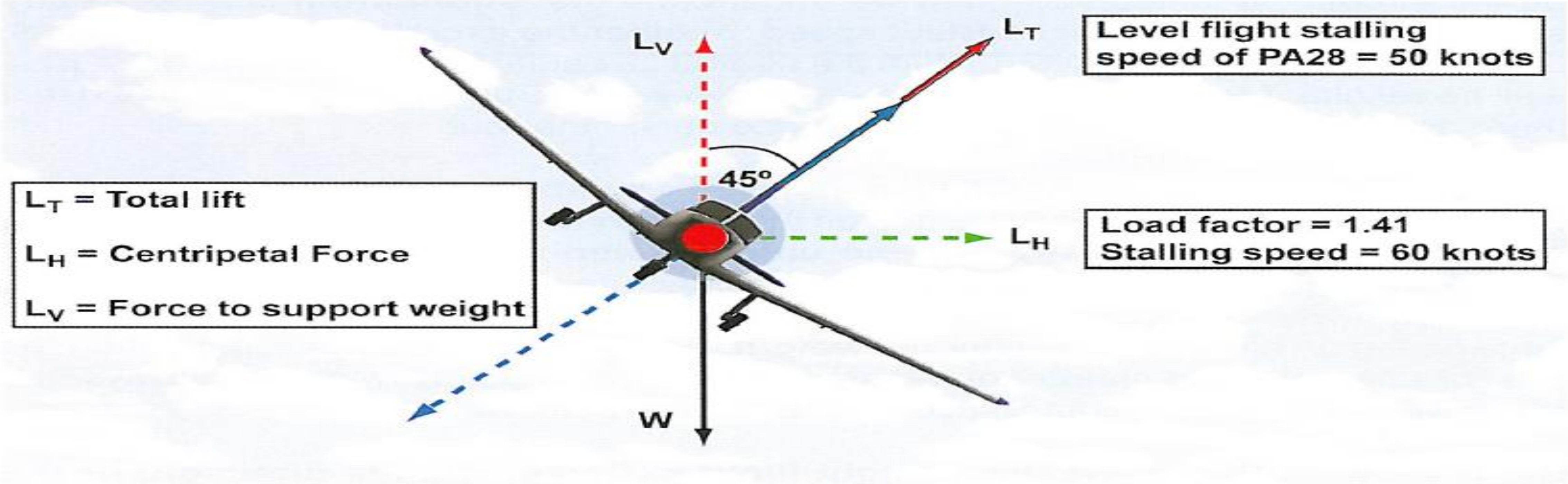


Figure 9.11 A 45° banked turn. The lift generated by the wings must both support the aircraft's weight and provide the turning (centripetal) force.

In the 45°-banked turn illustrated, the **total lift** force, $\mathbf{L_T}$, has to do two jobs. $\mathbf{L_T}$ is not only causing the aircraft to turn but is also supporting the **weight** of the aircraft (which continues to act vertically downwards) so as to maintain the aircraft in level flight. To achieve both these objectives, the **total lift** force in the turn needs to be greater than that required for straight and level flight. In *Figure 9.11*, as in the following two diagrams, the blue lift arrow depicts the magnitude of the **lift** required to maintain the aircraft in straight flight, and the red arrow depicts the **extra lift** that the wings must generate to enable the aircraft to turn while maintaining its altitude.

If level flight is to be maintained, as the angle of bank is increased, the angle of attack (and, therefore, $\mathbf{C_L}$) of the wing must also be increased by a progressive backward pressure on the control column. This increases the **lift** force (**Lift = $\mathbf{C_L \, \frac{1}{2} \rho v^2 S}$**) to a value, $\mathbf{L_T}$, such that the vertical component, $\mathbf{L_V}$, of the **total lift** is sufficient to balance the aircraft's **weight** and maintain level flight, while the horizontal component of the **total lift**, $\mathbf{L_H}$, provides the **centripetal force** required to turn the aircraft.

Airspeed in the Turn.

To the pilot, the increase in angle of attack required to generate the **extra lift** for the turn will be apparent as an increase in the back pressure on the control column sufficient to maintain the correct attitude and constant altitude. However, as the back pressure increases, and with it the angle of attack, $\mathbf{C_D}$ naturally increases, along with $\mathbf{C_L}$, causing the total **drag** to rise (**Drag** = $\mathbf{C_D}$ $\frac{1}{2}\rho \mathbf{v^2}$ **S**). The increased **drag** will naturally lead to a reduction in **airspeed**, if **thrust** is not increased. While the reduction in **speed** is small in a medium level turn, up to 30° angle of bank, and may be acceptable, this would not be the case in a 45°-banked turn, or above. In a 45°-banked turn, it is important to increase **thrust** to maintain the entry **speed** because of the increased **stalling speed**. You will learn more about **stalling speed** in turns in the relevant chapters of this book, though, for your interest, we include in the diagrams the **stalling speed** for the angles of bank illustrated. For instance, in a 45°-banked turn, the **stalling speed** of a PA28 Warrior is around 60 knots: 10 knots higher than its straight flight **stalling speed** of 50 knots

Load Factor.

In a 45°-banked turn, the **lift** force required to generate the necessary **centripetal force** and **centripetal acceleration** for the turn is 1.41 times the magnitude of the aircraft's **weight**. The pilot will clearly sense this increase in force, which is also acting on him, as an **inertial reaction** to the increase in **lift**. In fact, the whole of the aircraft structure will be subjected to the **inertial reaction** to the increase in **lift** generated by the wings, and sense this reaction as an increase in **load factor**. As you will learn in later chapters, it is the increased **wing loading** caused by the higher **load factor** which causes the increase in stalling speed in a turn (the derivation of the value of **load factor** is covered on Page 296).

In a correctly flown turn, the pilot will feel the extra **lift** force as an apparent increase in **weight** pressing him firmly into his seat. In a 60°-banked turn, the **lift** force required for the turn is twice the magnitude of the aircraft's **weight**, and the pilot actually feels that his own **weight** has doubled. *(See Figure 9.12).*

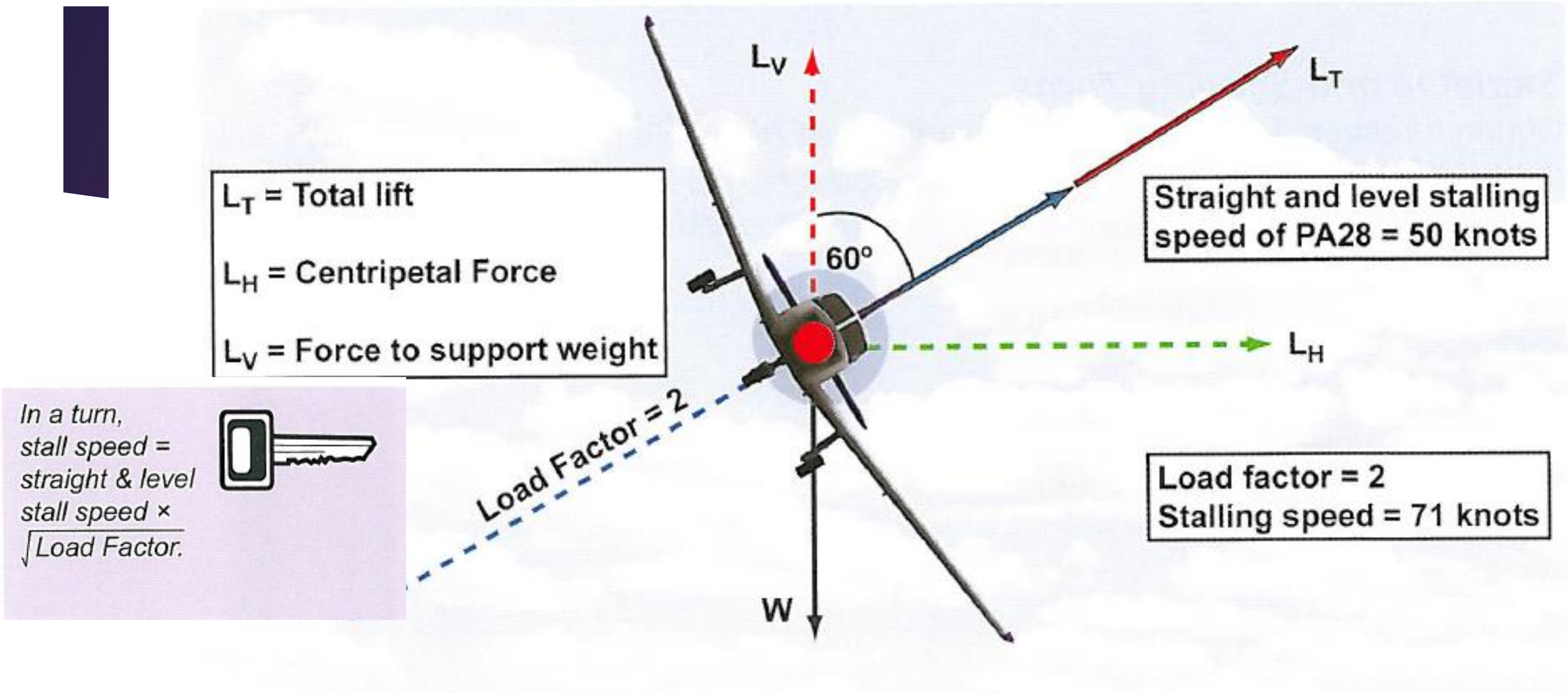
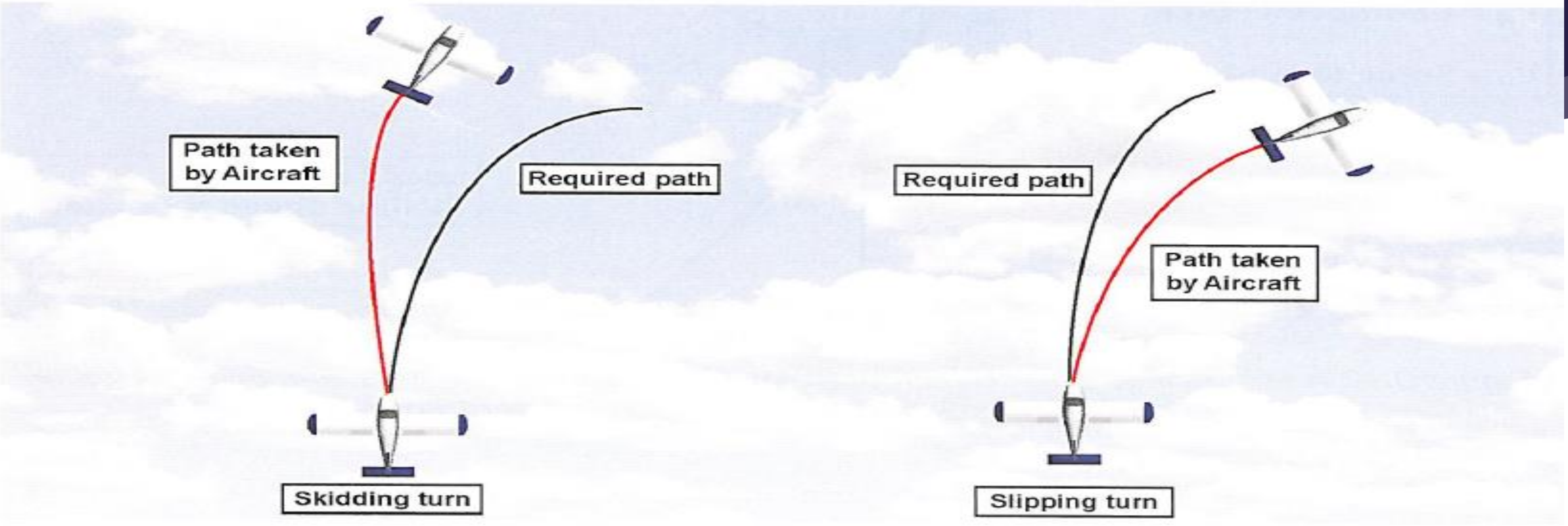


Figure 9.12 A 60° banked turn. The lift required for the turn is twice its straight flight value. Load Factor is 2, and the stalling speed is 71 knots.

Skidding and Slipping Turns.

During turning manoeuvres, uncoordinated use of the aileron and rudder may cause the turn to be unbalanced. In an unbalanced turn, the aircraft will either **slip** or **skid** through the air, while it is turning. *Figure 9.14*, illustrates the difference between



slip and **skid**. Basically, for a given radius of turn at a given speed, there is only one correct angle of bank. If an aircraft is overbanked for its turn, or if the pilot has applied too little rudder, the aircraft will **slip** into the turn. On the other hand, if the pilot has applied to small an angle of bank for the turn, or used too much rudder, the aircraft will **skid** out of the turn.

Co-ordination of Turns - Slip and Skid.

Slip and **skid** is displayed by the inclinometer which is the bottom portion of the 'turn co-ordinator', or the 'turn and slip' indicator. *(See Figure 9.15.)* The inclinometer consists of a glass tube filled with liquid, and contains a ball.

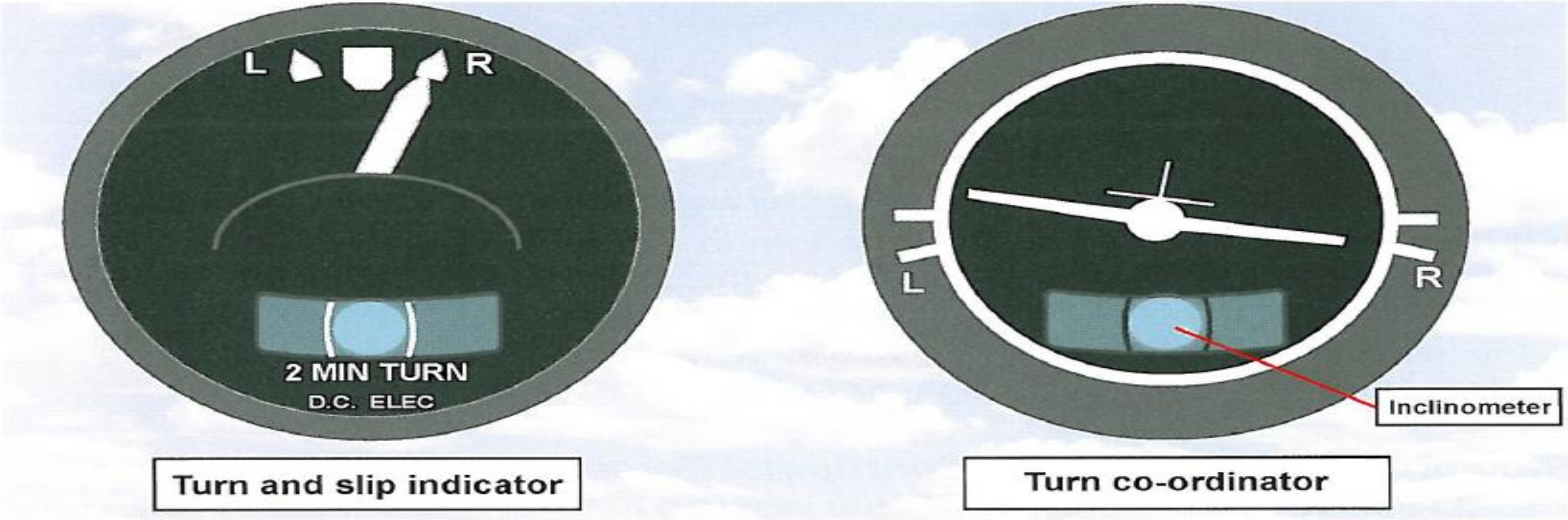


Figure 9.15 The Turn and Slip Indicator and Turn Co-ordinator, showing a balanced rate one turn.

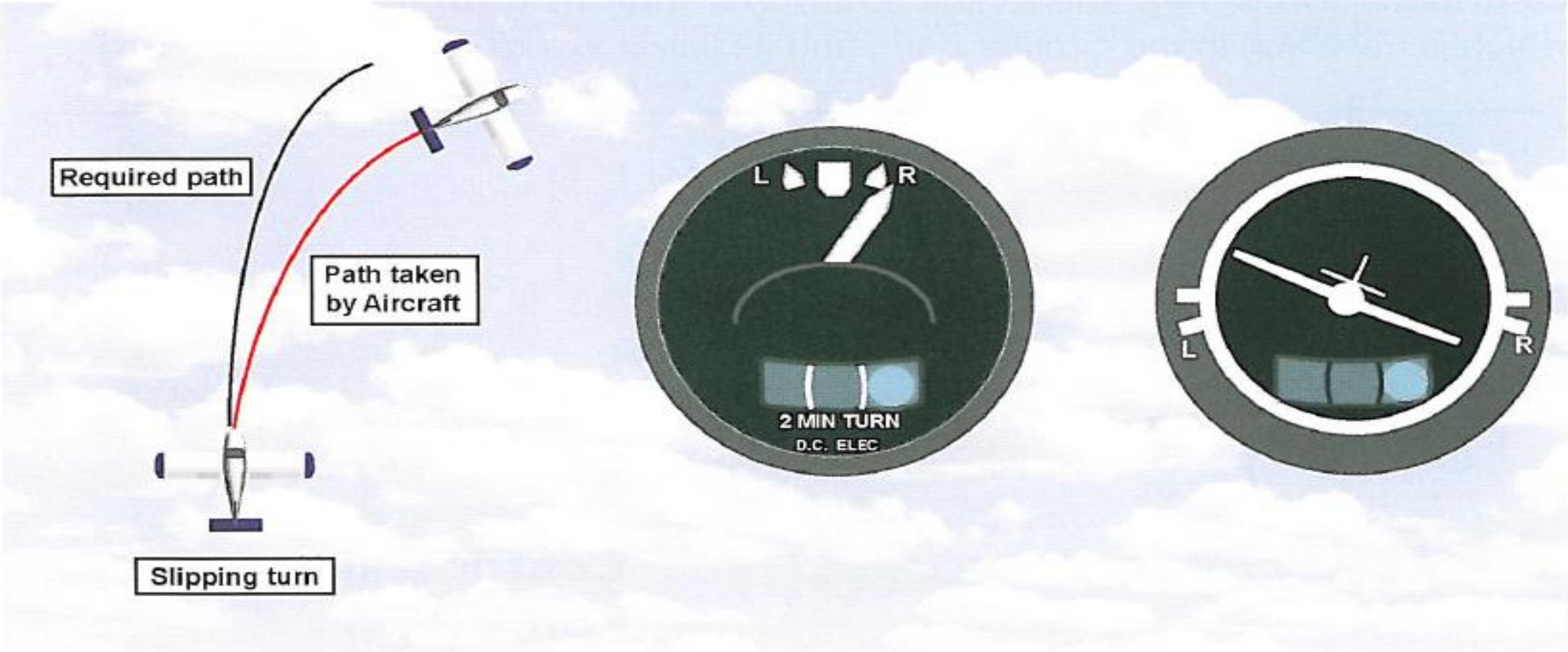


Figure 9.16 The ball indicates a slip in the direction of turn to the right.

The **slip** may have been caused because too much bank or too little rudder has been applied. Therefore, reducing the bank angle could return the aircraft to **balanced flight**. However, the simple rule to "re-balance" the turn, is to 'step on the ball' i.e. apply sufficient right rudder to return the ball to the middle position, between the two vertical lines.

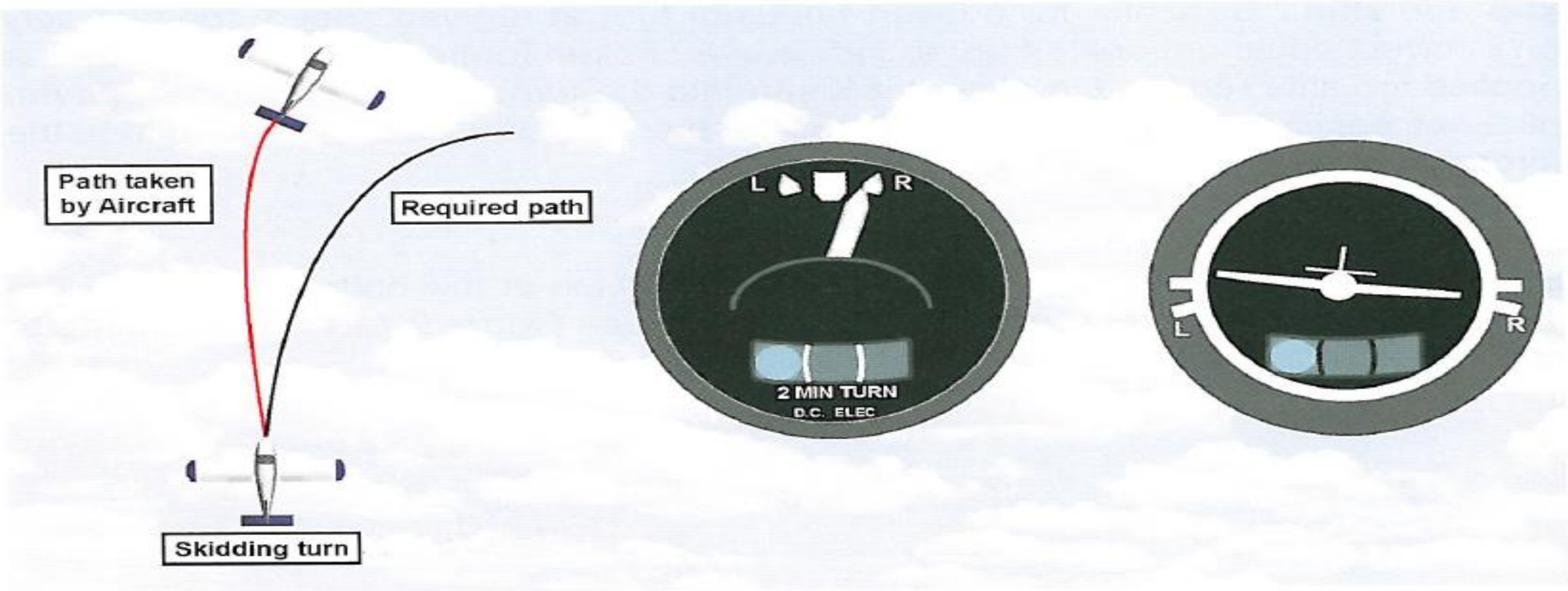


Figure 9.17 The ball indicates a skid away from the direction of turn.

If the aircraft were **skidding** out of the turn to the right, as in *Figure 9.17,* the ball would be displaced to the left. It could be that there is too little bank angle or too much rudder for the rate of turn being flown, but the easiest solution to return the ball to the middle is to apply left rudder. This amounts to the same thing as reducing right rudder. The simple answer, though, as before, is to "step on the ball."

Rate of Turn, Airspeed and Centripetal Force.

The magnitude of the **centripetal force** required to turn an aircraft varies with both **airspeed** and **rate of turn**. (The **rate of turn** is a measure of the time taken to complete a full 360° turn.) If the **rate of turn** is doubled (that is, with half the radius of turn) while maintaining a given **airspeed**, the **centripetal force** required to execute the turn is also doubled. If the **airspeed** were doubled but the **rate of turn** were to remain the same (constant radius), the **centripetal force** would need to be four times as great. The basic mathematical formula behind these statements is shown in *Figure 9.18*. The formula expresses the mathematical relationship between **centripetal force**, $\mathbf{F_{CP}}$, the radius of turn (i.e. **rate of turn**), the mass of the body which is travelling in the circular path, and its linear velocity.

$$F_{CP} = \frac{\text{mass} \times v^2}{r}$$

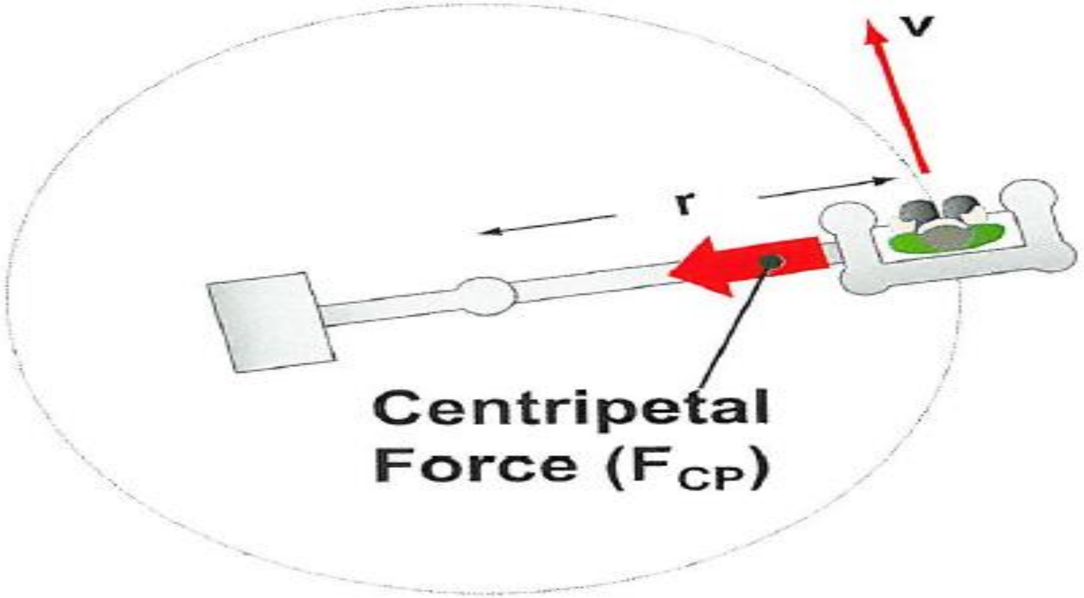
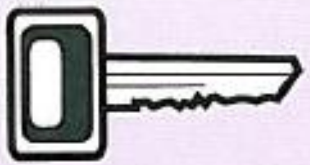


Figure 9.18 Mathematical relationship between centripetal force, $\mathbf{F_{CP}}$, the radius of turn (i.e. rate of turn), the mass of the body, and the linear velocity, v.

In civilian flying, procedural turns are carried at a rate of 180° per minute, or 3° per second. This **rate of turn** will be indicated on an aircraft's **Turn and Slip Indicator** and termed as a **rate one turn**. At normal light aircraft cruising speeds, a **rate one turn** will not require a **centripetal force** which will cause you any discomfort; a **rate one turn** at 90 knots would require, for instance, only 16° of bank.

The rate at which any aircraft turns is determined by **true airspeed** and **angle of bank**. At a given **true airspeed,** a given **angle of bank** will provide a certain **rate of turn**. A simple way to estimate the **angle of bank** required for a **rate one turn** of 3° per second, at a given **true airspeed**, is to take 10% of the **true airspeed** in knots, and add 7; for example, at 100 knots**,** a **rate one turn** is achieved with 17° **angle of bank**.

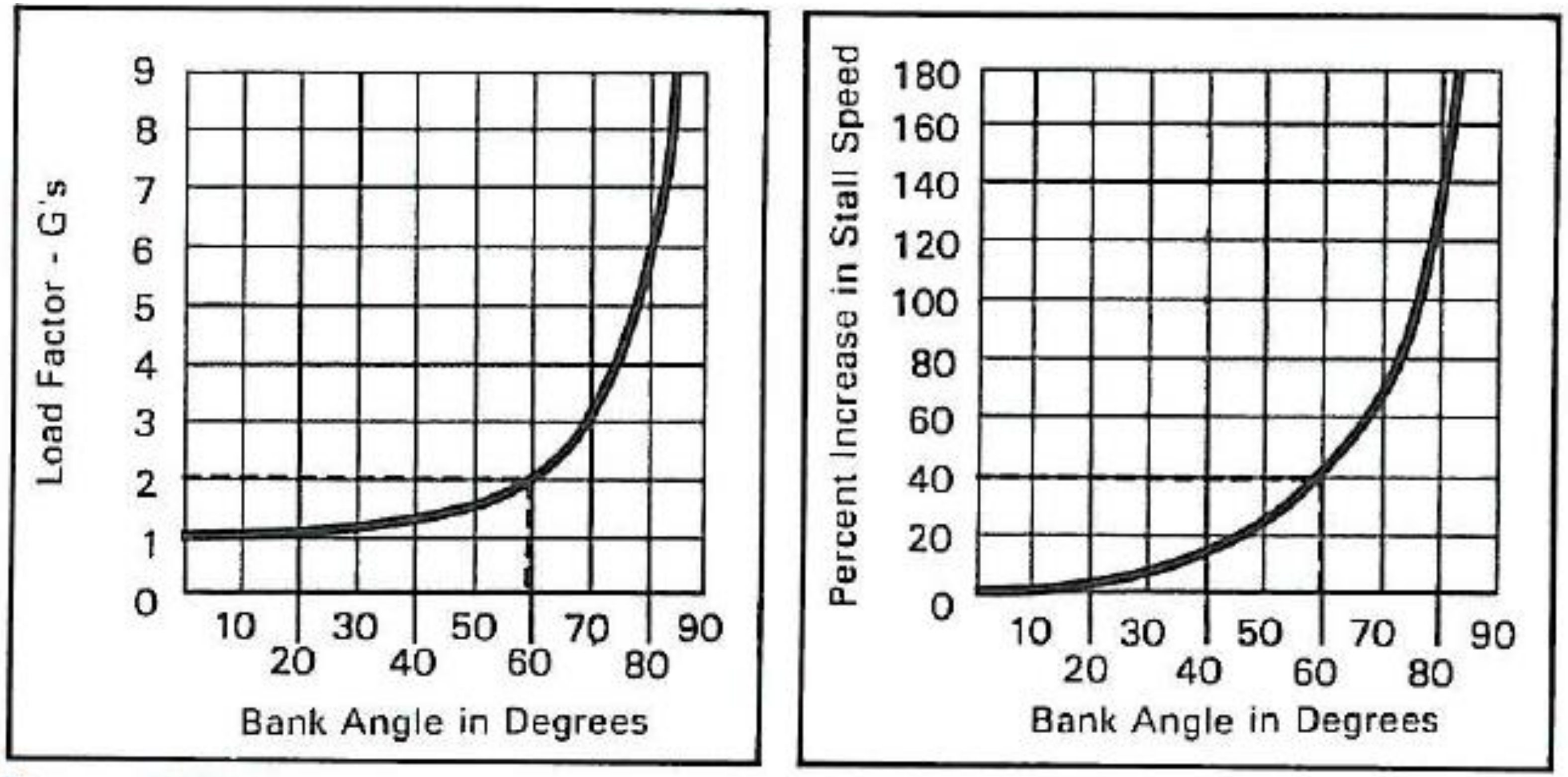


During a Rate One turn, an aircraft changes direction at a rate of 3° per minute.

To determine the angle of bank, in degrees, for a Rate One turn, divide the True Airspeed in knots by 10 and add 7.

LOAD FACTOR AND STALL SPEED

Earlier you learned that you can stall an airplane at any airspeed and in any flight attitude. You can easily stall an airplane in a turn at a higher-than-normal airspeed. As the angle of bank increases in level turns, you must increase the angle of attack to maintain altitude. As you increase the angle of bank, the stall speed also increases. [Figure 1-38]



Most small general aviation airplanes with a gross weight of 12,500 pounds or less, and nine passenger seats or less, are certified in either the normal, utility, or acrobatic categories. A normal category airplane is certified for nonacrobatic maneuvers. Training maneuvers and turns not exceeding 60° of bank are permitted in this category. The maximum limit load factor in the normal category is 3.8 positive G's, and 1.52 negative G's. In other words, the airplane's wings are designed to withstand 3.8 times the actual weight of the airplane and its contents during maneuvering flight. By following proper loading techniques and flying within the limits listed in the pilot's operating handbook, you will avoid excessive loads on the airplane, and possible structural damage.

In addition to those maneuvers permitted in the normal category, an airplane certified in the utility category may be used for several maneuvers requiring additional stress on the airframe. A limit of 4.4 positive G's or 1.76 negative G's is permitted in the utility category. Some, but not all, utility category airplanes are also approved for spins. An acrobatic category airplane may be flown in any flight attitude as long as its limit load factor does not exceed six positive G's or three negative G's.

MANEUVERING SPEED

An important airspeed related to load factors and stall speed is the **design maneuvering speed (V_A)**. This limiting speed normally is not marked on the airspeed indicator, since it may vary with total weight. The POH and/or a placard in the airplane are the best sources for determining V_A. Although some handbooks may designate only one maneuvering speed, others may show several. When more than one is specified, you will notice that V_A decreases as weight decreases. An aircraft operating at lighter weights is subject to more rapid acceleration from gusts and turbulence than a more heavily loaded one.

Any airspeed in excess of V_A can overstress the airframe during abrupt maneuvers or turbulence. The higher the airspeed, the greater the amount of excess load that can be imposed before a stall occurs. V_A represents the maximum speed at which you can use full, abrupt control movement without overstressing the airframe. If you are flying at or below this speed, any combination of pilot-induced control movement, or gust loads resulting from turbulence, should not cause an excessive load on the airplane. This is why you should always fly at or below V_A during turbulent conditions.

٣٥. If airspeed is increased during a level turn, what action would be necessary to maintain altitude? the angle of attack

A. And angle of bank must be decreased.
B. Must be increased or angle of bank decreased.
C. Must be decreased or angle of bank increased.

٣٦. If a standard rate turn is maintained, how long would it take to turn ٣٦٠°

A. ١ minute.
B. ٢ minutes.
C. ٣ minutes.

٣٧. While maintaining a constant angle of bank and decreased load factor.

A. Loss of the vertical component of lift
B. Loss of horizontal component of lift and the increase in centrifugal force.
C. Rudder deflection and slight opposite aileron throughout the turn.

٣٨. Why is it necessary to increase back elevator pressure to maintain altitude during a turn? to compensate for the

A. Loss of the vertical component of lift.
B. Loss of the horizontal component of lift and the increase in centrifugal force.
C. Rudder deflection and slight opposite aileron throughout the turn.

٣٩. To maintain altitude during a turn, the angle of attack must be increased to compensate for the decrease in the

A. Forces opposing the resultant component of drag.
B. Vertical component of lift.
C. Horizontal component of lift.

٤٠. The ratio between the total air load imposed on the wing and the gross weight of an aircraft in flight is known as

A. Load factor and directly affects stall speed.
B. Aspect load and directly affects stall speed.
C. Load factor and has no relation with stall speed.

٤١. Load factor is the lift generated by the wings of an aircraft at any given time

A. Divide by the total weight of the aircraft.
B. Multiplied by the total weight of the aircraft.
C. Divide by basic empty weight of the aircraft

٤٢. For a given angle of bank, in any airplane, the load factor imposed in a coordinated constant altitude turn

A. Is constant and the stall speed increases.
B. Varies with the rate of turn.
C. Is constant and the stall speed decreases.

٤٣. Airplane wing loading during a level coordinated turn in smooth air depends upon the

A. Rate of turn.
B. Angle of bank.
C. True airspeed.

٤٤. (Refer to figure ٣) If an aircraft with a gross weight of ٣,٠٠٠ pounds was subjected to a ٦٠° constant-altitude bank, the total load would be

A. ٣,٠٠٠ pounds.
B. ٦,٠٠٠ pounds.
C. ١٢,٠٠٠ pounds.

٤٥. (Refer to figure ٣) If the airspeed is increased From ٩٠ knots to ١٣٥ knots during a level ٦٠° banked turn, the load factor will

A. Increase as well as the stall speed.
B. Decrease and the stall speed will increase.
C. Remain the same but the radius of turn will increase.

٤٦. Baggage weighing ٩٠ pounds is placed in a normal category airplane's baggage compartment which is placard at ١٠٠ pounds. If this airplane is subjected to a positive load factor of ٣.٥ Gs, the total load of the baggage would be

A. ٣١٥ pounds and would be excessive.
B. ٣١٥ pounds and would not be excessive.
C. ٣٥٠ pounds and would not be excessive.

٤٧. Which factor below is the best indication of positive or negative Gs in an aircraft?

A. Change in the amount of pressure by the pilot needed on the controls.
B. Change in how heavy or light you feel in your seat.
C. Change in control-surface effectiveness.

٦٣. Which basic flight manoeuvre increases the load factor on an airplane as compared to straight-and-level flight?

A. Climbs.
B. Turns.
C. Stalls.

٦٥. During an approach to a stall, an increased load factor will cause the airplane to

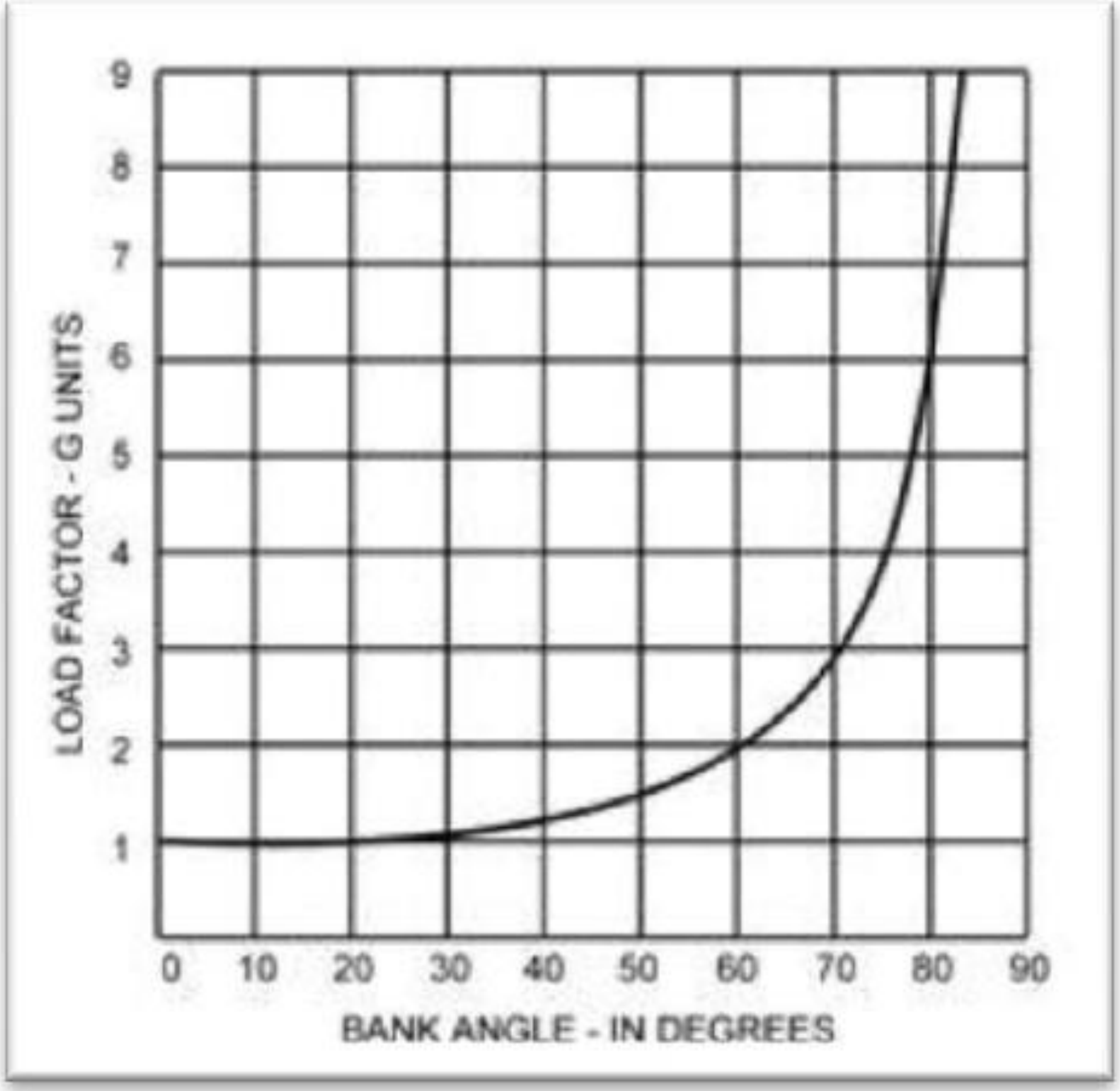
A. Stall at a higher airspeed.
B. Have a tendency to spin.
C. Be more difficult to control.

٦١. (Refer to Figure ٣) If an airplane weighs ٤,٥٠٠ pound's what approximate weight would the airplane structure required to support during a ٤٥°banked turn while maintaining altitude ?

A. ٤,٥٠٠ pounds.
B. ٦,٧٠٠ pounds.
C. ٧,٢٠٠ pounds.

٦٤. What force makes an airplane turn?

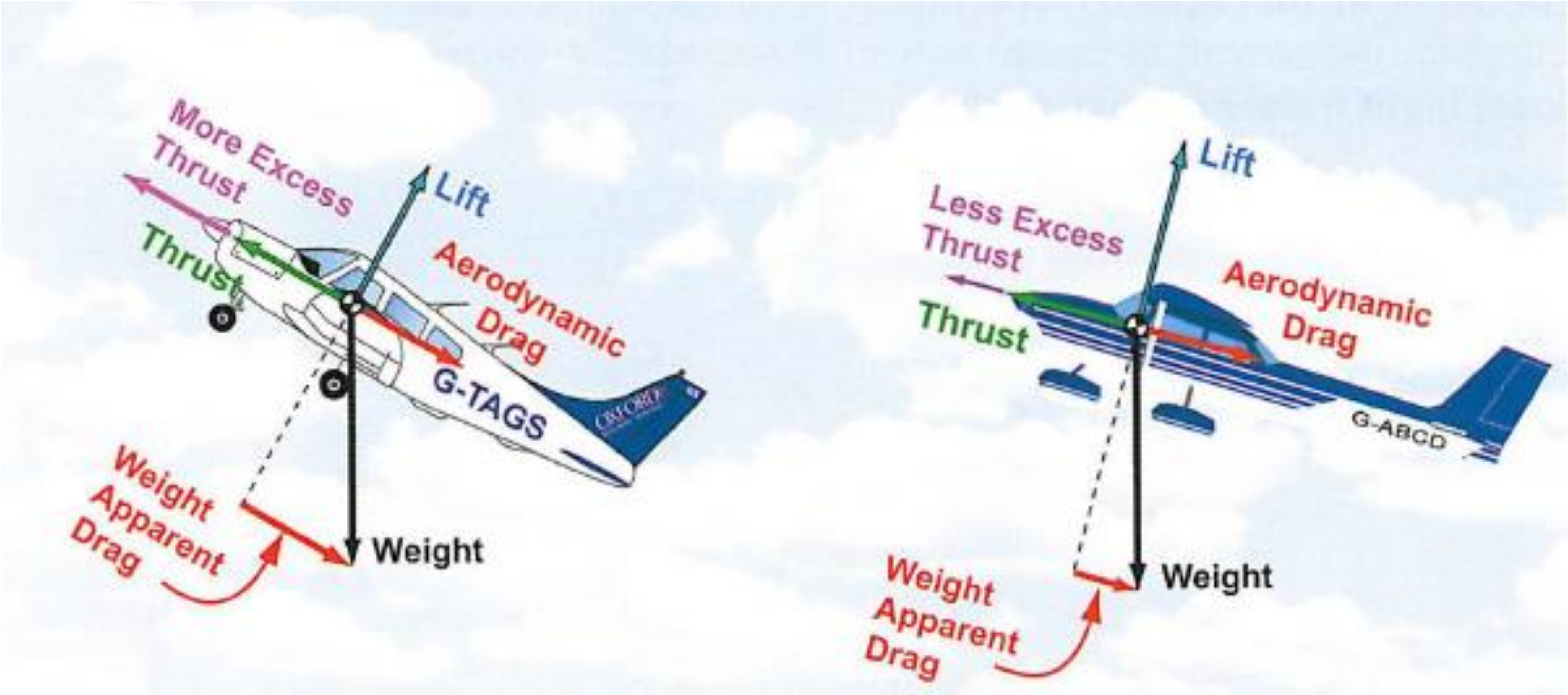
A. The horizontal component of lift.
B. The vertical component of lift.
C. Centrifugal force.


LOAD FACTOR - G UNITS
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
BANK ANGLE - IN DEGREES

FORCES ACTING ON A CLIMBING AIRPLANE

When you transition from level flight into a climb, you must combine the change in pitch attitude with an increase in power. If you attempt to climb just by pulling back on the control wheel to raise the nose of the airplane, momentum will cause a brief increase in altitude, but airspeed will soon decrease.

The amount of thrust generated by the propeller for cruising flight at a given airspeed is not enough to maintain the same airspeed in a climb. Excess thrust, not excess lift, is necessary for a sustained climb. In fact, during a true vertical climb, the wings supply no lift, and thrust is the only force opposing weight. [Figure 1-33]


More Excess Thrust
Lift
Thrust
Aerodynamic Drag
G-TAGS
Weight Apparent Drag
Weight
Lift
Less Excess Thrust
Aerodynamic Drag
Thrust
G-ABCD
Weight Apparent Drag
Weight

FORCES ACTING ON A DESCENDING AIRPLANE

Let's continue our discussion by considering the forces of weight, lift, thrust, and drag as they affect a descending airplane. If you are using power during a stabilized descent, the four forces are in equilibrium. During the descent, a component of weight acts forward along the flight path. As speed increases, this force is balanced by an increase in parasite drag.

During a power-off glide, the throttle is placed in an idle position so the engine and propeller produce no thrust. In this situation, the source of the airplane's thrust is provided only by the component of weight acting forward along the flight path. In a steady, power-off glide, the forward component of weight is equal to and opposite drag.

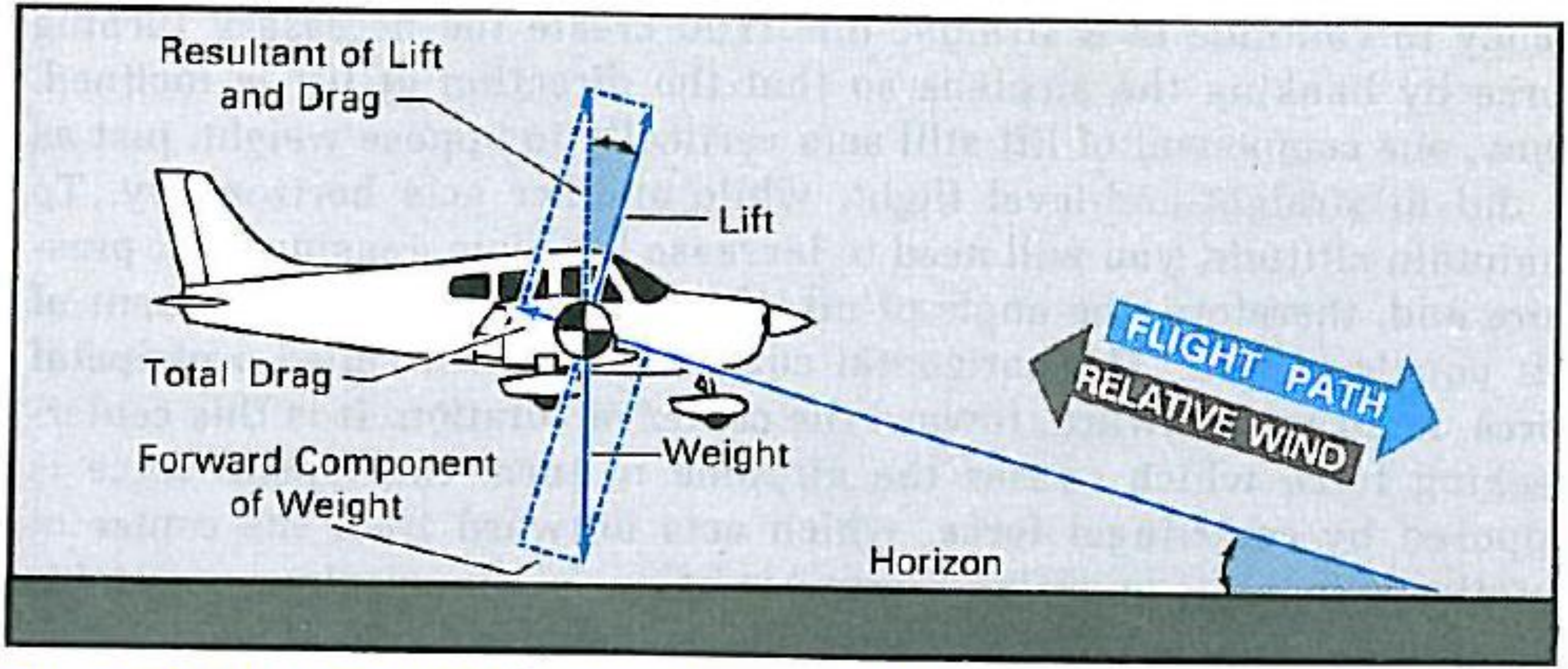


Figure 1-34. In a constant-airspeed, power-off descent, weight is balanced by the resultant of lift and drag. Notice that the angle between the lift vector and the resultant is the same as the angle between the flight path and the horizon. This is the glide angle of the airplane. If drag increases, the angle between the lift vector and the resultant vector increases and, consequently, the glide angle steepens.

١٥. Which is true regarding the forces acting on an aircraft in a steady-state descent? The sum of all

A. Upward forces is less than the sum of all downward forces.
B. Rearward forces is greater than the sum of all forward forces.
C. Forward forces is equal to the sum of all rearward forces.

٦٣. Which basic flight manoeuvre increases the load factor on an airplane as compared to straight-and-level flight?

A. Climbs.
B. Turns.
C. Stalls.

CHAPTER 10
LIFT AUGMENTATION

LIFT AUGMENTATION.

Take-Off and Landing.

When an aircraft takes off and lands, it is highly desirable that the lift force generated by its wing should be sufficient to support the weight of the aircraft at as low a speed as possible, so that take-off and landing distances will be as short as possible.

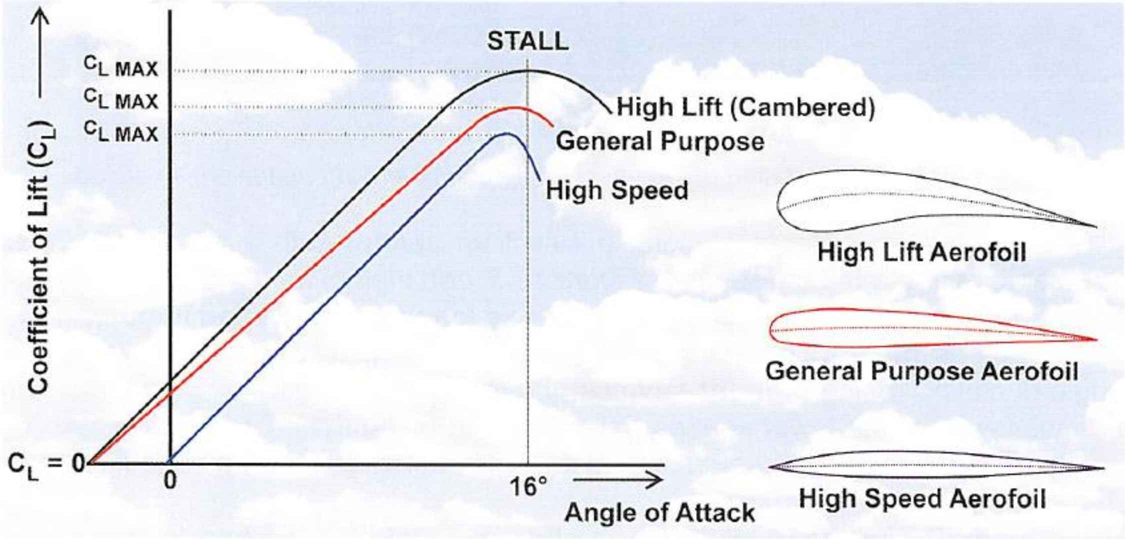


Figure 10.1 $C_{L\ MAX}$ varies according to the type of aerofoil.

The Cruise.

But take-off and landing take up only a small period of time when considering the whole duration of an aircraft's flight. The greater part of flight is spent in the cruise. However, at high cruise speeds, a thickly-cambered wing-section would cause considerable drag and require the aircraft to fly in a pronounced nose down pitch attitude, as depicted in *Figure 10.2 overleaf*.

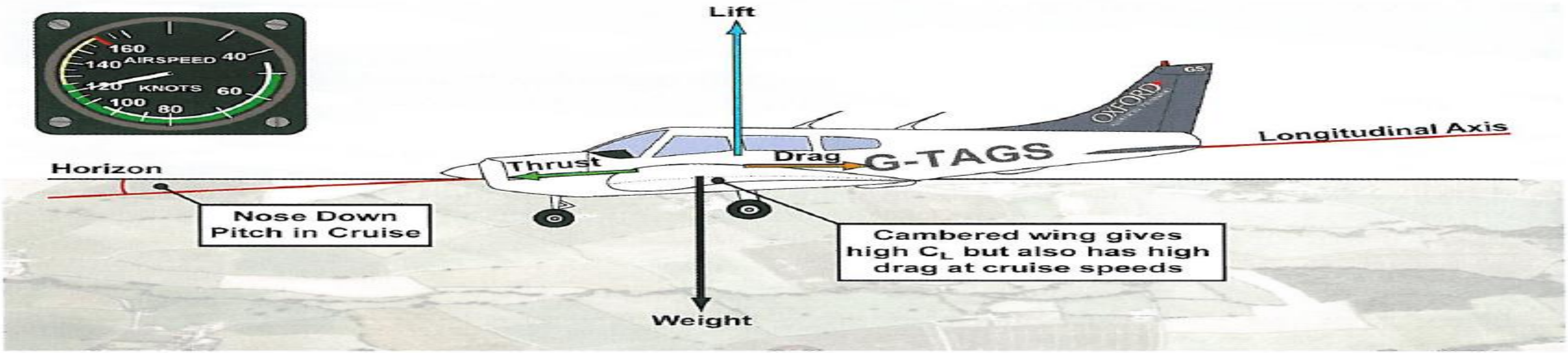


Figure 10.2 A representation of the effect of high-camber wing on the cruise attitude.

It is usual, therefore, for designers to select an aerofoil with a less pronounced camber to optimise the cruise, as in *Figure 10.3*, and then to modify the shape of the aerofoil section by having mechanical, **movable leading and trailing edges**, known collectively as **high-lift devices,** to increase camber and, thus, C_L for any given angle of attack. Using **high-lift devices**, the lift-force generated by an aerofoil can be maintained at the lower speeds of landing and take-off, and so reduce take-off and landing distances. *Figure 10.4* depicts both leading and trailing edge flaps.

Using **high-lift devices**, a pilot may, in effect, convert his wing from a high speed wing to a high lift wing as he wishes.

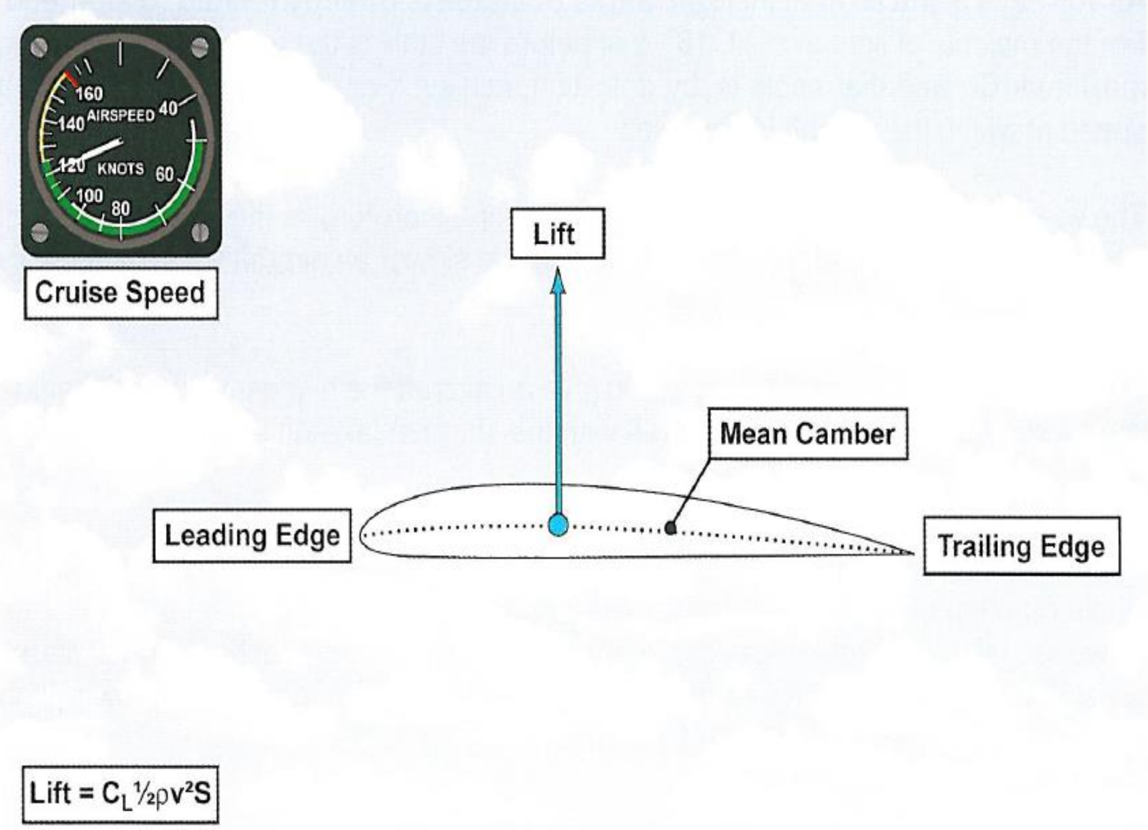


Figure 10.3 Aerofoil shape optimised for the cruise.

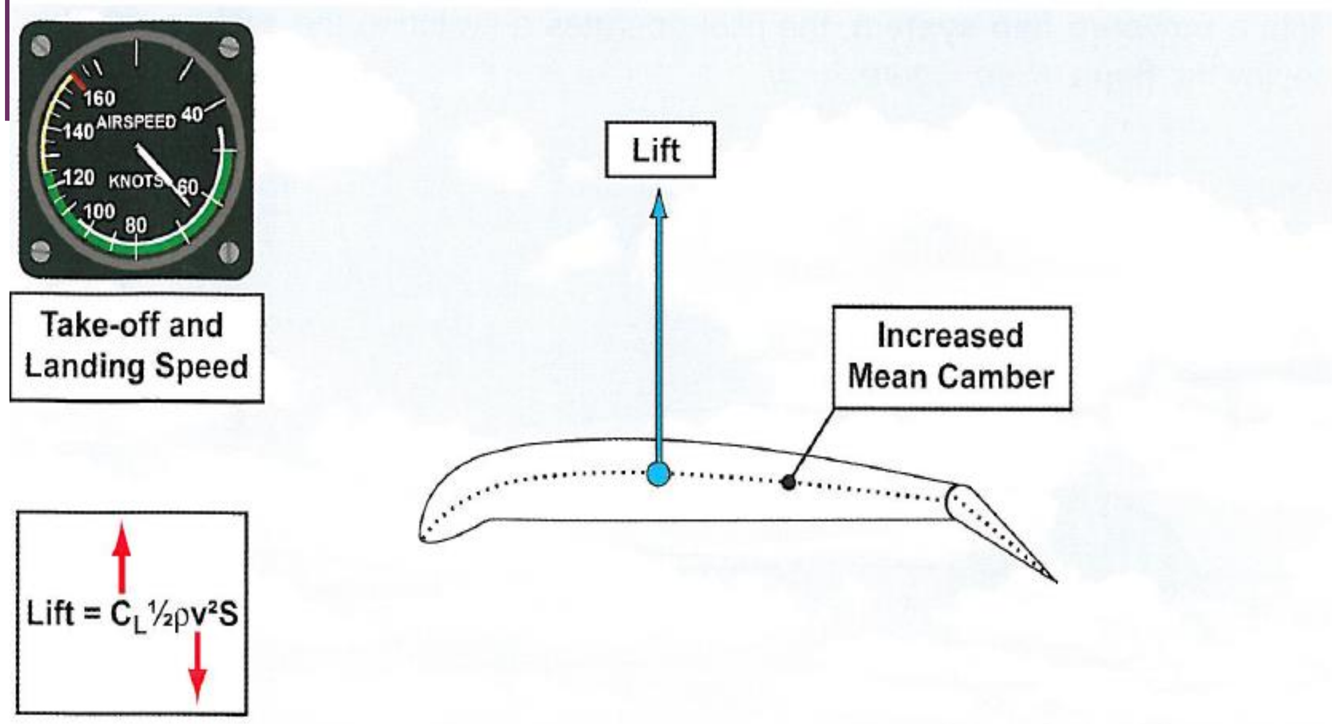


Figure 10.4 High lift devices mechanically alter the camber of an aerofoil to maintain lift at lower speeds.

Operation of the Flaps.

The **flaps** are operated by the pilot in the cockpit. The controlling mechanism can be purely **mechanical** or powered **electrically**, **hydraulically** or **pneumatically**. The **mechanical** system of flap operation provides the pilot with a lever in the cockpit which is connected via rods or cables to the **flaps**.

With **mechanically operated flaps** it is the pilot who provides the force to actuate the system.

With a **powered flap system**, the pilot operates a switch in the cockpit in order to deploy the **flaps**. (*See Figure 10.6*).

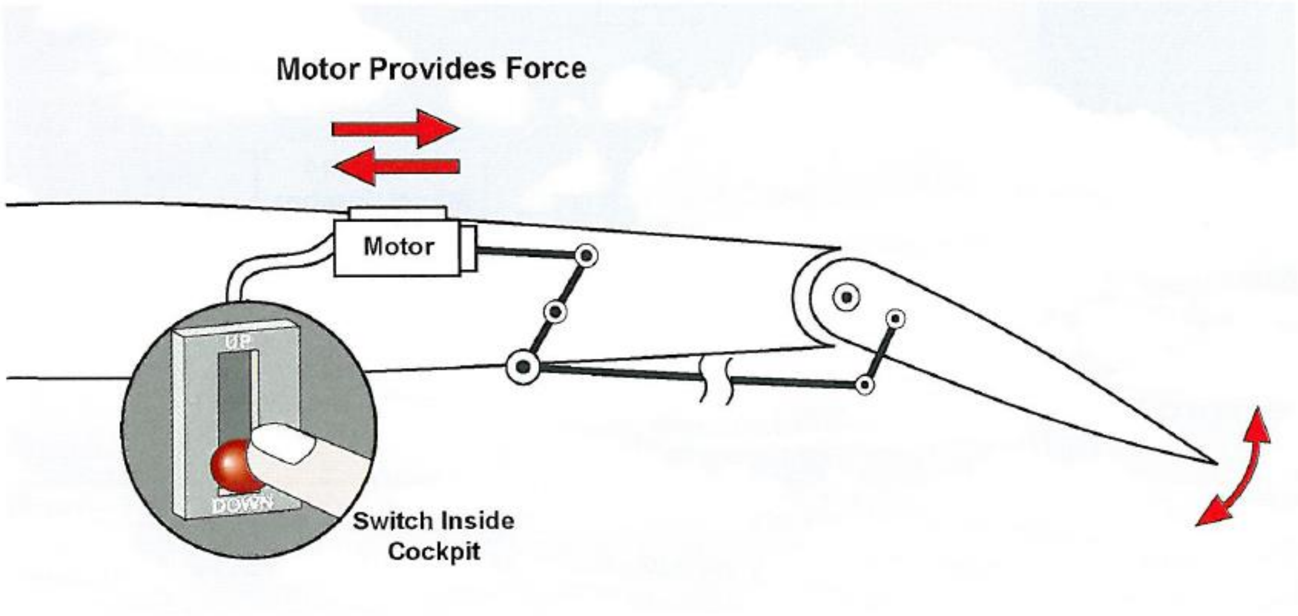


Figure 10.6 Powered operation of the flaps.

TYPES OF TRAILING EDGE FLAP.

There are several types of trailing edge flap in use.

The Plain Flap.

The **plain flap**, depicted in *Figure 10.9*, is simple in construction and gives a good increase in $\mathbf{C_{LMAX}}$, but also causes a large increase in **drag**. The **plain flap** is used mainly on low speed aircraft where very short take-off and landing performance is not required.

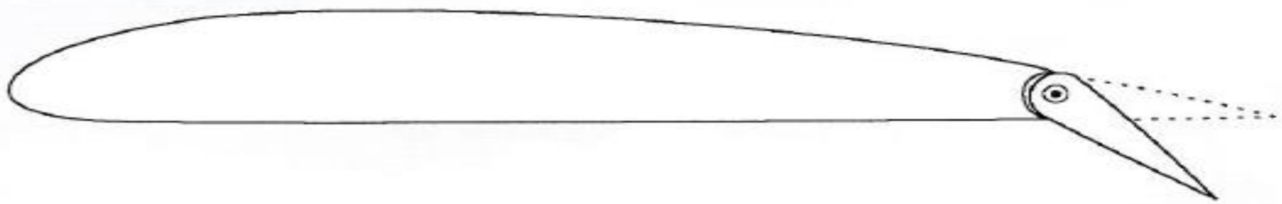


Figure 10.9 The plain flap.

The Split Flap.

The **split flap** forms part of the surface of the lower trailing edge, the upper surface contour being unaffected when the flap is lowered, as can be seen in *Figure 10.10, overleaf*. The **split flap** gives a slightly higher $\mathbf{C_{LMAX}}$ than the **plain flap** at higher angles of attack, but drag is also higher since the depth of turbulent air behind the wing is greater, when a **split flap** is deployed.

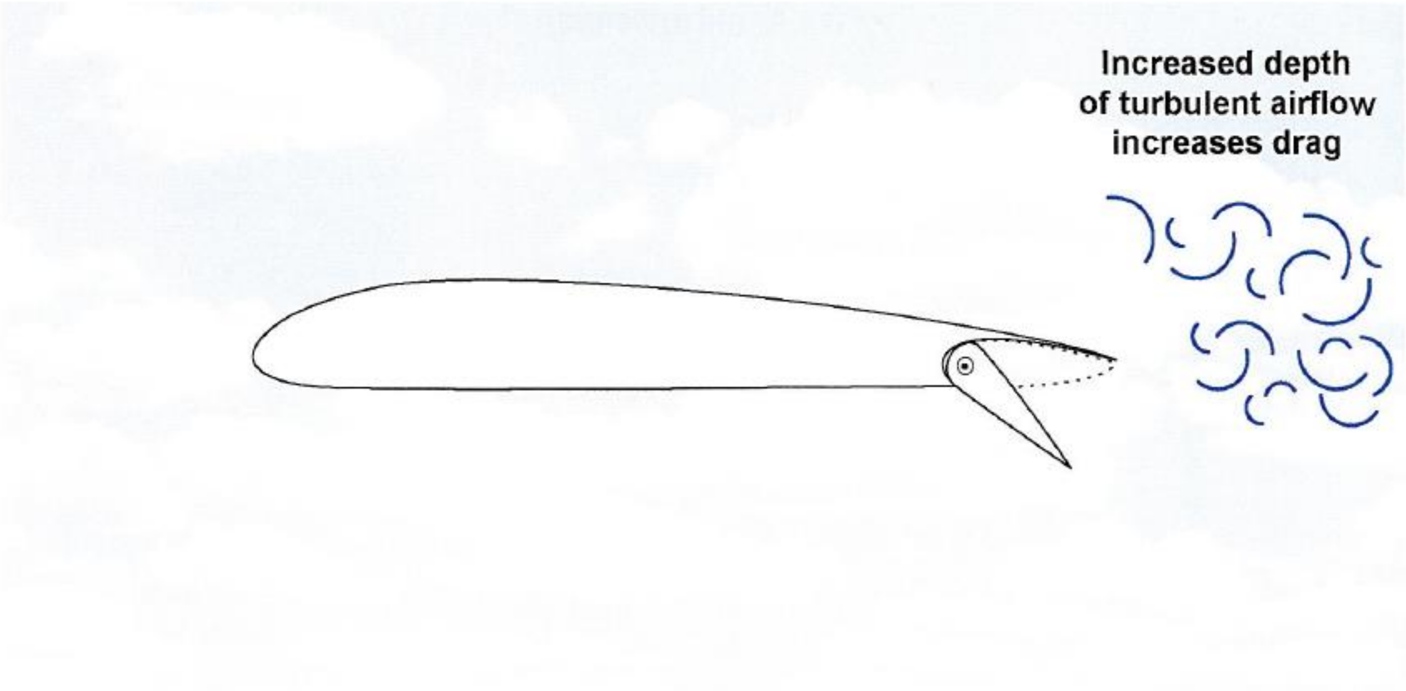


Figure 10.10 The split flap.

The Slotted Flap.

The **slotted flap** depicted in *Figure 10.11*, is much more complex in construction than either the **plain** or **split flap**. For the same area of **flap**, the **slotted flap** gives a greater increase in C_{LMAX} and produces less drag than both the **plain** and **split flaps**. This is achieved by directing high pressure air from below the wing through the slots formed between the **flap** and the trailing edge. The re-direction of airflow, in this way has the effect of re-energising the **boundary layer** and so **delaying separation**. See *Figure 10.11*.

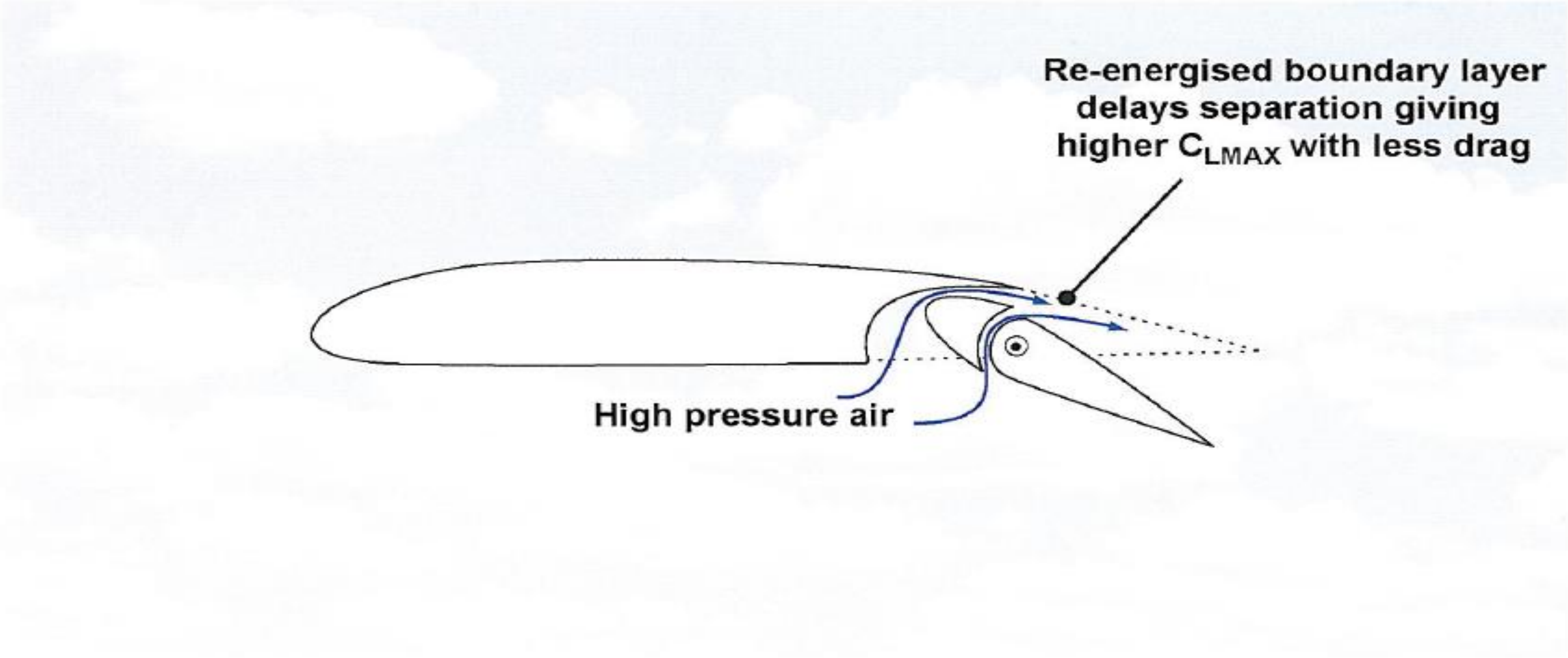


Figure 10.11 The slotted flap.

The Fowler Flap.

The **Fowler Flap**, depicted in *Figure 10.12*, not only increases camber but also wing area, **S**. You will recall that **S** is a factor in the **lift formula: Lift =** C_L **½ ρ v² S**, where **S** is the **surface area of the wing**.

The **Fowler Flap** produces the largest increase in C_{LMAX} of all **flap** types. Because the **Fowler Flap** increases **chord length** as well as wing camber, the **thickness/ chord ratio** is reduced, leading to a reduction in **drag**. Larger aircraft usually have slotted **Fowler flaps** which are even more efficient.

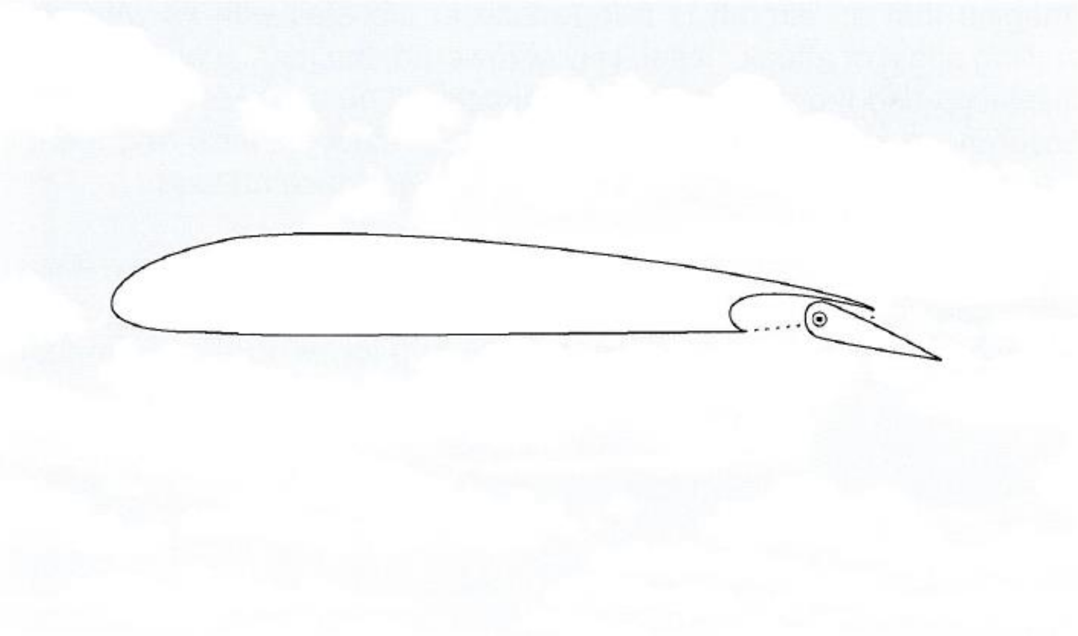


Figure 10.12 The Fowler flap.

COMPARISON OF C_L AND C_{LMAX} FOR DIFFERENT TYPES OF FLAP.

A comparison of the **coefficient of lift, C_L**, and the **coefficient of drag, C_D**, for a basic wing section and for a wing with different types of **flap** deployed, at the same angle of attack, is shown graphically in the right hand graph in *Figure 10.13*.

Compared to the basic wing section, it can be seen that all types of **flap** increase **C_L** and **C_D**, at a given angle of attack. Note that the **Fowler Flap** almost doubles **C_L**, compared to the basic wing section for a modest increase in **drag**.

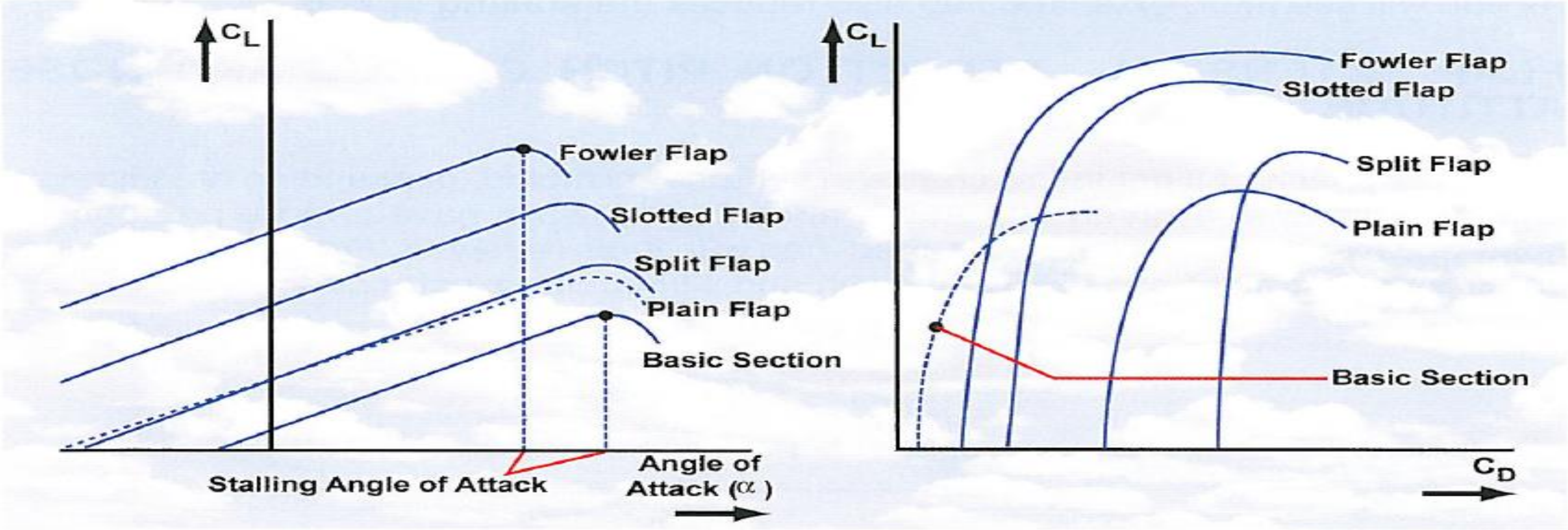
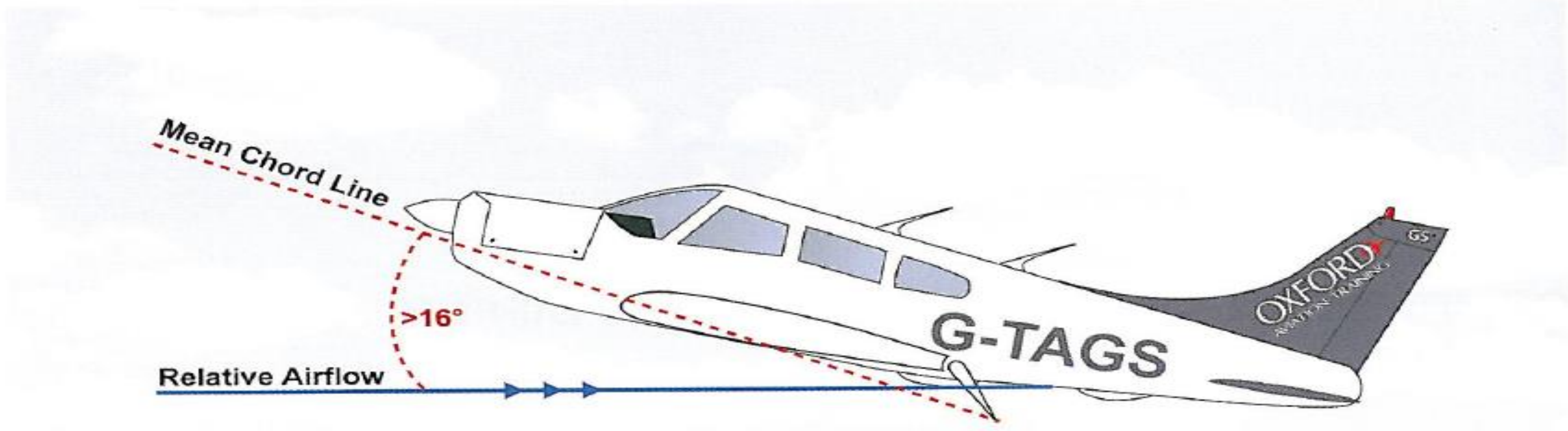


Figure 10.13 Comparison of C_L and C_D for different types of flap.

The Effect of Flap on Stalling Angle of Attack.

Take particular note from the left hand graph in *Figure 10.13*, of what happens to the **stalling angle of attack** for the overall wing when flaps are extended, remembering that C_{LMAX} is reached just before the **stall**. You see that, with flaps extended, the stall occurs at a lower angle of attack than for the basic wing section: the so-called "clean wing".

Lowering flaps reduces the **stalling angle of attack** of the wing. As a consequence, when carrying out a stalling exercise from straight and level flight, with flaps extended, the pilot will notice that the aircraft stalls at a lower nose altitude than with the wing clean.



FLAP EXTENSION - EFFECT ON PITCH CHANGE AND NOSE ATTITUDE.

Whatever phase of flight the aircraft is in, whether climbing, descending or in straight and level flight, **at a given speed** the aircraft will always have a more pronounced nose-down attitude with flaps extended than with flaps retracted. *Figure 10.15* depicts an aircraft in straight and level flight with and without flaps extended.

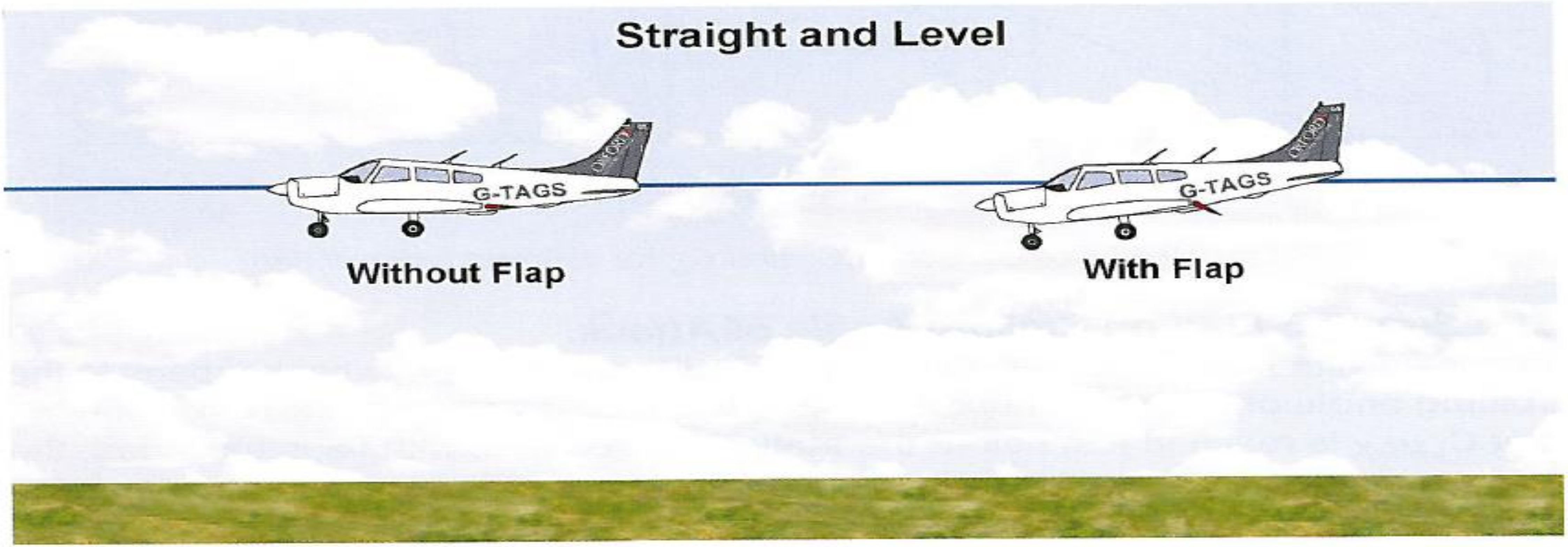


Figure 10.15 At any given speed, an aircraft with flaps extended has a more pronounced nose-down attitude than with flaps raised.

It is possible that the aircraft may adopt a nose-down pitch attitude of its own accord when the pilot extends flaps. This depends on the aircraft type. But whether or not an aircraft initially pitches up or down, on flaps selection, will often depend on whether the aircraft is of a high, low or mid wing design *(see Figure 10.16)*.

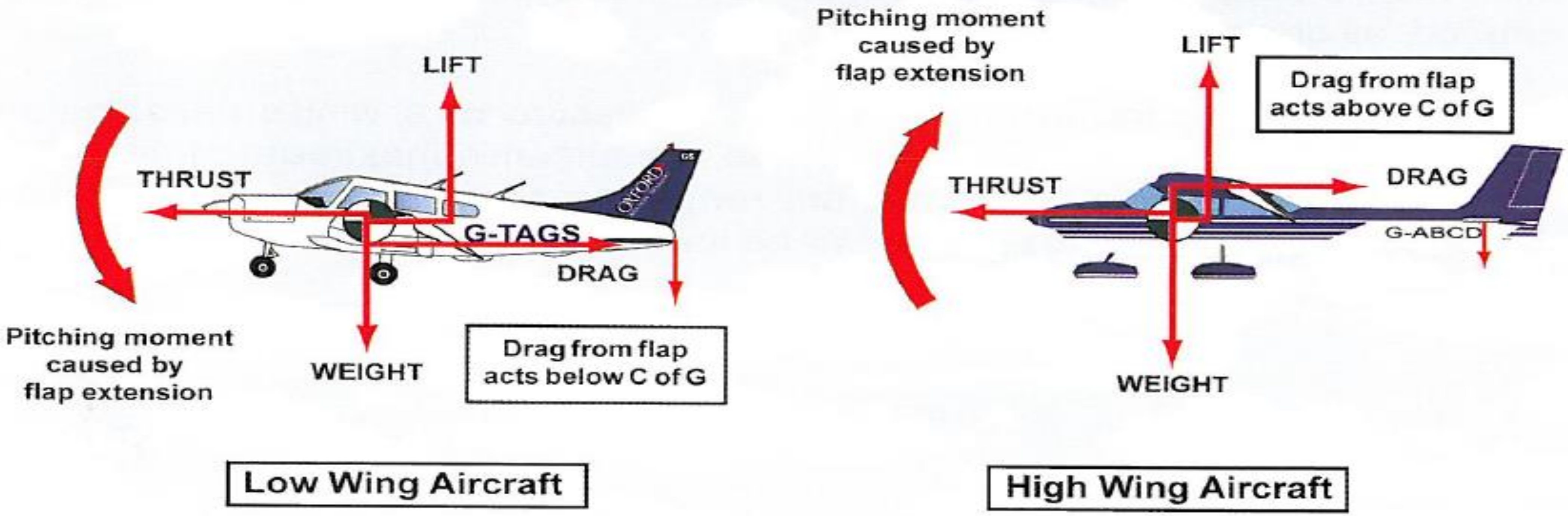


Figure 10.16 The thrust-drag couple either opposes or assists the pitching moment, depending upon the position of the wing.

Maximum Lift-Drag Ratio.

As we saw in *Figure 10.13*, the selection of **flaps** increases both **lift** and **drag**, but not in the same proportion. The proportional increase in **drag** is always greater, which means that, **with flaps deployed, the maximum lift/drag ratio is always reduced**, as depicted in *Figure 10.18*.

As you have learnt, the **lift-drag ratio** is a measure of a wing's **aerodynamic efficiency**, and so, when **flaps** are lowered, the aircraft's **maximum climb angle**, **best glide performance** and **maximum range** are all **reduced**. The greater the angle of flap setting used, the greater will be the reduction in these aspects of aircraft performance.

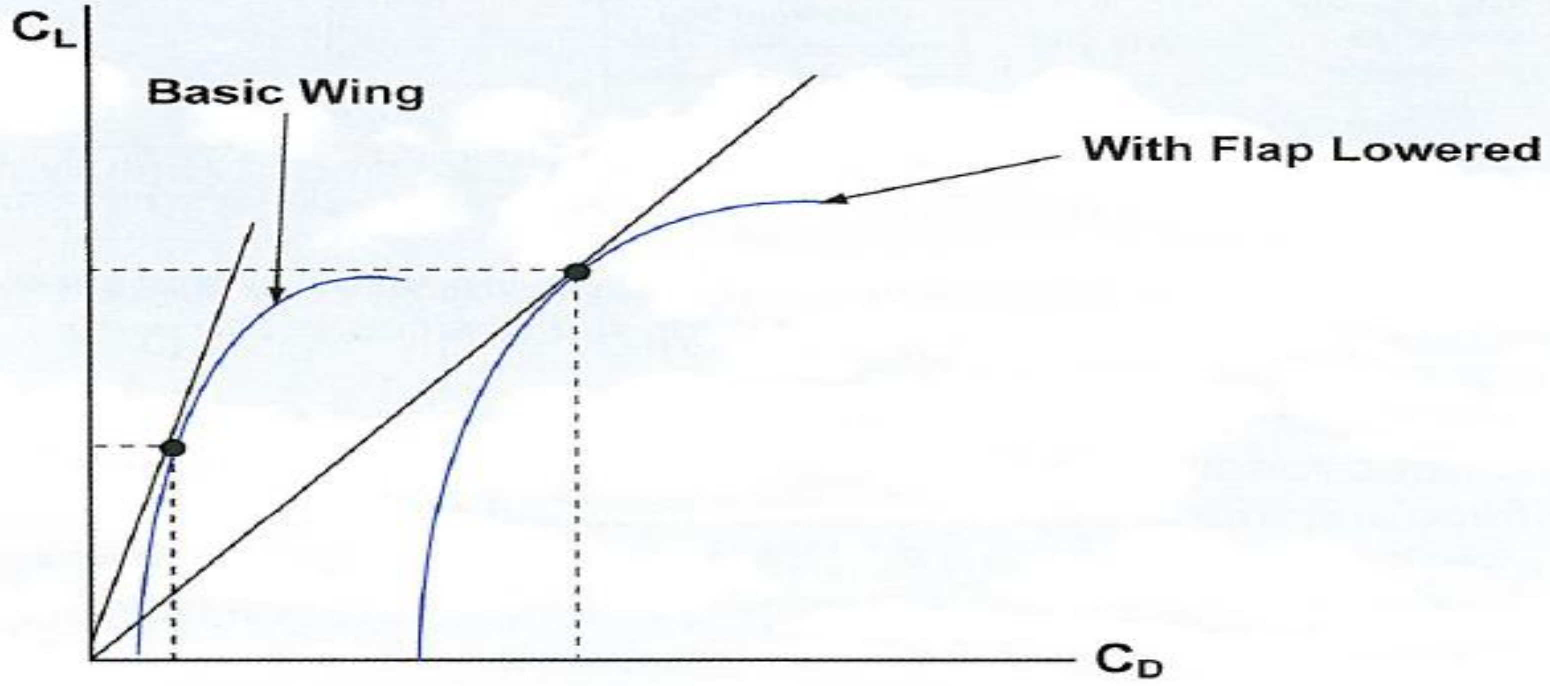


Figure 10.18 Selecting flap always reduces the lift/drag ratio.

Take-Off Flap.

For **take-off**, increasing **C_L** to its maximum value by selecting a large amount of **flap** would give the lowest minimum flight speed, but **drag** would also be at its maximum which could reduce acceleration to such an extent that the **take-off** distance would be unacceptably long. Consequently, a **smaller flap setting than full flap** is usually used for **take-off**. The Pilot's Operating Handbook, will state the optimum **flap** setting to be used.

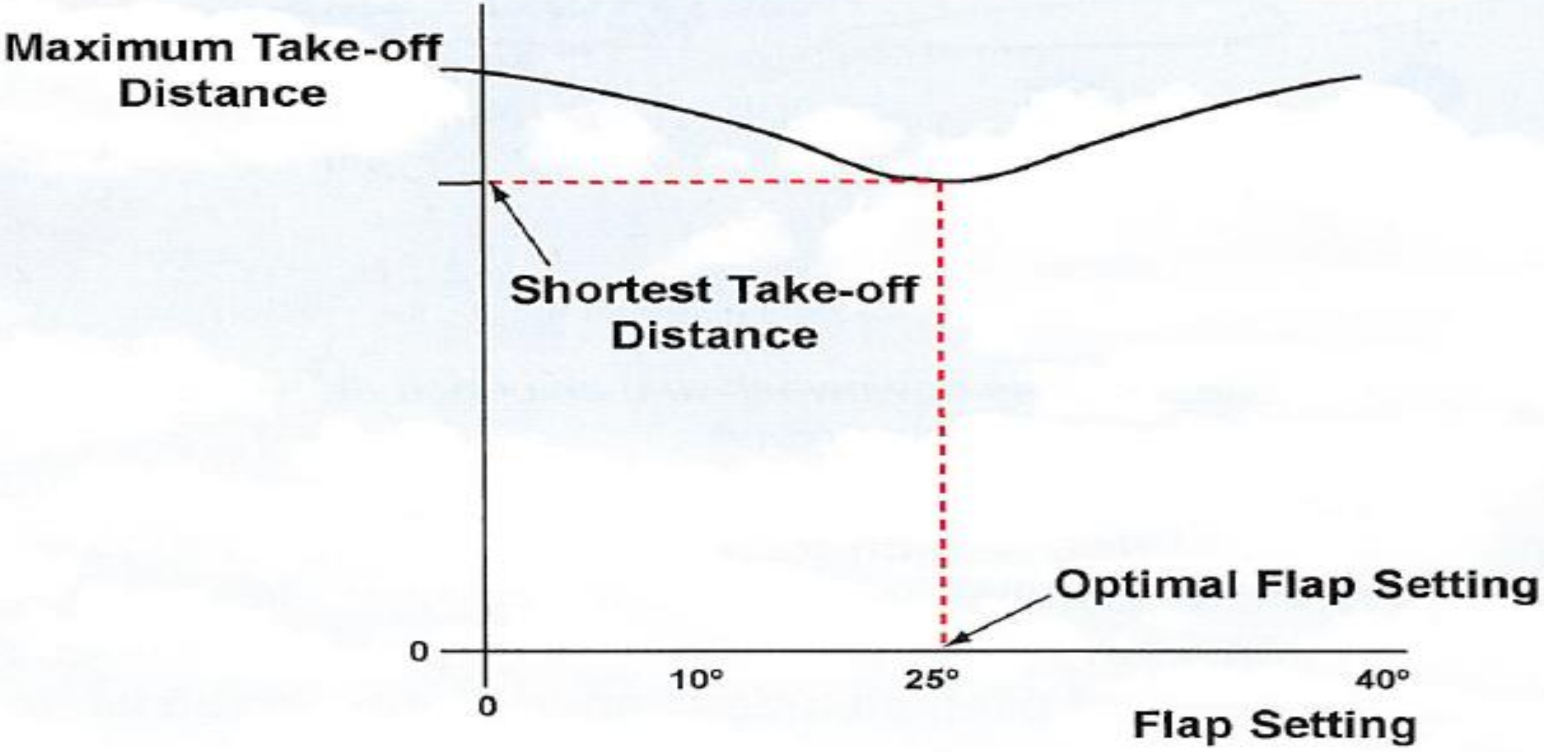


Figure 10.19 Optimum Flap Setting for Take-off.

Flap Retraction after Take-Off.

After **take-off** the **flaps** are retracted to improve the climb angle. However, great care must be exercised when raising **flap**. Because of the changes in $\mathbf{C_L}$, **drag** and **pitching moments** which occur on **flap** retraction, the **flaps** should be raised in stages.

Furthermore, to prevent any sudden loss of lift as the **flaps** are retracted, the aircraft must first be accelerated to a safe speed, but not beyond $\mathbf{V_{FE}}$ (see overleaf).

The important consideration at this stage of flight is that the aircraft should not be allowed to sink, especially when it is close to the ground.

Landing Flap.

When **landing**, the high drag associated with the use of higher **flap** settings is a benefit to the aircraft. The less favourable **lift - drag ratio** also enables a suitably steep glide path to be flown for the approach, and, after touch-down, the extra drag will help reduce the distance of the landing run. The higher values of C_L produced with flaps lowered will enable the approach to be flown at the lowest possible speeds. The approach speed must remain, however, at least **1.3 times the stalling speed.** During the approach, the **flaps** are lowered in stages to reduce the effects of the changes in **lift**, **drag** and **pitch attitude** on the aircraft.

Flap should not be selected until the airspeed is within the defined operating range (white arc).

Figure 10.20 Deployment of landing flap.

The **flaps-extended speed-range** is marked on the **Airspeed Indicator** by a **white arc**, as shown in *Figure 10.21*. The flaps can be safely operated if the aircraft's speed is within this arc. $\mathbf{V_{FE}}$ is the airspeed reading at the higher end of the white arc. In *Figure 10.21*, $\mathbf{V_{FE}}$ is 104 knots. Bear in mind that not only must the flaps not be lowered until the airspeed has reduced below $\mathbf{V_{FE}}$, but flaps must also be fully retracted before the aircraft accelerates above $\mathbf{V_{FE}}$.

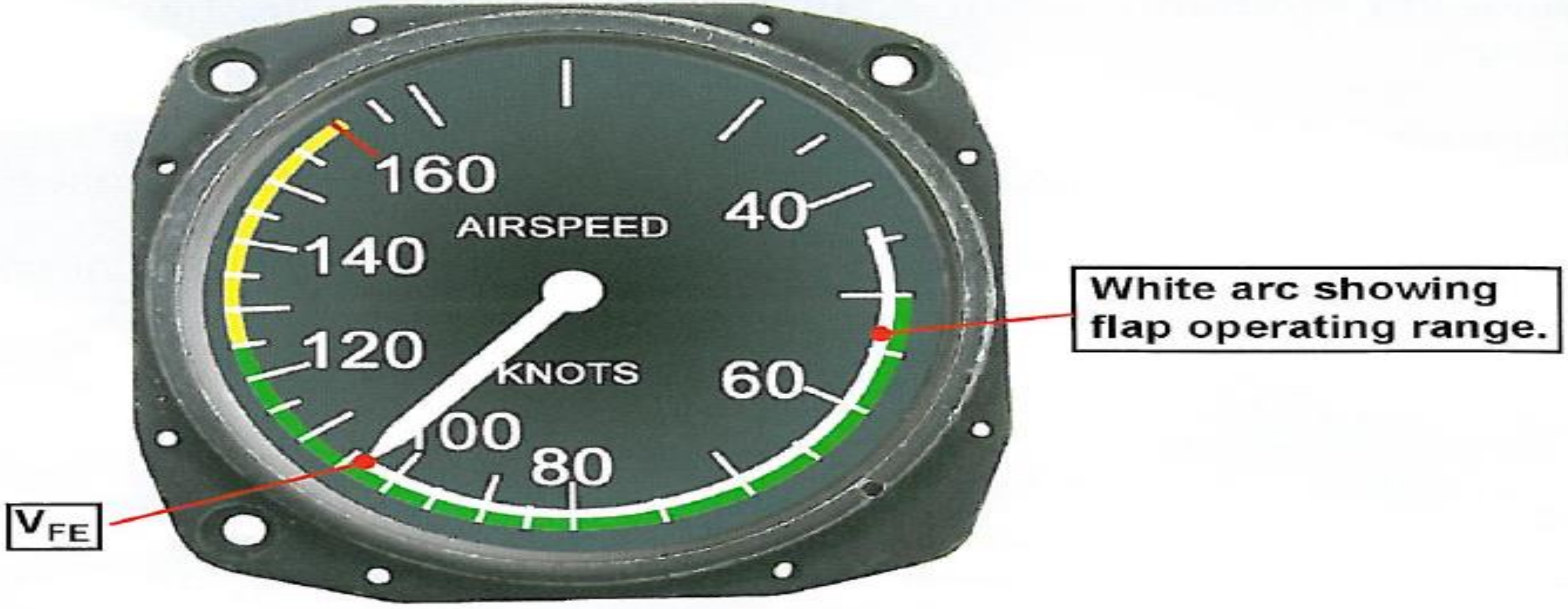


Figure 10.21 The flaps can safely be operated if the aircraft's speed is within the white arc.

Flap Selection for Approach and Landing.

On the approach to land, the pilot gradually slows the aircraft down, progressively selecting more stages of **flap**. Remember that, when selecting **flaps**, it is necessary to pitch the nose of the aircraft down in order to maintain the value of $\mathbf{C_L}$ constant by reducing the angle of attack. This action will also improve the pilot's view of the airfield and the runway.

Full **landing flap** is selected only when the pilot is confident of achieving the runway aiming point and has committed himself to land.

LEADING EDGE HIGH-LIFT DEVICES.

There are two types of **leading edge high-lift device**. These are the **slot** and **slat** illustrated in *Figure 10.22*, and the **leading edge flap** shown in *Figure 10.23.*

You should note that the term **slot** is applied to the gap which connects the under-surface and upper-surface of the wing's leading edge. The **slot** can either be fixed, as in the higher of two drawings in *Figure 10.22,* or it can open or close depending on the position of a moveable auxiliary aerofoil known as a **slat**, depicted in the lower drawing at *Figure 10.22.*

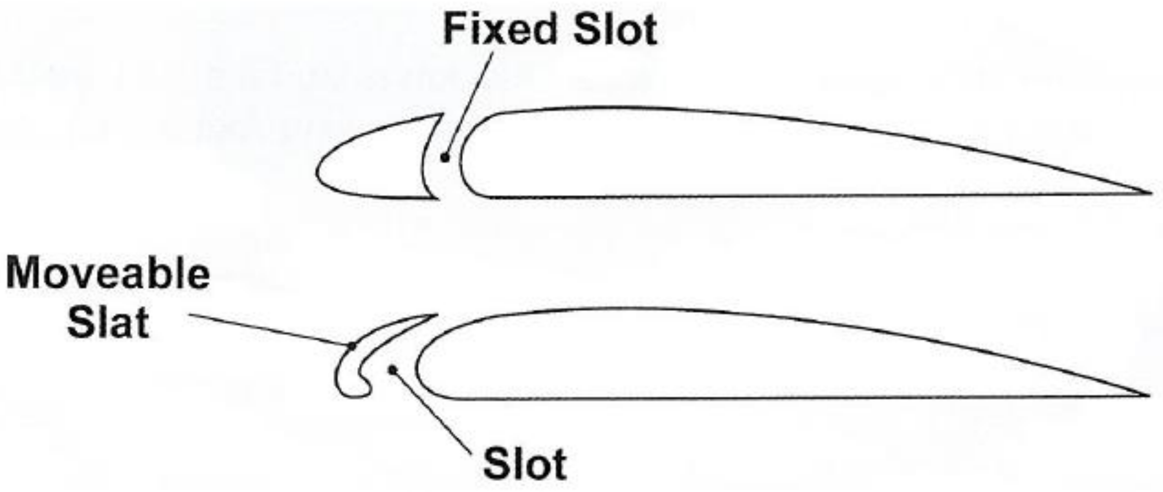


Figure 10.22 The slot and the slat.

Leading edge flaps are a complex mechanical flap system, used only on large jet transport aircraft. (*See Figure 10.23*). Those few light aircraft with leading edge high lift devices are more likely to use slots or slats.

Figure 10.23 A typical leading edge flap on a jet transport aircraft.

The main purpose of **leading edge devices** is to delay separation of the airflow from the upper surface of the wing. This **increases the stalling angle of attack** and the corresponding value of $\mathbf{C_{LMAX}}$. (*See Figure 10.24*). Note the difference between **leading edge high-lift devices** and **trailing edge flaps** in this respect. While both devices increase $\mathbf{C_{LMAX}}$, **leading-edge high lift devices** cause the **stalling angle of attack** to **increase, trailing edge flaps cause the** stalling angle of attack **to decrease.**

The Leading Edge Slot.

The **leading edge slot** is a fixed gap between the lower surface and the upper surface of the wing leading edge, stretching from near the wing root to just short of the wing tip.

The **leading edge slot** re-directs high pressure air from below the wing, through the slot, in order to re-energise the boundary layer and so delay separation. *See Figure 10.25.*

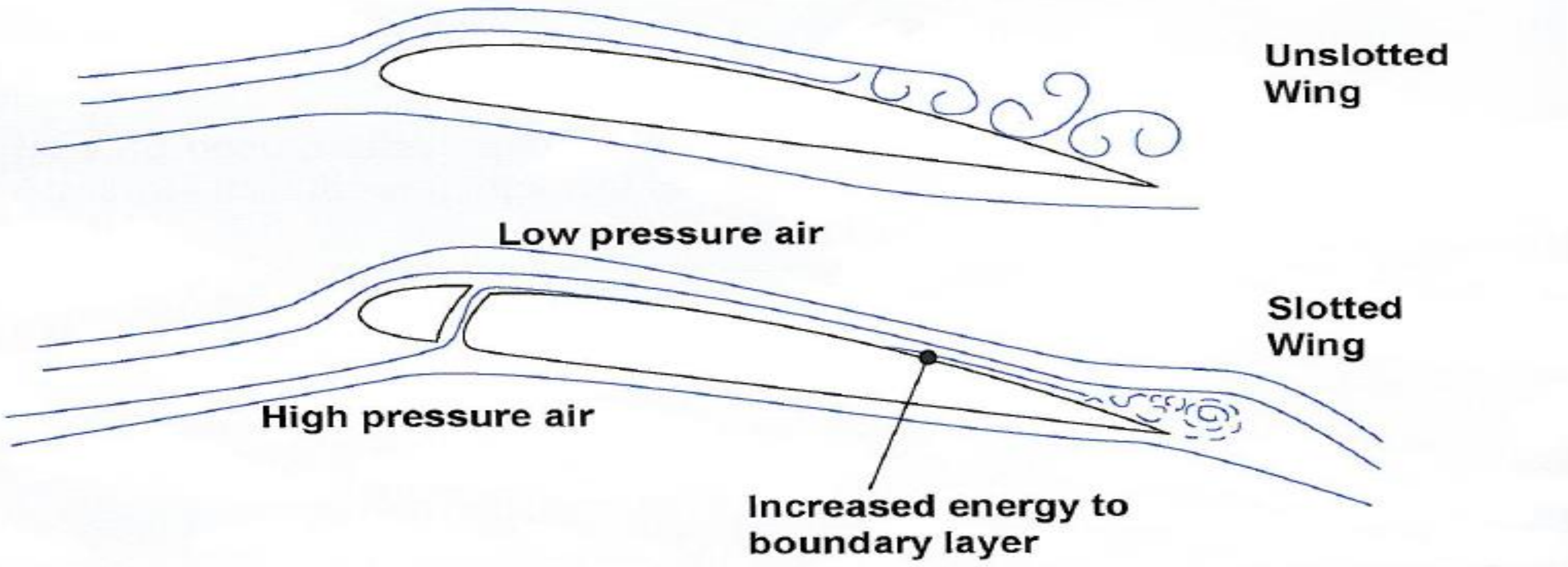


Figure 10.25 The leading edge slot redirects high pressure air from the undersurface of the wing to the upper surface of the wing.

The Leading-Edge Slat.

A **slat** is a small moveable aerofoil section attached to the leading edge of the wing. When the **slat** deploys by moving away from the leading edge, it forms a **slot**, as depicted in *Figure 10.31*.

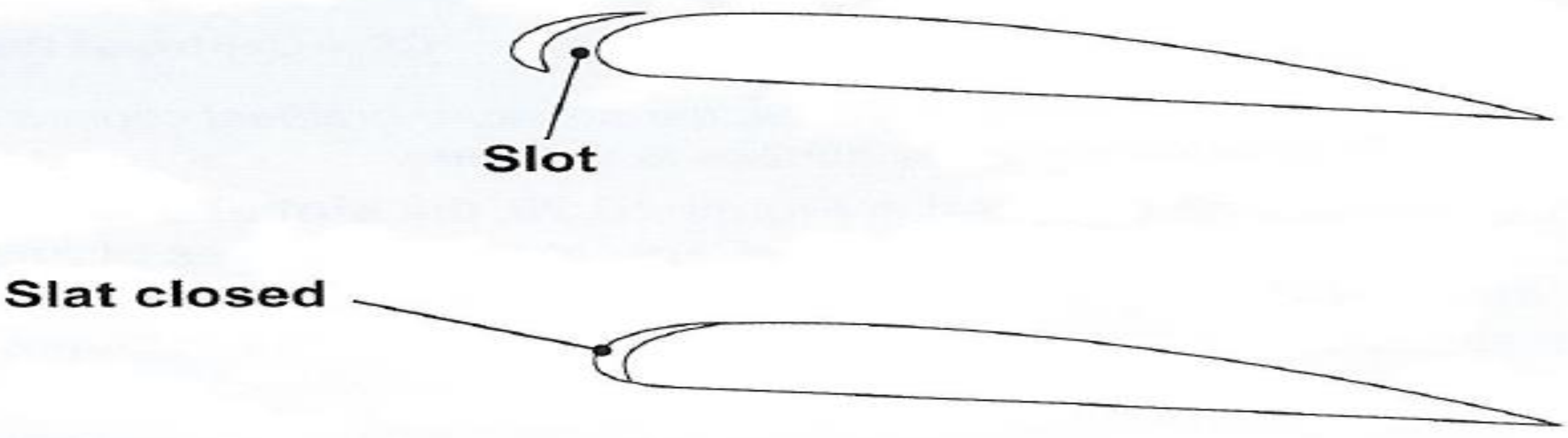


Figure 10.31 Operation of the slat creates an opening which forms a slot.

The **slat** normally operates automatically in response to varying airflow pressures at the leading edge of the wing. At small angles of attack the high pressure at the leading edge holds the **slat** closed, as shown in *Figure 10.32*.

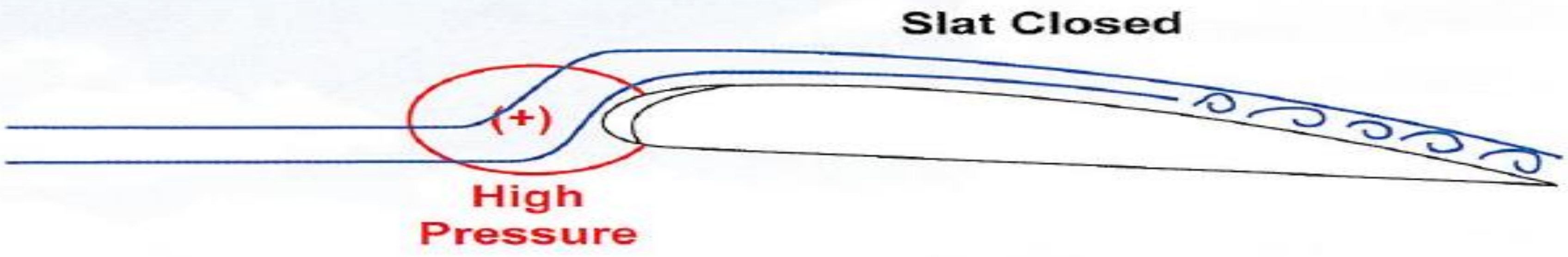


Figure 10.32 High pressure at the leading edge keeps the slat closed at small angles of attack.

١. One of the main functions of flaps during the approach and landing is to

A. Decrease the angle of descent without increasing the airspeed.
B. Provide the same amount of lift at a slower.
C. Decrease lift, thus enabling a steeper-than-normal approach to be mad.

١٢٠. With flaps deployed, at a constant IAS in straight and level flight, the magnitude of tip vortices:

.

A. Increases.
B. Increases or decreases depending upon the initial angle of attack.
C. Decreases.

١٩. What does the white arc on the airspeed indicator represents?

A. Normal operating range.
B. Flap operating range.
C. Maximum structural cruising speed.

CHAPTER 11 STABILITY

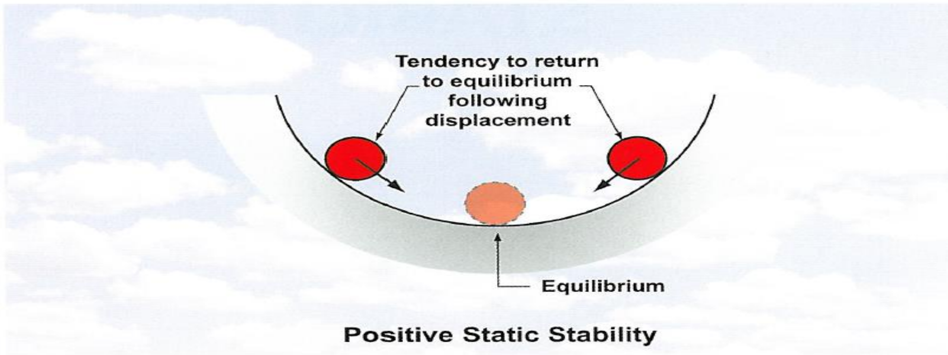


Figure 11.1 Positive Static Stability.

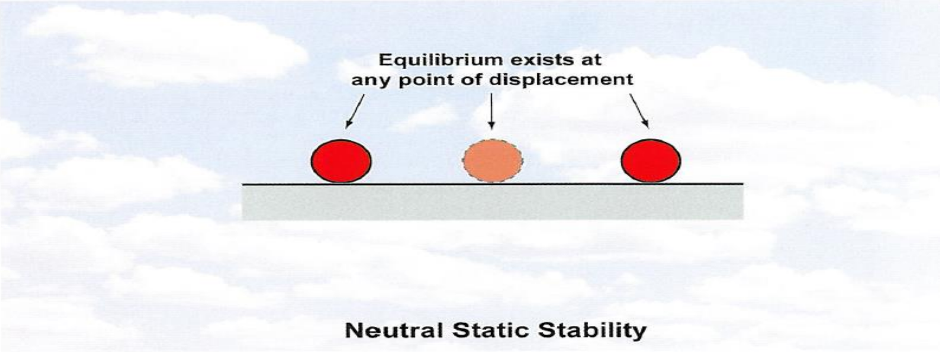


Figure 11.2 Neutral Static Stability.

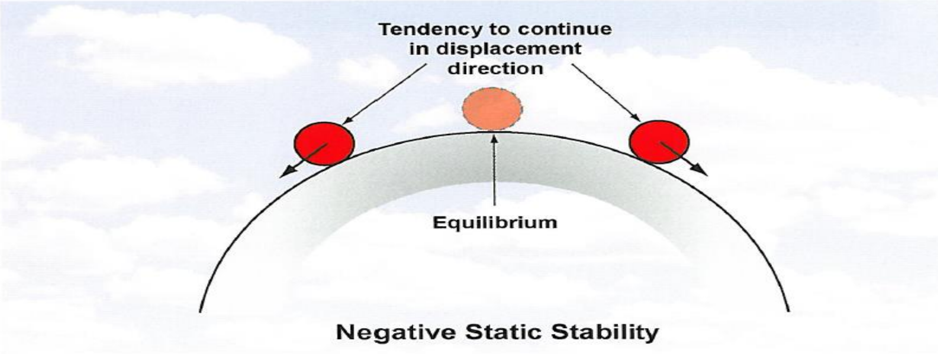


Figure 11.3 Negative Static Stability.

AIRCRAFT STABILITY.

INTRODUCTION.

The dictionary defines **stability** as "firmly fixed"; "established"; "not to be moved"; "not changeable". Applied to an aircraft, the word **stability** means that if the aircraft is flying in a certain direction, at a certain pitch attitude at a certain bank angle, the aircraft will tend to maintain both direction and attitude.

An aircraft which is **stable** will resist any change to its flight path and, if temporarily disturbed from a steady state of flight, will tend to return to its original flight path and attitude without any control input from the pilot. **Stability** is inherent in the aircraft by design and varies, from one aircraft to another, depending on type and role. An aerobatic aircraft, for instance, would normally be less **stable** than an aircraft designed specifically for touring.

An aircraft possesses two types of **stability**: static and dynamic.

Static Stability.

Static stability refers to the initial response of an aircraft when disturbed from a given attitude or flight path. **Static stability** can be further subdivided into three different types.

- **Positive static stability**. *(See Figure 11.1).*
- **Neutral static stability**. *(See Figure 11.2).*
- **Negative static stability**. *(See Figure 11.3).*

Dynamic Stability.

The word **dynamic** refers to **movement**, and the expression **dynamic stability** refers to the response of an aircraft tending to correct any displacement from its flight path or attitude over a period of time. **Dynamic stability** is subdivided into:

- **Positive dynamic stability**. *(See Figure 11.4a).*
- **Neutral dynamic stability**. *(See Figure 11.4b).*
- **Negative dynamic stability**. *(See Figure 11.4c).*

- **Positive static stability**. *(See Figure 11.1).*

- **Neutral static stability**. *(See Figure 11.2).*

- **Negative static stability**. *(See Figure 11.3).*

If an aircraft <u>tends to return</u> to its original state or attitude after it has been displaced, it is said to possess **positive static stability;** put more simply, the aircraft is said to be **stable**. However, if the aircraft tends to remain in the state or attitude that it acquires after a disturbance, it is said to be **neutrally, statically stable**. **Negative static stability** is the tendency for the aircraft, once disturbed, to continue to depart further from its original attitude or flight path. Such an aircraft is said to be **unstable**.

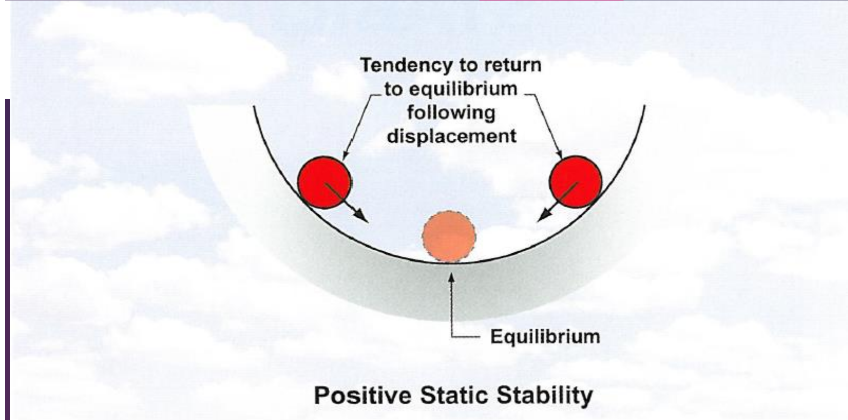


Figure 11.1 Positive Static Stability.

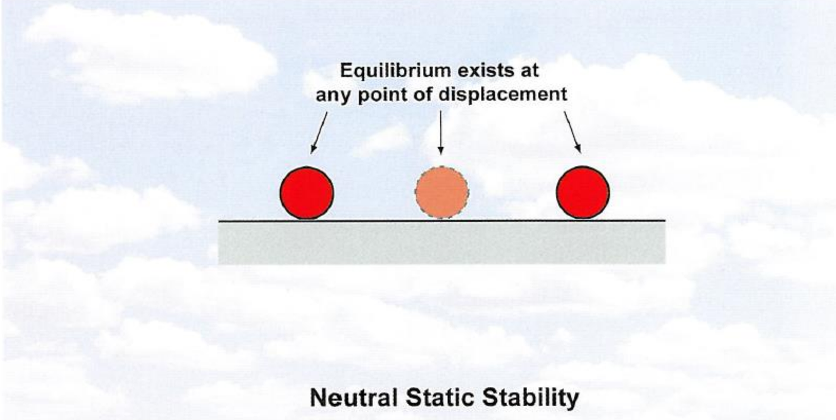


Figure 11.2 Neutral Static Stability.

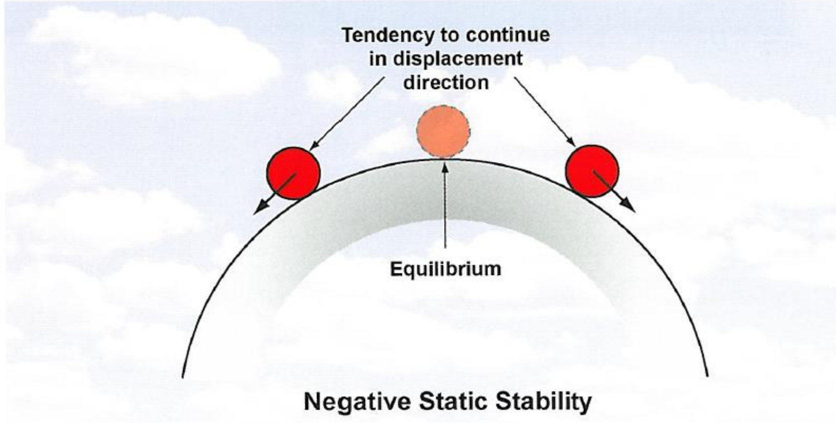


Figure 11.3 Negative Static Stability.

- **Positive dynamic stability**. *(See Figure 11.4a).*
- **Neutral dynamic stability**. *(See Figure 11.4b).*
- **Negative dynamic stability**. *(See Figure 11.4c).*

Let us assume that an aircraft has been disturbed in such a way that its nose pitches up, as depicted in *Figure 11.4*, at Points (a), (b) and (c). In order to return to its original attitude, the aircraft's initial response must be to pitch nose down again. But, of course, as the aircraft attempts to regain its original attitude it is continuing along its flight path.

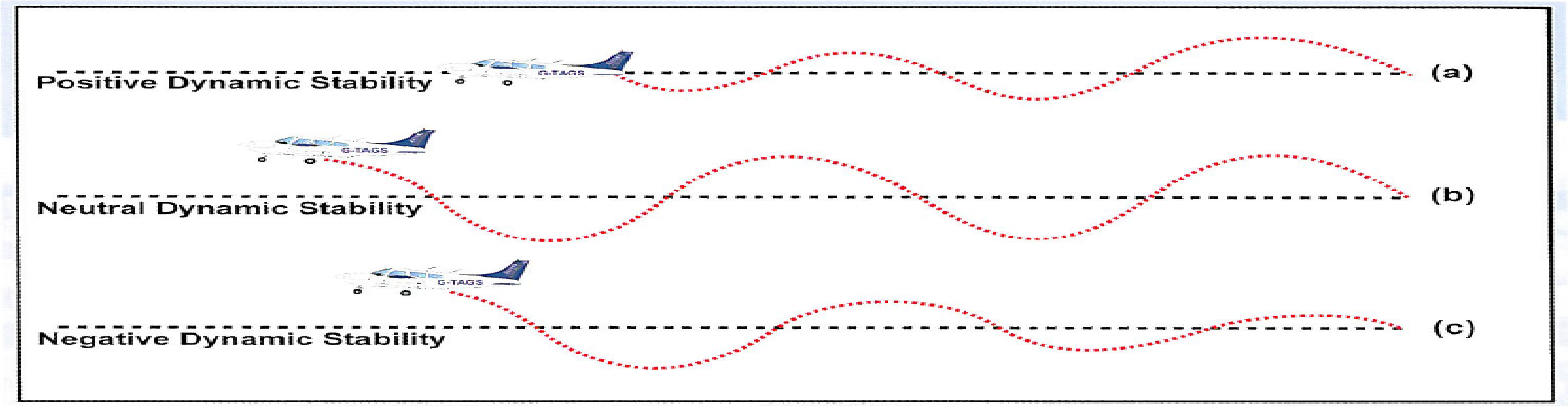


Figure 11.4 Degrees of Dynamic Stability.

It should be noted that in all the above situations the aircraft <u>tended</u> to try to regain its original flight path and displayed **positive <u>static</u> stability**, even when it was not **<u>dynamically</u> stable**. An aircraft that has **positive dynamic stability <u>must</u>** possess **positive static stability**.

THE AIRCRAFT'S THREE AXES.

An aircraft has three reference axes about which it rotates in flight, when manoeuvred. They are: the **longitudinal axis**, the **lateral axis** and the **normal axis**. All three axes pass through the **Centre of Gravity (C of G)** of the aircraft as shown in *Figure 11.5*.

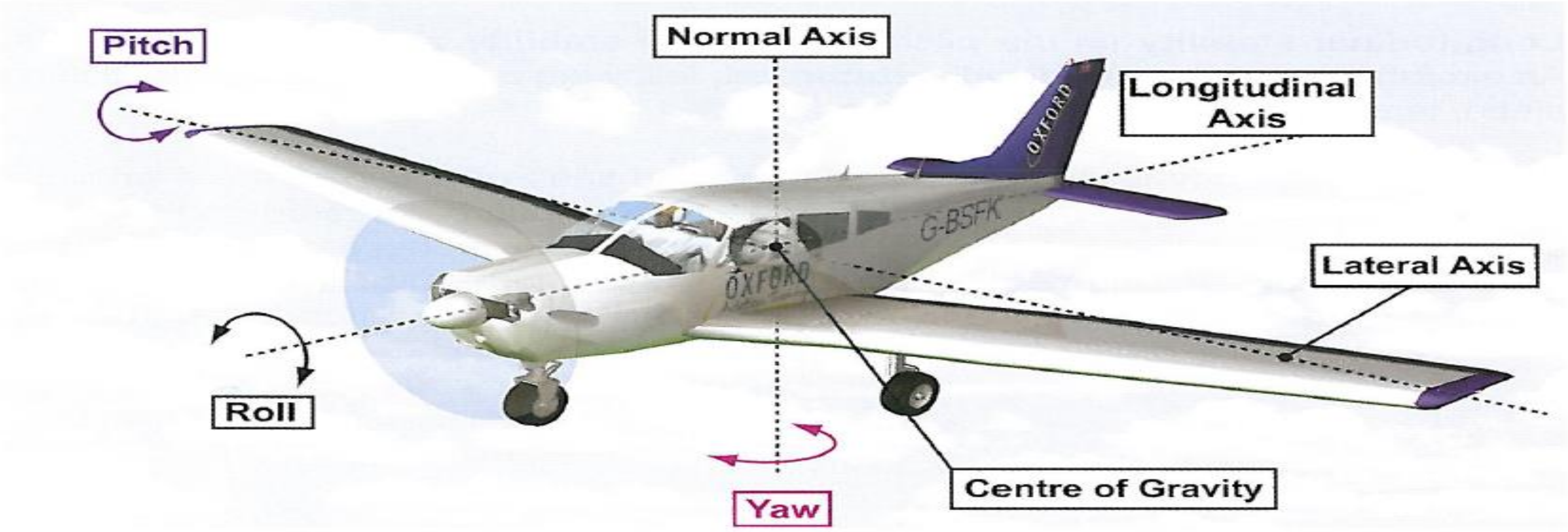


Figure 11.5 The three axes about which an aircraft rotates.

The **longitudinal axis** runs from nose to tail, passing through the **C of G**. Movement about the **longitudinal axis** is called **roll**. Whenever you consider **stability,** think of the motion about the axis concerned. An aircraft that is **laterally stable,** i.e. stable in roll, is **stable** about its **longitudinal axis**.

The **lateral axis** runs parallel to a line from wing tip to wing tip and passes through the **C of G**. The aircraft **pitches** about the **lateral axis.** An aircraft which is **stable** in **pitch** is said to be **longitudinally stable**.

The **normal axis** passes vertically through the **C of G** at 90° to the longitudinal axis. Movement about the **normal axis** is called **yaw**. Stability in **yaw** about the **normal axis** is termed **directional stability.**

A **very stable** aircraft would offer a large resistance to the pilot's flight-control inputs. This characteristic would reduce an aircraft's **controllability** and **manoeuvrability**, requiring significant physical force from the pilot to move the controls. The opposite situation would prevail if the aircraft were **neutrally stable** or **unstable.** In this case, the aircraft would be very manoeuvrable, and the flight controls very easy to move.

LONGITUDINAL STABILITY.

Longitudinal stability (in the pitching plane), is **stability about the lateral axis**. An aircraft which is **longitudinally stable** will, following a disturbance in the pitching plane, tend to return to its original pitch attitude.

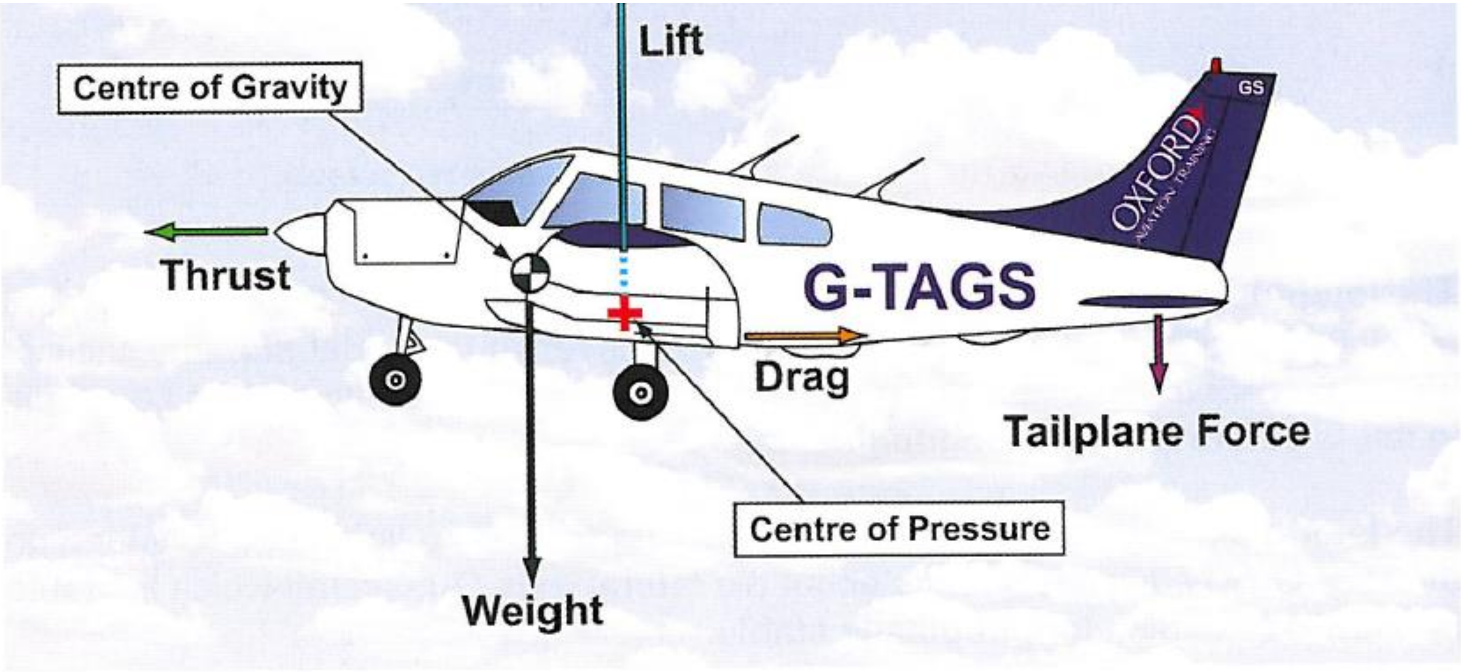


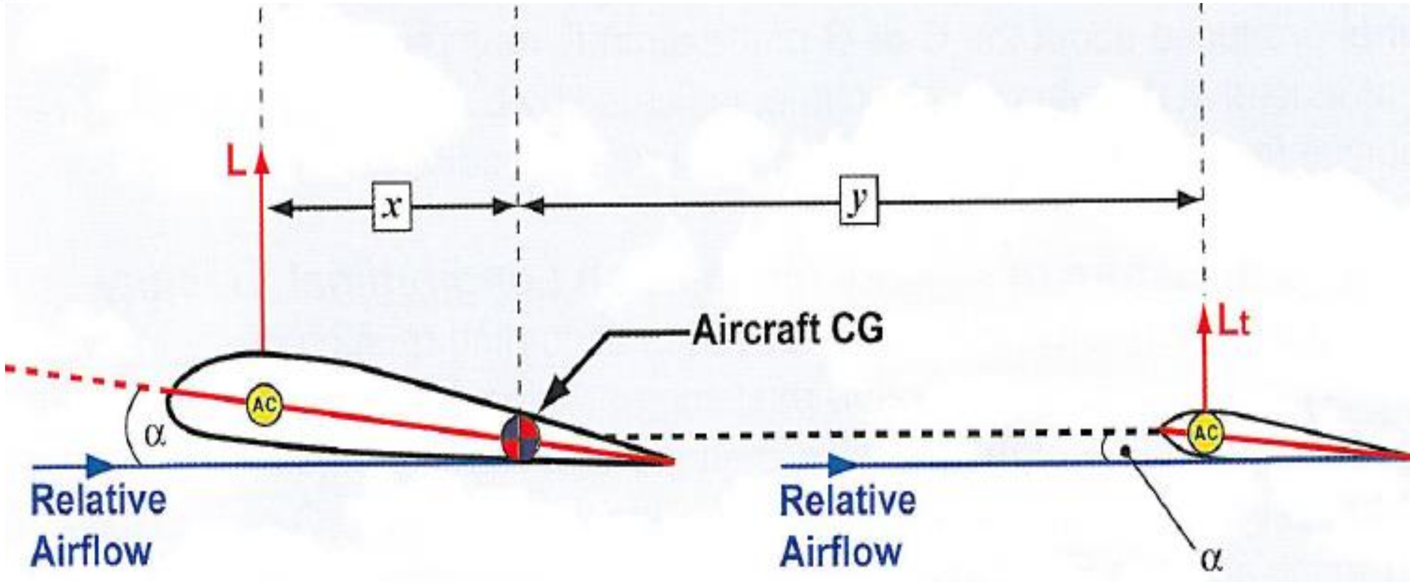
Figure 11.6 The tailplane gives an aircraft longitudinal stability.

If you think back to what you have learnt about **couples** and **turning moments** and examine *Figure 11.6*, you will see that the degree of **longitudinal stability** that an aircraft possesses depends on, amongst other things, the position of the **Centre of Gravity** (through which the **weight** acts) relative to the position of the **Centre of Pressure** (through which the **lift force** acts), and on the distance of the **tailplane** from the **Centre of Gravity**.

It should be clear that, when considered in isolation, a wing is **dynamically <u>unstable</u>** longitudinally. Look at *Figure 11.7, overleaf*. As the wing begins to pitch up (that is, as angle of attack increases), the **Centre of Pressure** moves forward and the **lift force** increases in magnitude. The wing would have a certain amount of **static stability** if its **Centre of Gravity** were in front of the initial position of the **Centre of Pressure**, but the wing is **highly unstable dynamically** and can not return to **equilibrium** unless a balancing turning moment is applied to it.

The **Aerodynamic Centre (AC)** of the wing is depicted at distance x, from the aircraft **Centre of Gravity (C of G)**, and the **AC** of the tailplane is at the greater distance y, from the **C of G**.

The **tailplane** or **horizontal stabilizer** is much smaller than the main wing and, as such, produces a much smaller **lift** force. In the diagrams, the **lift** force produced by the wing is designated, **L**, and the lift from the tailplane $\mathbf{L_t}$. $\mathbf{L_t}$, thought smaller than **L**, is, however, positioned at a greater distance from the aircraft's **C of G** and, so, generates a stabilising moment in pitch.



We will now assume that the **wing** and the **tailplane** experience the same momentary gust. (*See Figure 11.10*). Exposure to this gust causes the **angle of attack,** and hence the **lift**, to increase at both wing and tailplane. The increase in **angle of attack**, in both cases, is taken to be $\Delta\alpha$.

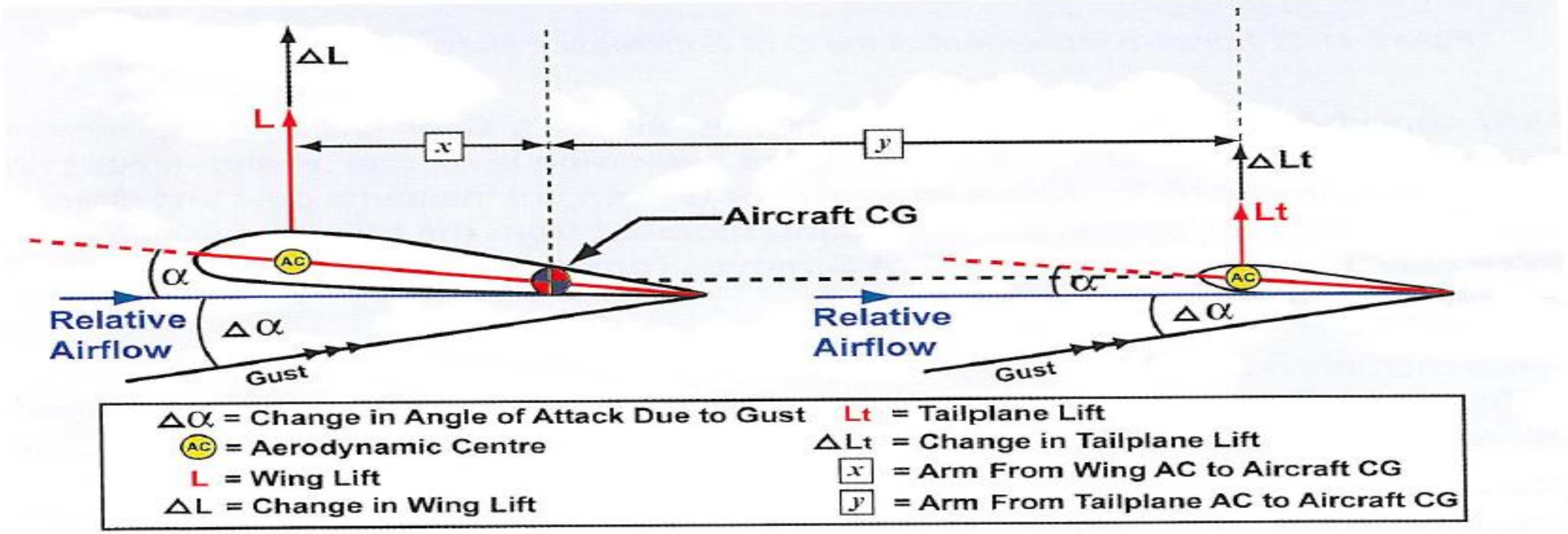


Figure 11.10 The tailplane moment is now greater than the wing moment.

The increase in wing lift ΔL, will be greater than the increase in tail lift, ΔL_t, and the aircraft will, therefore, tend to pitch nose-up.

The Effects of Centre of Gravity Moment on Longitudinal Stability.

The **C of G** of an aircraft is not fixed but varies according to such changing values as the **weight (or mass)** of the pilot, passengers, baggage and fuel load. It is, of course, not only their **weight** but also their **position** and **distribution** within the aircraft which will affect the **C of G** position. Remember that the **C of G** is the point through which acts the resultant of all the separate weight forces which make up the total weight of the aircraft.

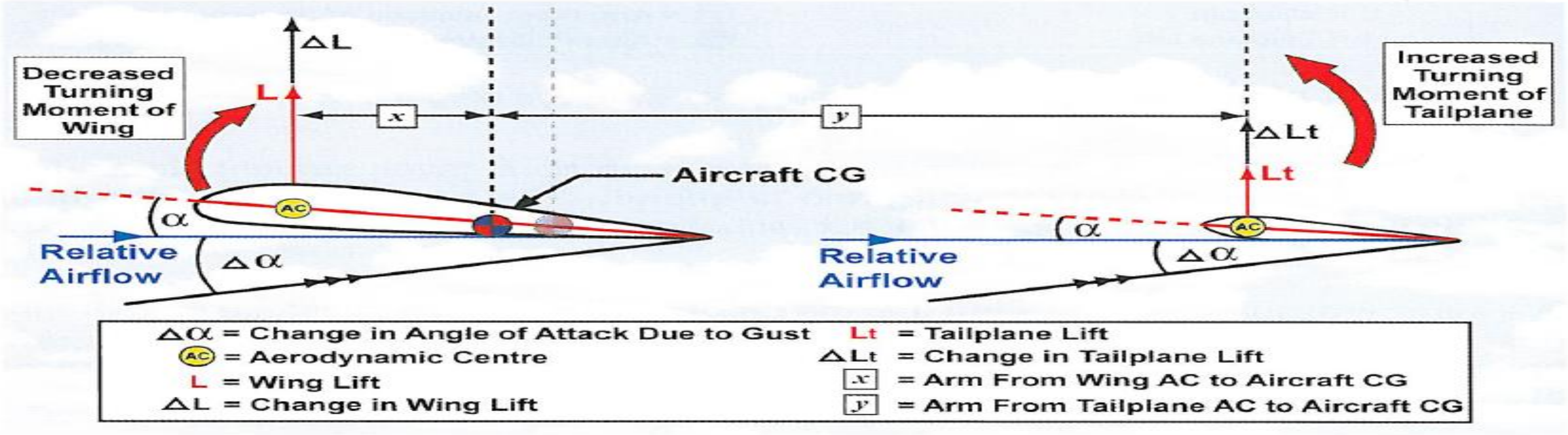


Figure 11.11 Forward movement of the C of G increases static longitudinal stability.

Now consider *Figure 11.11* which depicts the aircraft's **C of G** as having moved forward. This has the effect of reducing the main wing lever arm x, and increasing the tailplane lever arm y. With a forward **C of G**, then, for the same gust and change in angle of attack as before, the **correcting moment from the tailplane** will be even more effective. **Thus, when the C of G moves forward, an aircraft's longitudinal stability increases.**

Centre of Gravity Limits.

If the **C of G** is moved even **further aft than the neutral point**, as depicted in *Figure 11.12*, the aircraft would become **longitudinally unstable.** For this reason an **aft C of G limit**, <u>forward of the neutral point</u>, is established and specified by the aircraft designer, in order to ensure **acceptable positive stability**, and adequate **controllability** and **manoeuvrability**.

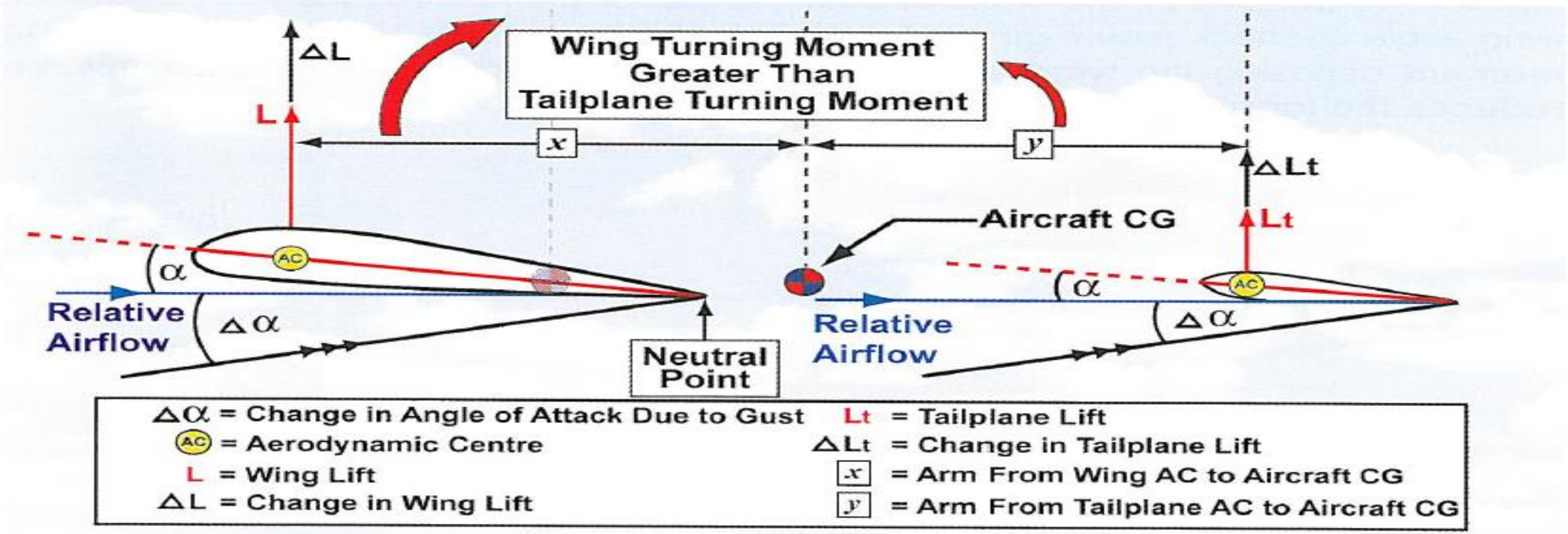


Figure 11.12 With the C of G further aft than the neutral point, the aircraft is longitudinally unstable.

The Effects of Downwash on Longitudinal Stability.

So far in our examination of longitudinal stability, we have assumed that a gust affecting the aircraft in the pitching plane modifies the angle of attack of the wing and the tailplane to the same extent. But any increase in downwash at the wing caused by, say, the lowering of flap or ground effect, will affect the tailplane angle of attack more than the wing angle of attack. As downwash reduces the effective angle of attack (See Chapter 5), the angle of attack at the tail plane is reduced more than the wing angle of attack *(see Figure 11.14)*. This in turn reduces the **tailplane turning moment** opposing the wing turning moment. **Therefore, increased downwash reduces the longitudinal stability of an aircraft.**

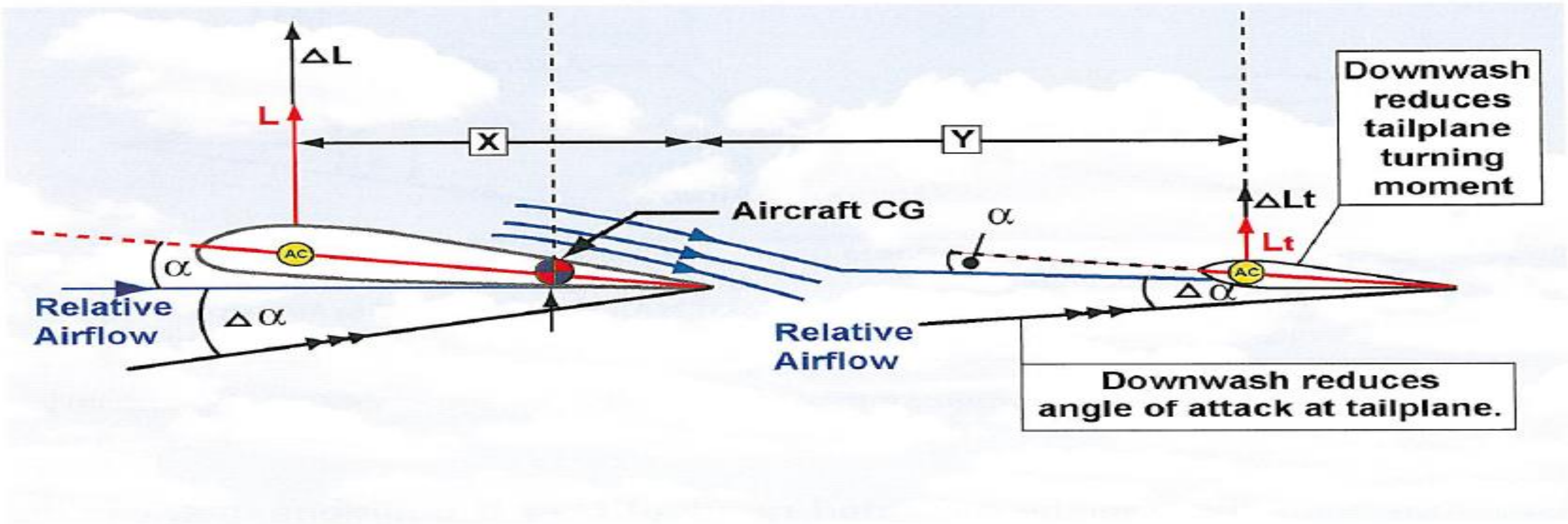


Figure 11.14 Increased downwash reduces longitudinal stability.

Power changes also affect longitudinal stability. If you reduce power during flight, a definite nose-down pitching tendency occurs due to the reduction of downwash from the wings and the propeller. This decreases the associated downward force on the tail, and reduces elevator effectiveness. Although this is a destabilizing factor, it is a desirable characteristic, because it tends to result in a nose-down attitude during power reductions. The nose-down attitude helps you maintain, or regain, airspeed.

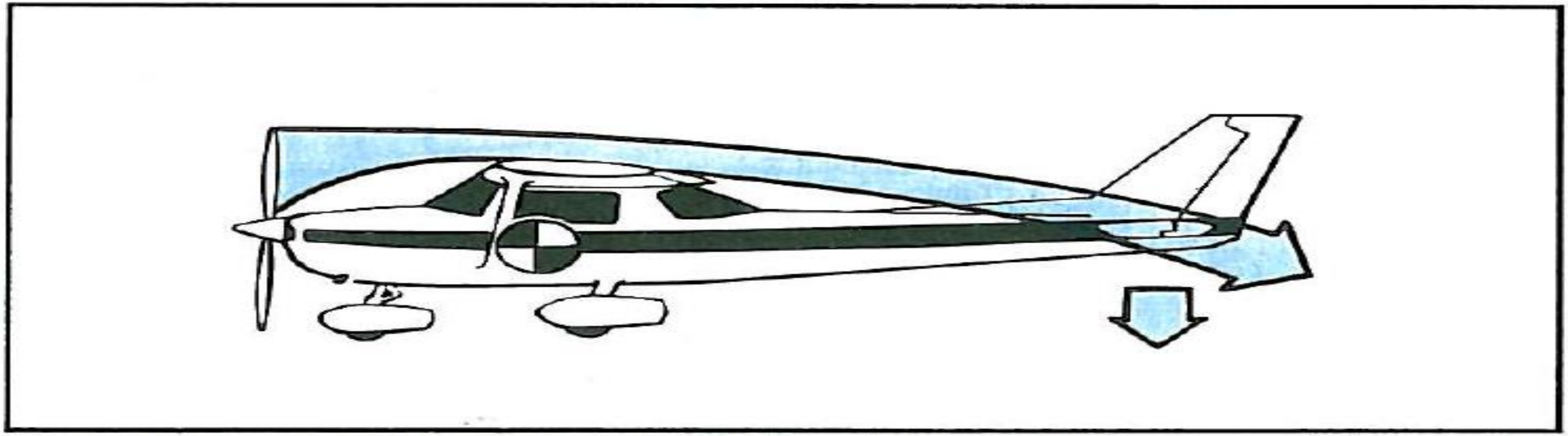
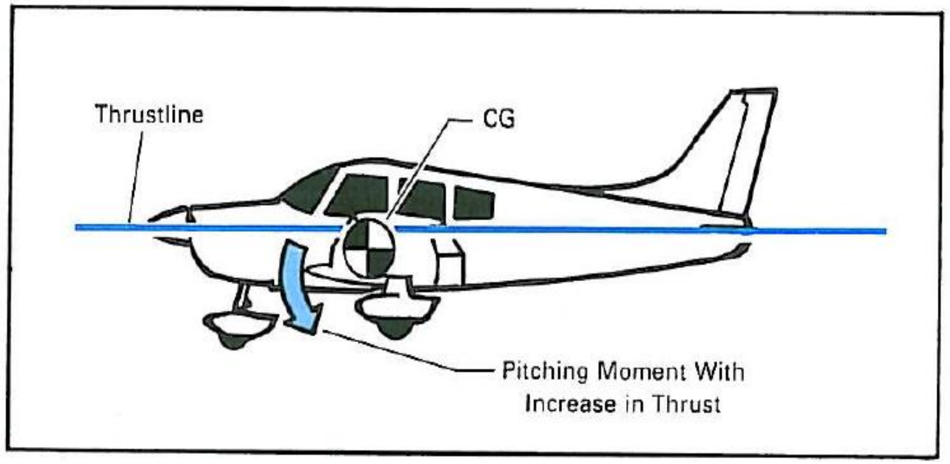


Figure 1-47. As the downwash from the propeller and the wings passes over the horizontal stabilizer, it "pushes" the tail section down. This tail-down force helps to balance the airplane about its lateral axis, and it influences the longitudinal stability of the airplane.

In most light general aviation airplanes, the thrustline is parallel to the longitudinal axis and above the CG. This creates a slight pitching moment around the CG. If thrust is decreased, the pitching moment is reduced and the nose heaviness tends to decrease. An increase in thrust increases the pitching moment and increases nose heaviness. Notice that these pitching tendencies are exactly the reverse of the pitching tendencies resulting from an increase or decrease in downwash. This thrustline design arrangement minimizes the destabilizing effects of power changes and improves longitudinal stability. [Figure 1-48]



LATERAL STABILITY.

Lateral stability is **stability in roll, about the longitudinal axis**, which runs from nose to tail through the aircraft's **C of G**, as depicted in *Figure 11.15*.

Figure 11.15 Lateral Stability is stability in roll about the longitudinal axis.

Wing Dihedral.

Greater and longer lasting stabilising moments can be produced if the plane of each wing is angled positively, above a horizontal datum parallel to the lateral axis, as in *Figure 11.17*. This is called **wing dihedral**. The greater the **dihedral**, the greater will be the **lateral stability**.

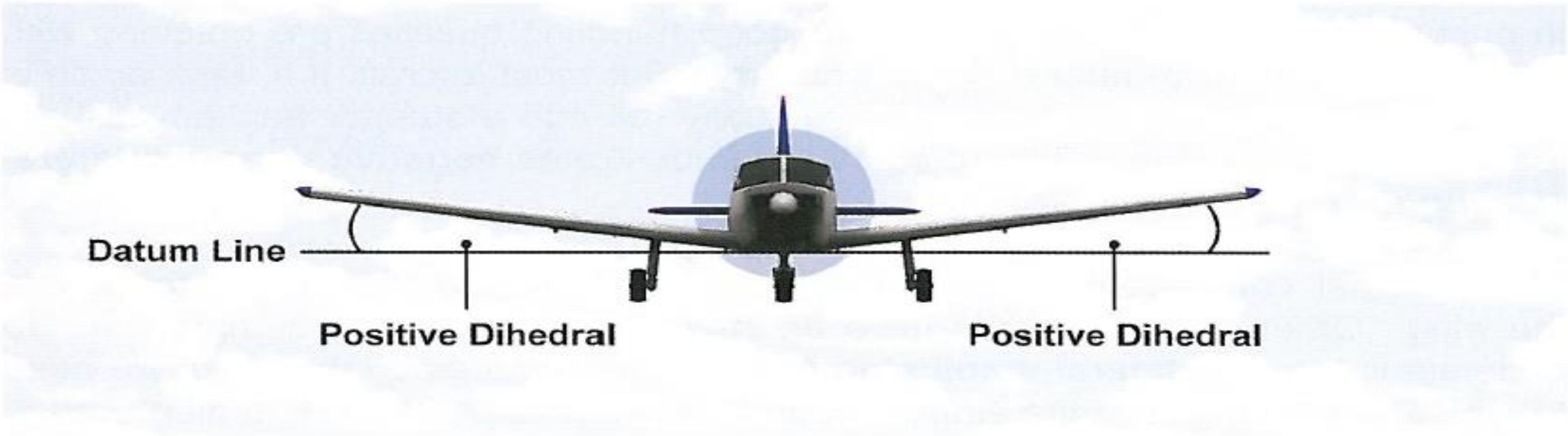


Figure 11.17 Wing dihedral.

How Wing Dihedral Contributes to Lateral Stability.

When a wing displaying positive **dihedral** is established in a sideslip, the sideways component of the **relative airflow** will meet the lower wing at a greater angle of attack than the upper wing *(see Figure 11.19)*.

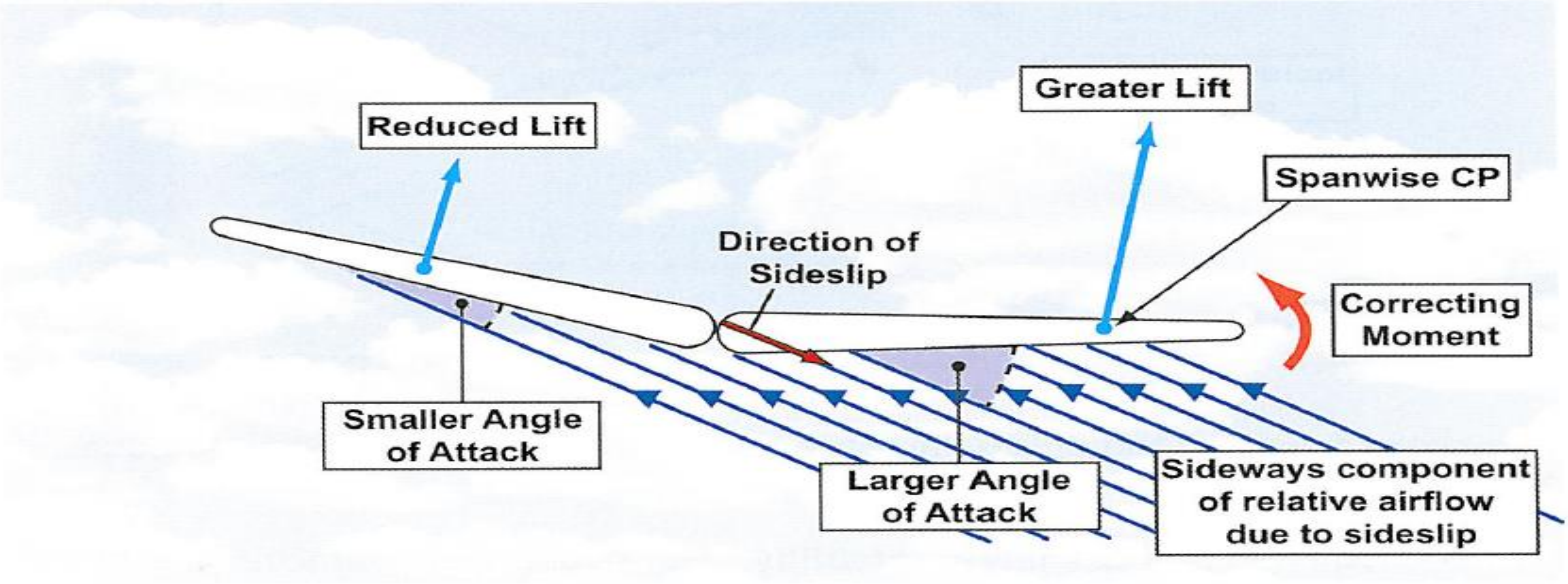


Figure 11.19 With dihedral the lower wing generates more lift in a sideslip.

This fact has two principal consequences, both of which will cause the lower wing to generate greater lift than the upper wing, and so tend to return the aircraft to the wings-level attitude.

- The greater angle of attack at the lower wing **increases** that wing's C_L, and therefore its **lift** force, compared to the **lift** produced by the upper wing.

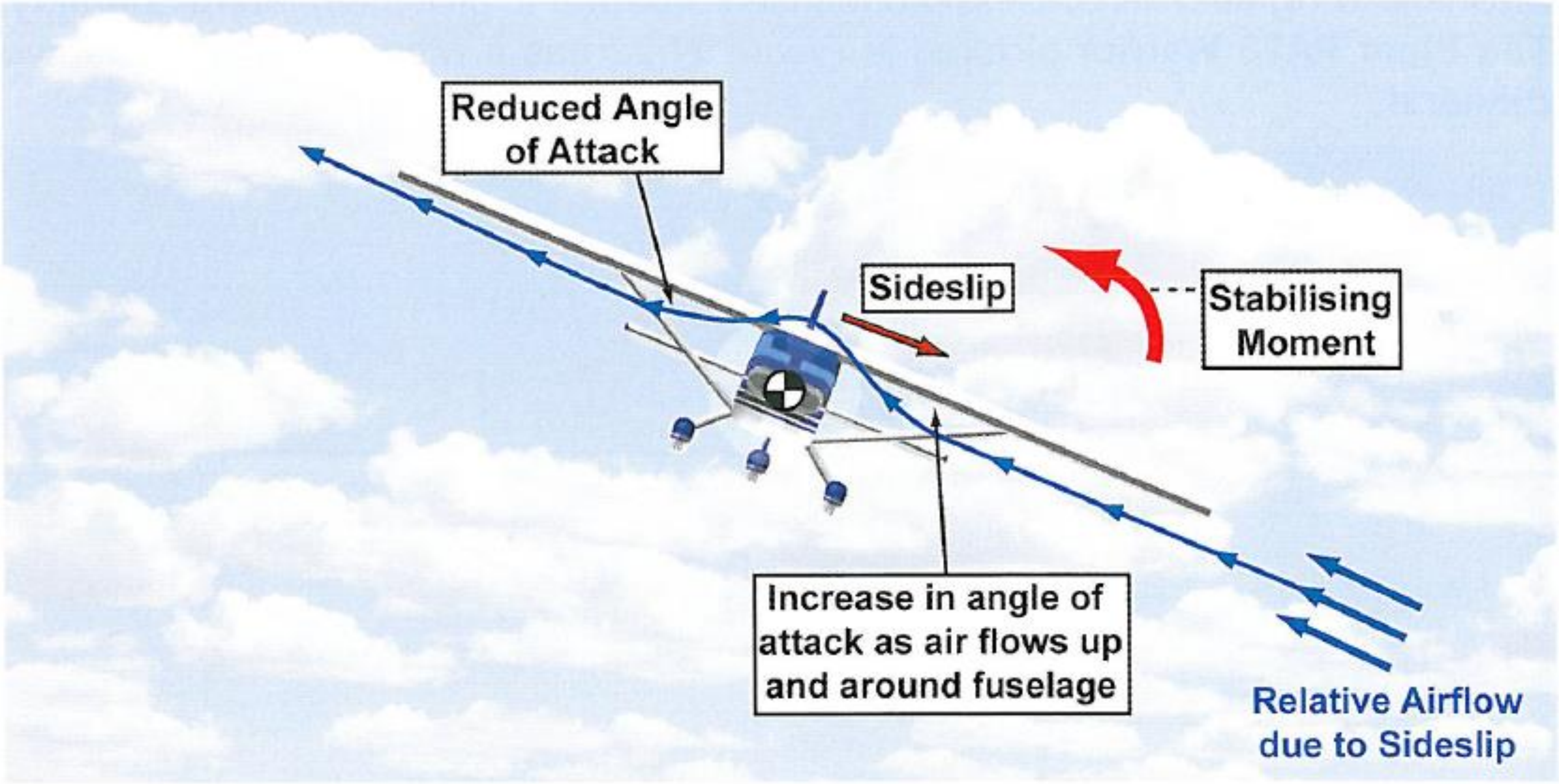
- The **wing tip** of the **lower wing** effectively becomes **a leading edge**. Consequently, the spanwise **Centre of Pressure (CP)** will now be nearer to the wing tip of the lower wing, causing the lower wing to generate more lift.

High-Wing Aircraft.

High-wing aircraft have such a degree of **inherent lateral stability** that their **wing dihedral** angle is normally very small. You can see the difference between the dihedral on a high-wing **Cessna 172** and the low wing **Piper PA 28** in *Figure 11.23*.

Figure 11.23 The difference in dihedral between low and high wing aircraft.

With a high-wing aircraft, during a sideslip, the sideways component of the **relative airflow** flows up around the fuselage on the lower wing, increasing its angle of attack and, thus, its lift, and flows down towards the higher wing decreasing its angle of attack and lift. This phenomenon contributes towards **positive lateral stability** *(See Figure 11.24)*.



The Effect of Wing Position on Lateral Stability.

Low-Wing Aircraft.

Certain characteristics of **low-wing** aircraft tend to reduce **lateral stability**.

Because of the position of the low-wing in relation to the fuselage, the sideways component of the **relative airflow** caused by the sideslip flows down around the fuselage at this junction with the lower wing, decreasing its angle of attack, and flows up towards the higher wing increasing its angle of attack, as depicted in *Figure 11.20*.

Figure 11.20 Low wing aircraft posess characteristics which reduce lateral stability.

The fuselage and side (or keel) surfaces above the **C of G** also exert a **stabilising** effect.

In addition, high wing aircraft produce a stabilising moment, contributing to their **lateral stability**, as a result of the pendulum effect, as depicted in *Figure 11.25*.

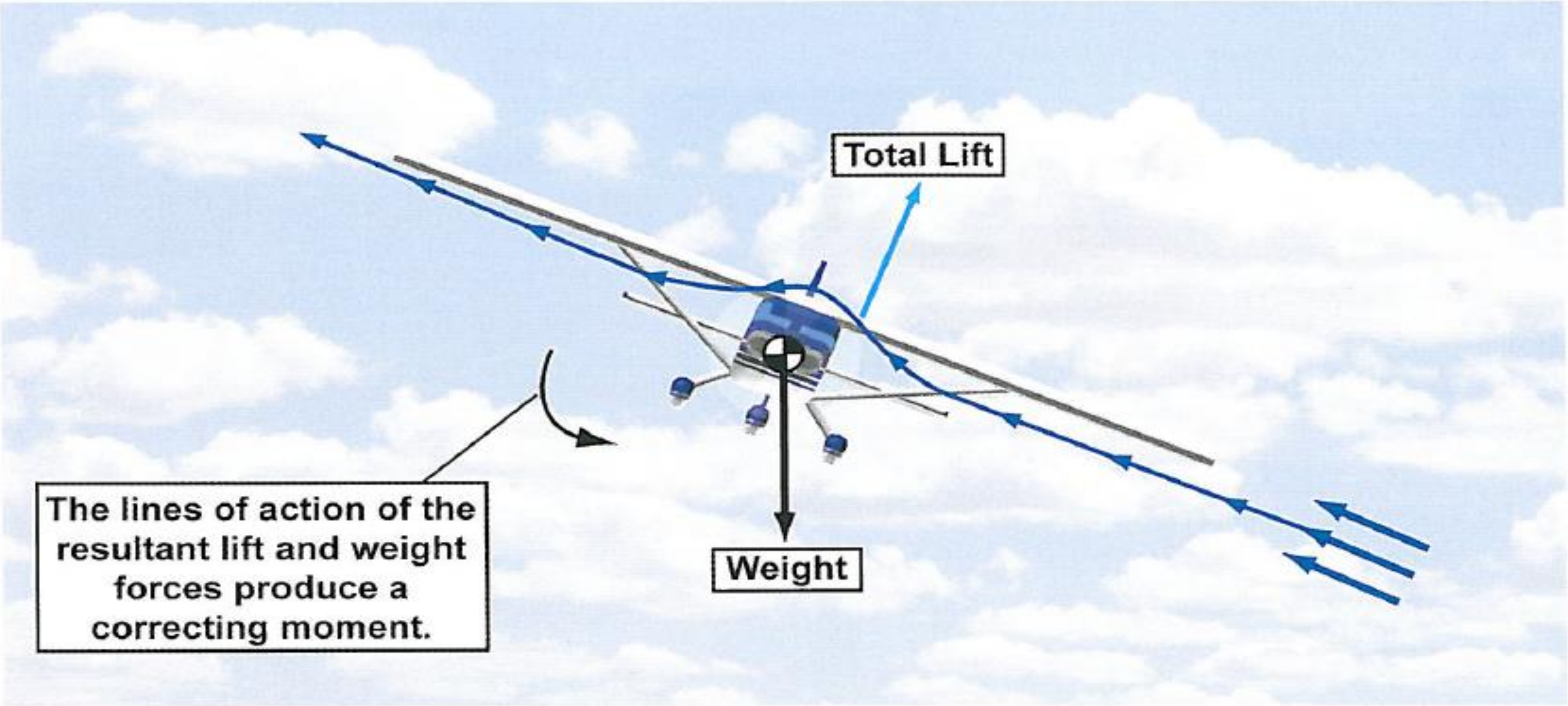


Figure 11.25 Lateral Stability characteristics of a high-wing: the Pendulum Effect.

Any **keel surface** (side surface) above the **Centre of Gravity (C of G)**, such as the **fuselage sides** or **fin**, will, during a side slip, set up forces creating a **restoring moment** which will tend to return the aircraft to the wings-level attitude.
(See Figure 11.21)

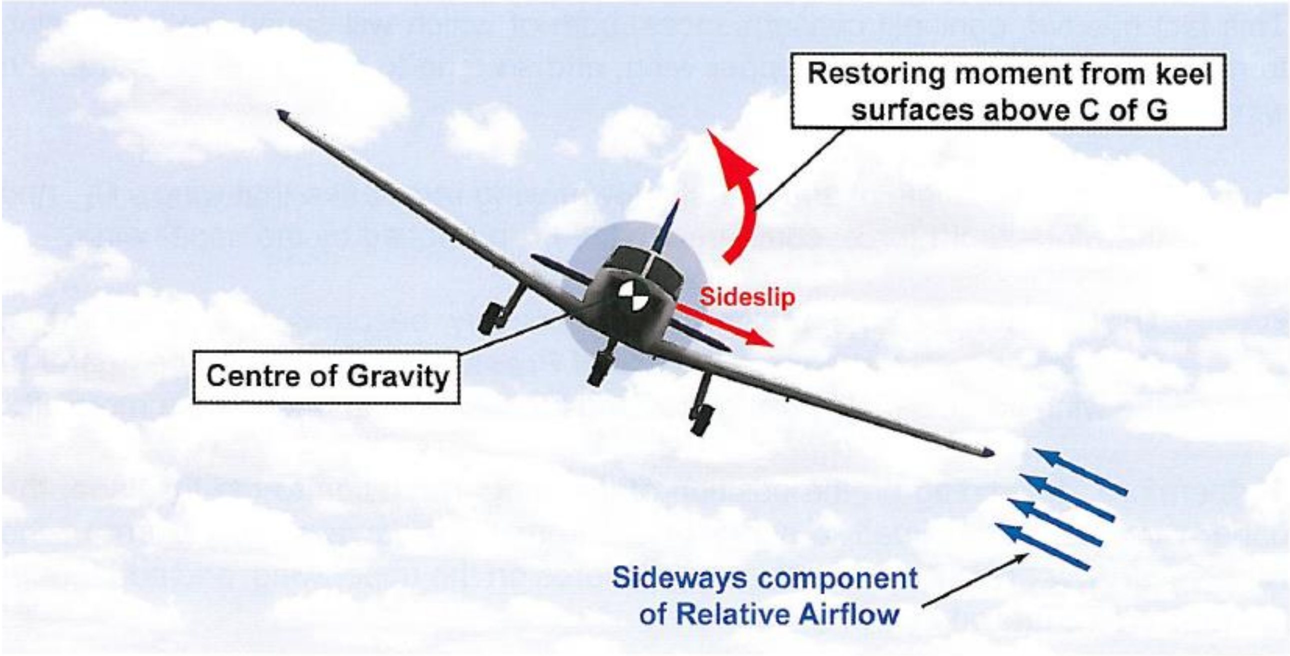


Figure 11.21 The keel surfaces above the C of G set up a restoring moment, adding to lateral stability.

Swept Back Wings.

The study of high speed flight is not a requirement for the Private Pilot's Licence. However, you should know that **sweepback** also contributes to **positive lateral stability**, because, during a sideslip, the lower wing effectively presents a greater span, and, thus, a greater aspect ratio to the **relative airflow**. The lower wing will therefore generate more lift giving rise to a restoring moment which tends to return the aircraft to the wings-level attitude. *(See Figure 11.26.)*

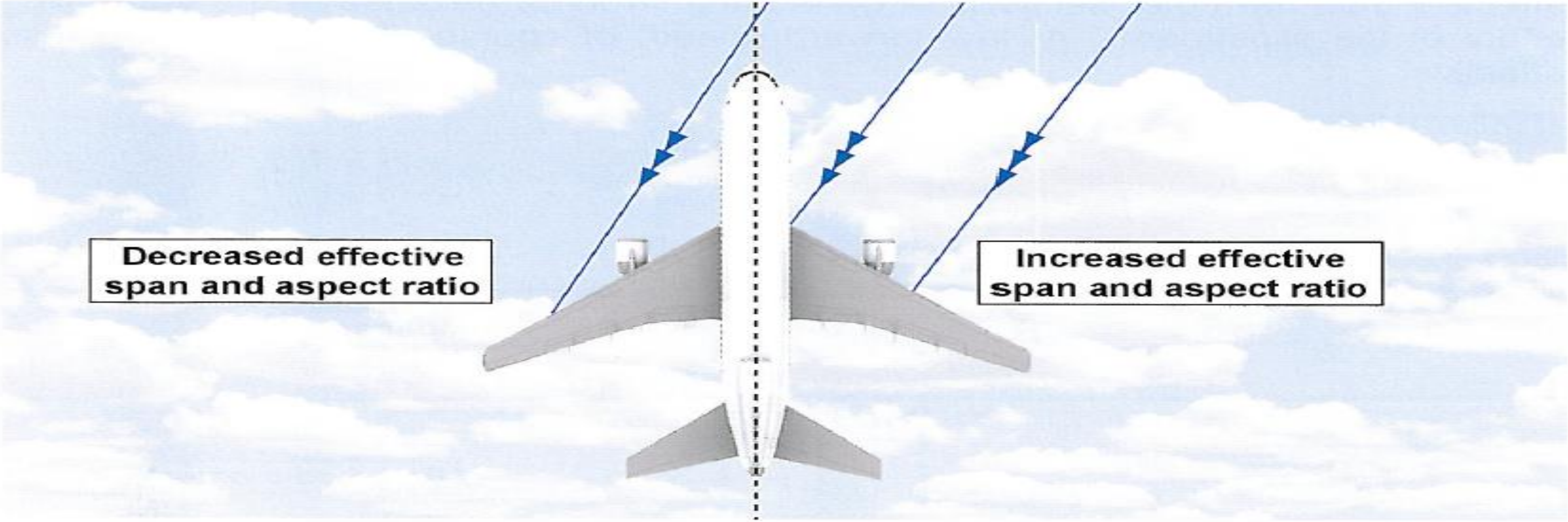


Figure 11.26 Lateral Stability characteristics of a swept-back wing.

Anhedral.

Jet aircraft with a wing of pronounced sweep-back may actually posses too much **positive lateral stability**. Such aircraft may, consequently have a wing with **anhedral**. **Anhedral** is negative dihedral and reduces **lateral stability.** *(See Figure 11.27).*

Figure 11.27 Anhedral reduces lateral stability.

The Effect of Flaps and Power on Lateral Stability.

You will recall that **flaps** reduce **longitudinal stability** because of their influence on **downwash**. **Lateral stability** is also reduced when **partial span flaps** are deployed.

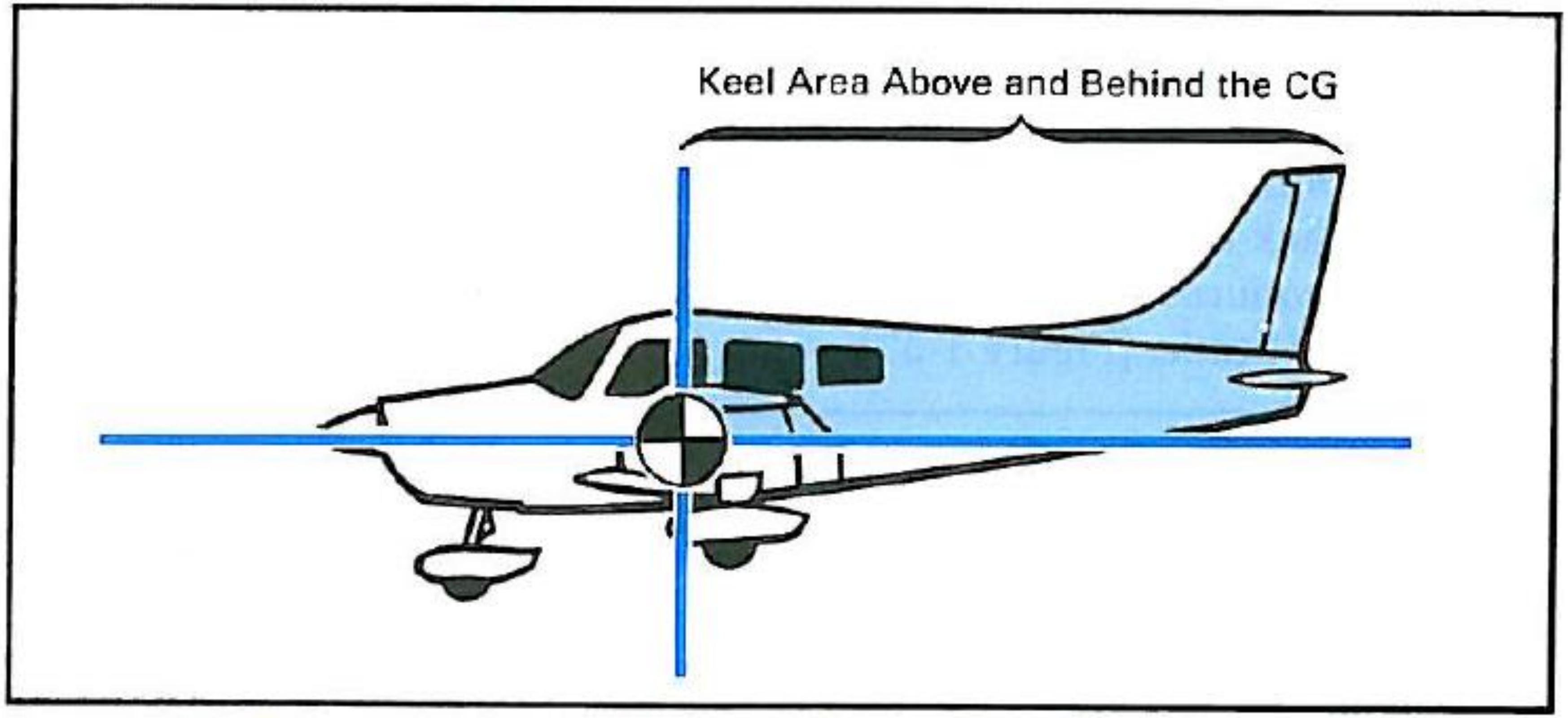
The deployment of **partial-span flaps** causes the lift on the inboard section of the wing to increase relative to the wing's outer section, as depicted in *Figure 11.28*. This phenomenon, which moves the spanwise **centre of pressure** inboard, reduces the spanwise **moment arm**. Consequently, during a sideslip, any modification of the lift force occurs closer inboard, reducing the correcting moment. The overall effect of deploying **flap**, then, is to **reduce lateral stability**.

The reduction in the **lateral stability** is most critical when the effects of **flap, propeller slipstream and low forward speed** are combined. The reduction in **lateral stability** would be conveyed to the pilot as a reduction in the control force required to manoeuvre the aircraft in roll.

Figure 11.29 High power settings at low forward speed reduce lateral stability.

WEIGHT DISTRIBUTION

You have no control of the design features that help maintain lateral stability, but you can control the distribution of weight and improve lateral stability. For example, most training airplanes have two fuel tanks, one inside each wing. Before you take off on a long flight, you normally fill both tanks. If you use fuel from only one tank, you will soon notice that



DIRECTIONAL STABILITY.

Introduction.

Directional stability is stability about the vertical, or **normal, axis.** Movement about this **axis** is called **yaw,** so **vertical stability** may also be defined as **stability in the yawing plane**. The **tail fin** or **vertical stabiliser** is the surface which contributes most to **directional stability**. *See Figure 11.30.*

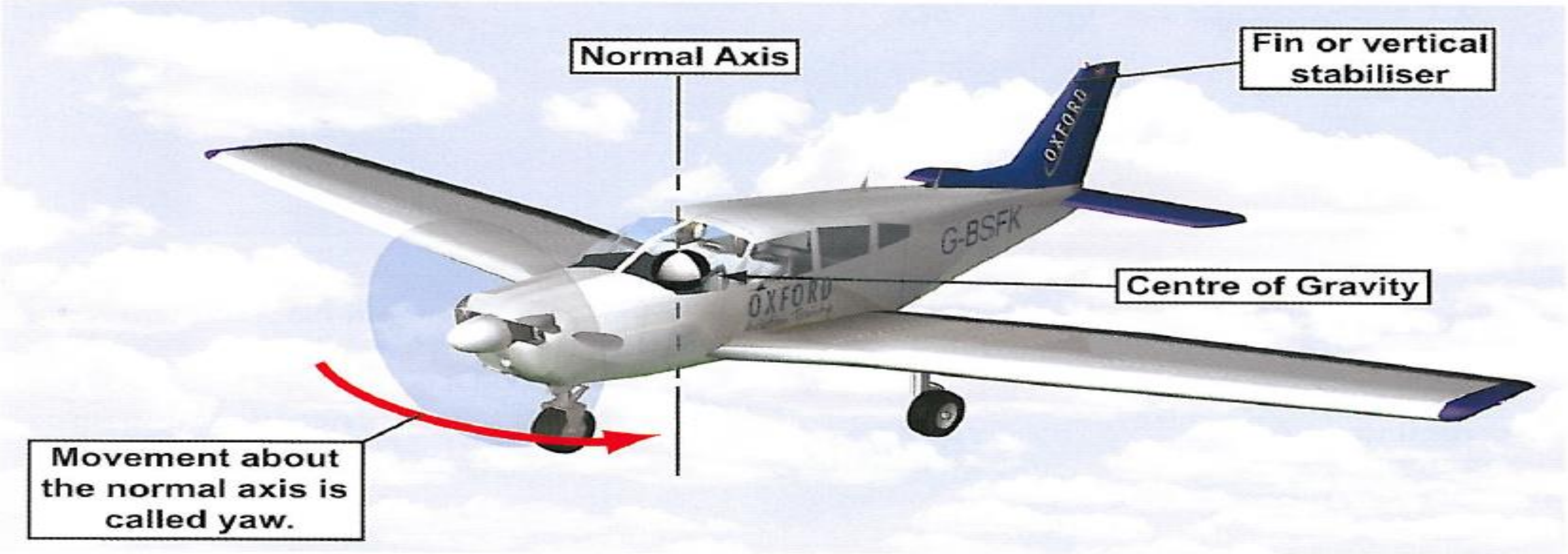


Figure 11.30 Directional stability is stability about the normal axis, in the yawing plane.

The Tail Fin or Vertical Stabiliser.

The **tail fin** is a **symmetrical aerofoil**. Therefore, with a **relative airflow** from straight ahead, the **fin** will be at **0º** angle of attack, as shown in *Figure 11.31*, and no aerodynamic force, except drag, will be produced by the **fin**.

But if the aircraft is disturbed in the **yawing plane,** the angle of attack at the **fin** increases, creating an aerodynamic force opposing the **yaw**, thus providing a **correcting turning moment** about the aircraft's **Centre of Gravity (C of G)**. The nose of the aircraft will, therefore, swing back to face the **relative airflow**, and the aircraft will have displayed **positive directional stability**. (See *Figure 11.32).*

Note that when an aircraft is disturbed in the **yawing plane**, it is moving **crabwise** through the air, with the **relative airflow** striking its keel surfaces at an oblique angle. This movement is referred to as **slip** or **skid**. In this flight condition, the **weathercocking** effect will also cause the aircraft to tend to swing back to face the relative airflow.

The Effectiveness of the Tail Fin.

The **correcting turning moment** produced by the **tail fin** which gives an aircraft **directional stability** depends on three factors. They are:

- The angle of attack caused by the disturbance in the **yawing plane**.
- The side-surface or area of the **fin,** and efficiency of the **fin's** aerofoil section.
- The length of the **moment arm** between the **fin** and the **C of G.**

A small **fin** at the end of a long fuselage may be just as efficient in giving an aircraft **directional stability** as a large **fin** at the end of a short fuselage.

The **stabilising action** of the **tail fin** can be supplemented by the use of **dorsal** and **ventral fins**, as illustrated in *Figure 11.34*, **Dorsal** and **ventral fins** are small aerofoil sections positioned above and below the fuselage, respectively, and are used to increase the keel area aft of the aircraft's **C of G**.

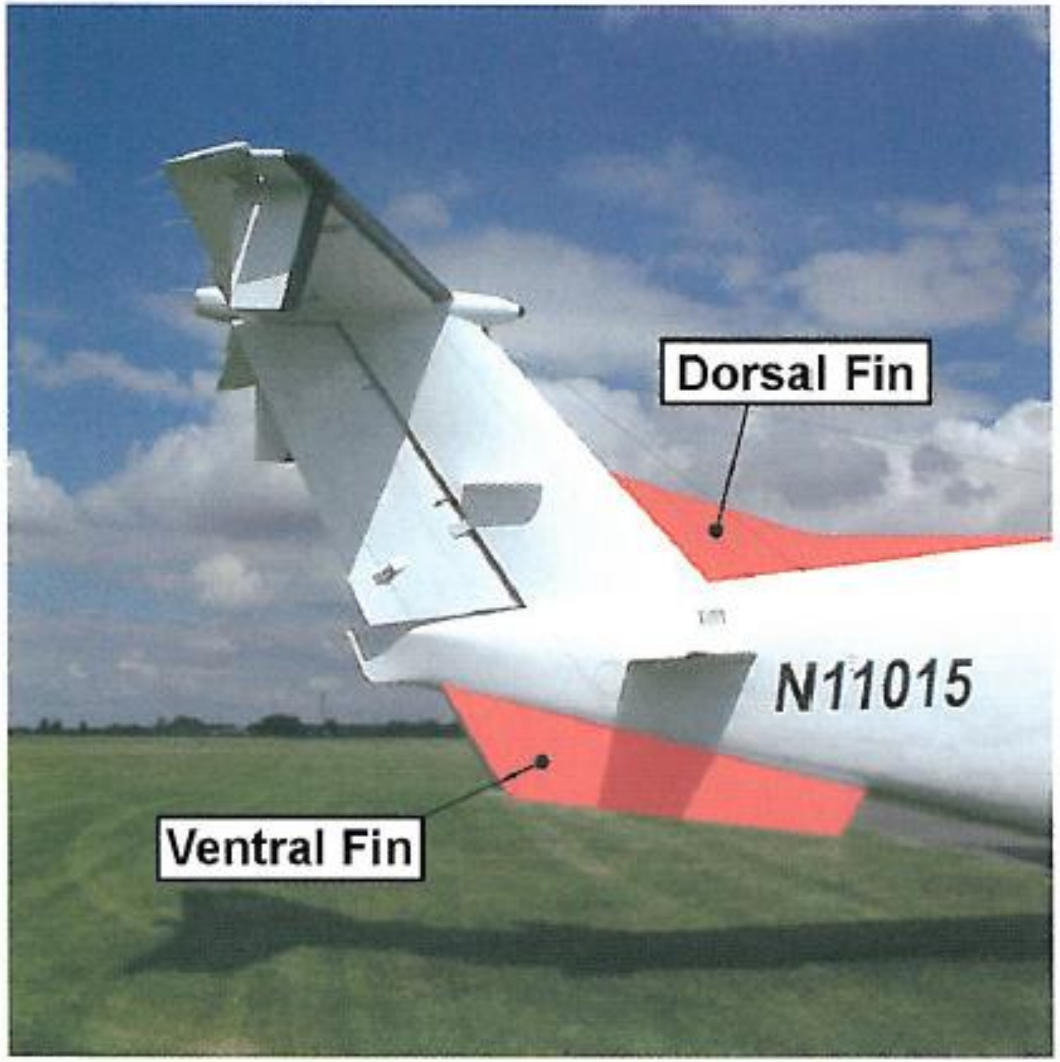


Figure 11.34 Dorsal and Ventral fins

THE INTERRELATIONSHIP BETWEEN LATERAL AND DIRECTIONAL STABILITY.

Having considered **lateral** and **directional stability** separately, we now need to examine why an aircraft's **lateral** and **directional** rotation about its **C of G** are not independent of each other. There is an important interrelationship between an aircraft's displacement in the **rolling plane** and its displacement in the **yawing plane**. **A displacement in the yawing plane will always influence an aircraft's motion in the rolling plane, and *vice versa*.**

Initial Roll Followed by Yaw.

If a pilot selects an **angle of bank** with ailerons alone, without making any further control movements, the aircraft responds initially by **rolling** about its **longitudinal axis**. The displacement of the ailerons which induces the roll generates increased lift on the up-going wing, while the lift on the down-going wing decreases. As you have learnt in the early chapters of this book, an increase in lift is always accompanied by an increase in drag. Therefore, the up-going wing will be held back relative to the down-going wing, causing the aircraft to **yaw** towards the upper wing. This initial yaw following a roll induced by ailerons alone is, as you will recall, called adverse yaw. The initial **roll**, therefore, has led to **yaw**. If there is no further control input from the pilot, subsequent developments will be as follows.

- The aircraft will **slip** towards the lower wing, and the side component of the **relative airflow** will, consequently, strike the aircraft's keel surfaces. In a conventional aircraft, the keel surfaces behind the **centre of gravity (C of G)** are of a greater area than the area of the keel surfaces forward of the **C of G**, and, therefore, because of the **sideslip**, the aircraft will now **yaw** in the direction of the lower wing.

- The **yaw** towards the lower wing naturally causes the higher wing to move forwards while the lower wing moves rearwards. The velocity of the airflow over the higher wing will, thus, be greater than that over the lower wing, further increasing the lift differential between the two wings ($\mathbf{Lift = C_L \tfrac{1}{2} \rho v^2 S}$) so as to <u>reinforce</u> the **rolling movement**.

- More **roll** will induce more **yaw** which will reinforce the **roll**, and so on.

Initial Yaw Followed by Roll.

If the aircraft is displaced in the **yawing plane** (that is, directionally, about its **normal axis**), one wing will move forward relative to the other. Unless the pilot intervenes, the forward moving wing will generate a greater lift force than the rearwards moving wing. The main reason for this is that, during the initial **yaw**, the velocity of the airflow over the forward-moving wing will be greater than that over the rearwards-moving wing, thus increasing lift, (**Lift =** $C_L \frac{1}{2} \rho v^2 S$).

Consequently, the aircraft will begin to **roll in the direction of yaw**. The **roll** will induce more **yaw**, which in turn will cause more roll, and so on. Again, unless the pilot intervenes, a spiral dive will ensue. An initial yaw, then, will be followed by roll in the same direction as yaw.

Although airplanes are designed with stabilizing characteristics which lighten your workload while you are flying, there are normally some undesirable side effects. Two of the most common ones are Dutch roll and spiral instability.

Dutch roll is a combination of rolling/yawing oscillations caused either by your control input or by wind gusts. In a typical case, when equilibrium is disturbed, the rolling reaction precedes the yaw, and the roll motion is more noticeable than the yaw motion.

The alternative to an airplane that exhibits Dutch roll tendencies is a design that has better directional stability than lateral stability. If directional stability is increased and lateral stability is decreased, the Dutch roll motion is adequately suppressed. However, this design arrangement tends to cause spiral instability.

Spiral instability is associated with airplanes that have strong directional stability in comparison with lateral stability. When an airplane with spiral instability is disturbed from a condition of equilibrium, a side slip is introduced. In this case, the strong directional stability tends to yaw the airplane back into alignment with the relative wind. At the same time, the comparatively weak dihedral effect lags in restoring lateral stability. Due to the yaw back into the relative wind, the outside wing travels faster than the inside wing and, as a result, more lift is generated by the outside wing. The yaw forces the nose of the airplane down as it swings into alignment with the relative wind. The net result is an overbanking and nose-down tendency which generally is considered less objectionable than Dutch roll.

As you can see, even a well-designed airplane may have some undesirable characteristics. Generally, designers attempt to minimize the Dutch roll tendency, since it is less tolerable than spiral instability. Because of this, many airplanes have some degree of spiral instability which generally is considered acceptable.

٣١. Longitudinal stability involves the motion of the airplane controlled by its

A. Rudder.
B. Elevator.
C. Ailerons.

٣٢. If the airplane attitude remains in a new position after the elevator control is pressed forward and released, the airplane display

A. Neutral longitudinal static stability.
B. Positive longitudinal static stability.
C. Neutral longitudinal dynamic stability.

٣٤. If an airplane is loaded to the rear of its CG range, it will tend to be unstable about it.

A. Vertical axis.
B. Lateral axis.
C. Longitudinal axis.

٥٣. An airplane said to be inherently stable will

A. Be difficult to stall.
B. Require less effort to control.
C. Not spin.

٥٨. Loading an airplane to the most aft CG will cause the airplane to be

A. less stable at all speeds.
B. less stable at slow speeds, but more stable at high speed.
C. less stable at high speeds, but more stable at low speeds.

DISCUSSION: Forward CG effects:
- More stable.
- Higher stall speed.
- Higher takeoff speed and longer ground roll.
- Reduced pitch authority.
- Slower cruise speed.

١٩٤. What flight characteristic could be expected when the CG of the airplane is located near the forward limit?

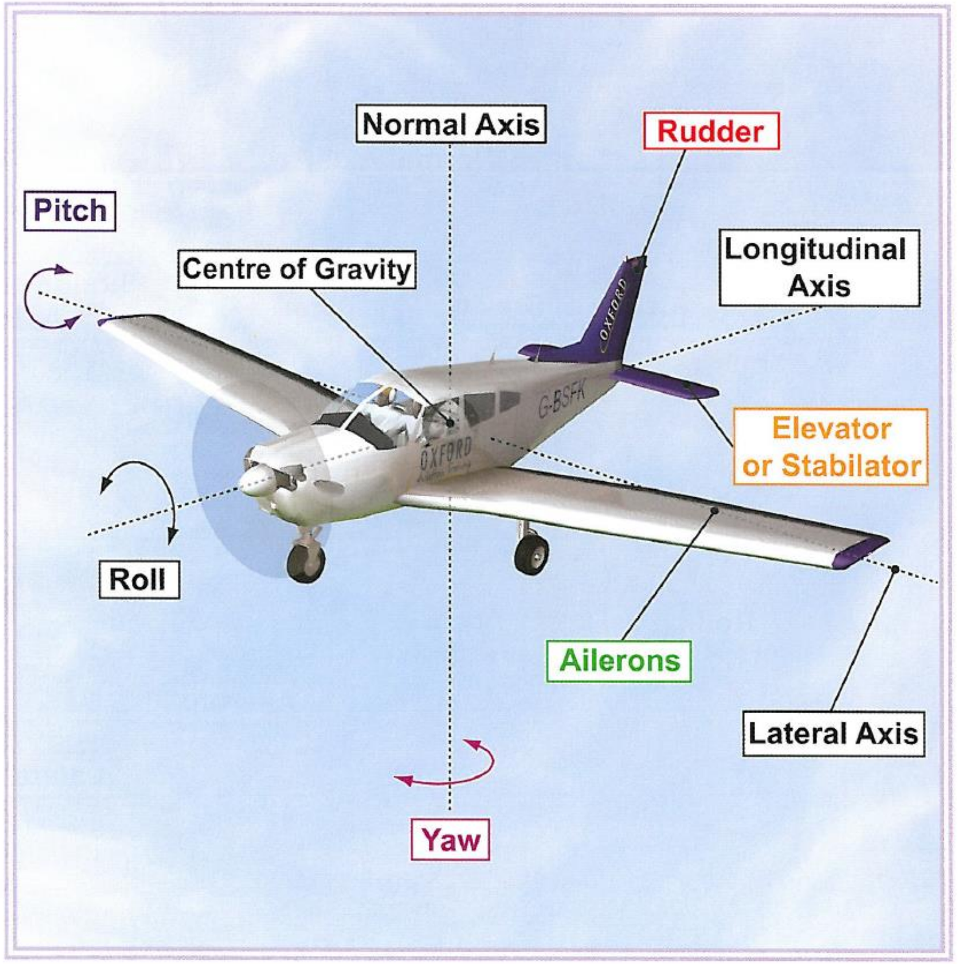
A. The airplane becomes more stable.
B. The airplane will have a lower takeoff speed and ground roll.
C. The airplane will have a lower stall speed.
D. The airplane performance is reduced due to decreased

١٩٥. What flight characteristic could be expected when the CG of the airplane is located at the aft limit?

A. The airplane will have a lower cruise speed for the power setting.
B. The airplane will become more stable.
C. Increased risk of stalls and spins.
D. The airplane will have a tendency to pitch-down due to the aft CG position.

DISCUSSION: - Increased risk of stall.
- Increased risk of spin that may be difficult or impossible to recover.
- Decreased stability.
- Higher cruise speed.

CHAPTER 12
FLIGHT CONTROLS AND TRIMMING



The Flying Control Surfaces and their Primary Effects.

An aircraft, generally possess three sets of **flying control surfaces**, each of which has an important **primary effect** on the movement of the aircraft about the respective axis.

- A **rudder** which controls the aircraft in **yaw**, about the **normal axis**. This type of control is called **directional control**.

- An **elevator** which controls the aircraft in **pitch**, about the **lateral axis**. This type of control is called **longitudinal control**.

- **Ailerons** which control the aircraft in **roll**, about the **longitudinal axis**. This type of control is called **lateral control**.

Movement in **yaw**, **pitch** and **roll** is generated by the deflection of the respective **control surface**: rudder, elevator or ailerons. The deflection of the control surfaces changes three characteristics of the aerofoil section: its **effective camber**, the orientation of its **mean chord line** and, thus its **angle of attack** with respect to the relative airflow.

The change in the aerofoil's **angle of attack** also modifies the **lift force** produced by that aerofoil, by varying the value of C_L, which, in turn, creates an **out of balance turning moment** about the aircraft's **C of G** which initiates a movement about the corresponding axis. *Figure 12.2* illustrates the principle of how the **mean chord line**, **angle of attack**, and **lift force** of a wing are modified through displacement of the **aileron**.

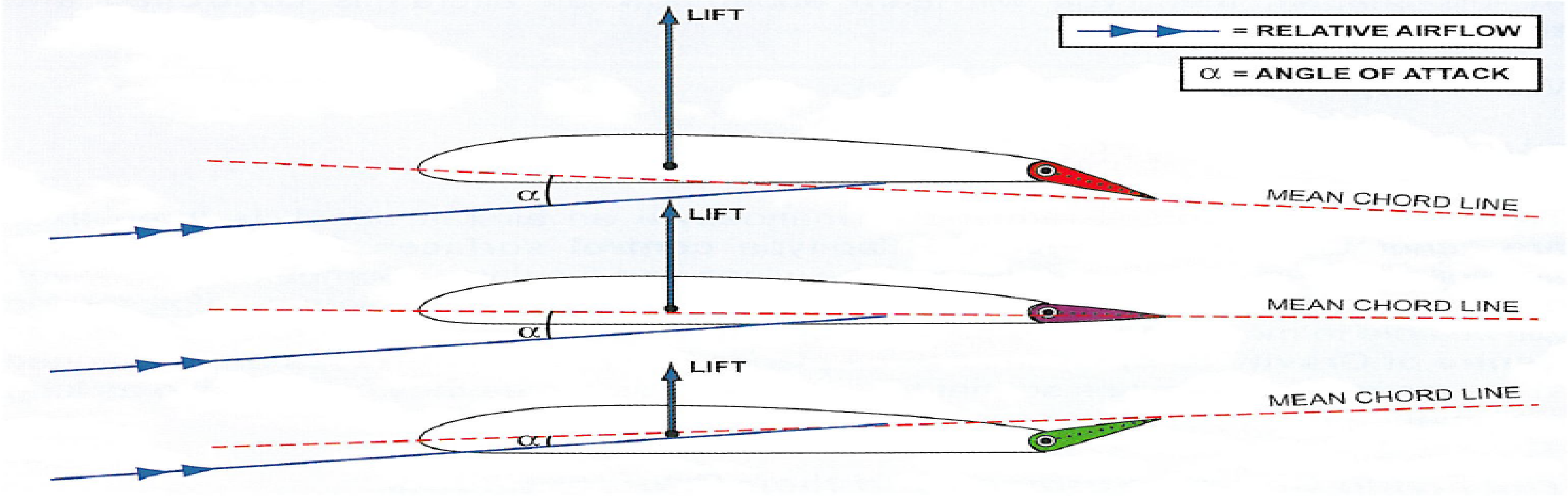


Figure 12.2 Displacement of a control surface modifies the aerodynamic force generated by the aerofoil. Here, aileron displacement is shown changing the lift force produced by a wing.

Figure 12.3 A stabilator or all-moving (flying) tailplane.

As we have mentioned, on some aircraft the complete aerofoil section can be displaced by the pilot to modify **angle of attack**. *Figure 12.3* illustrates this type of **horizontal control surface** in the tail assembly, on a PA28 Warrior. This type of control surface is called a **stabilator**, or, in older parlance, **an all-flying tailplane**.

THE FLYING CONTROL SURFACES.

Directional Control about the Normal Axis.

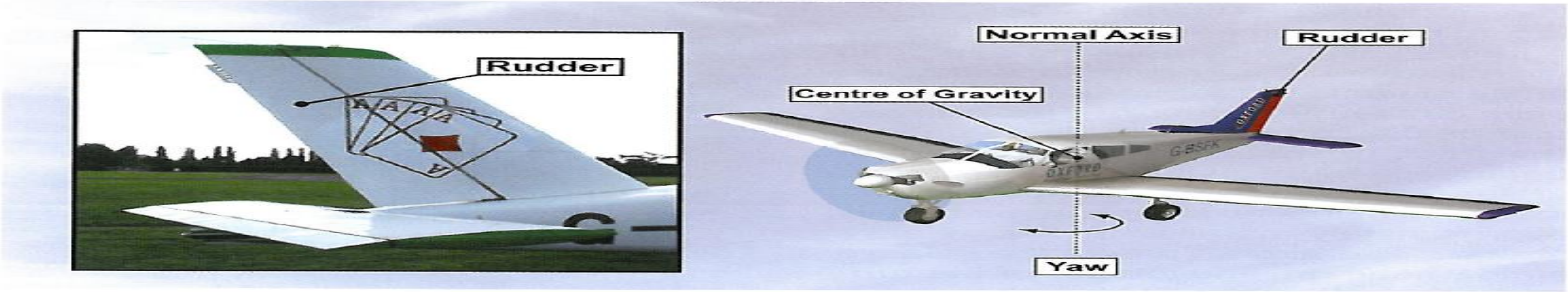


Figure 12.4 The rudder controls the aircraft in yaw, about its normal axis.

The **rudder** is a symmetrically-cambered, hinged aerofoil section, mechanically linked by cables and rods to the **rudder pedals**, which are operated by the pilot's feet. When the **rudder pedals** are central, the **rudder** itself is central. Pushing the right **rudder pedal** forward deflects the **rudder** to the **right**, generating an aerodynamic force which causes the aircraft to **yaw** to the **right** as in *Figure 12.5.*

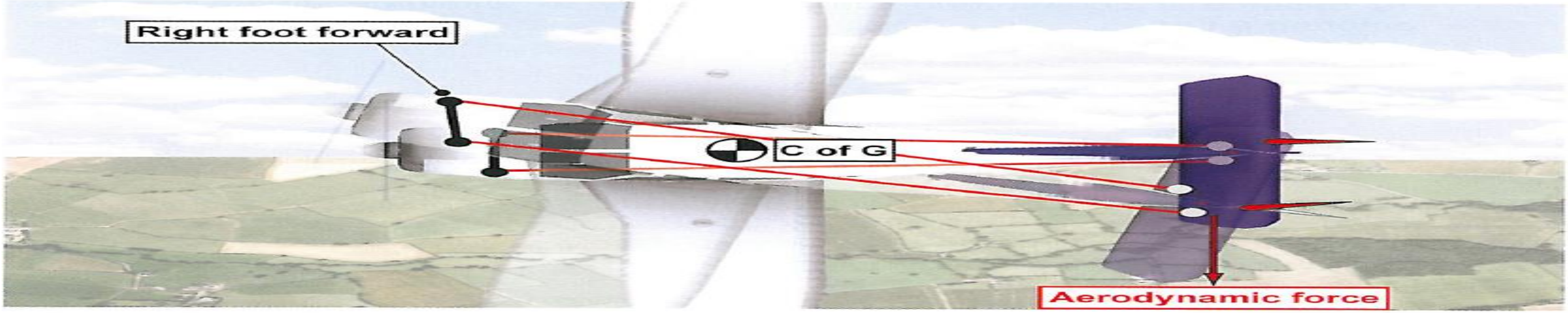


Figure 12.5 Pushing the right rudder pedal forward causes the aircraft to yaw to the right.

Balanced Flight.

You should note that although the rudder is said to give **directional control**, this latter expression can be very misleading. The rudder is <u>not</u> used to turn the aircraft and change direction. A turn is initiated by applying aileron in the direction of the turn to select an angle of bank, the rudder being used to balance the manoeuvre. **The primary use of the rudder, then, is to enable the pilot to maintain the aircraft in balanced flight**, whether in straight or turning flight. In **balanced flight**, the longitudinal axis of the aircraft is approximately parallel to the relative airflow. The aircraft meets the relative airflow head-on, and the ball of the **turn and slip indicator** will be in its central position, between the two vertical markers, as depicted in *Figure 12.6.*

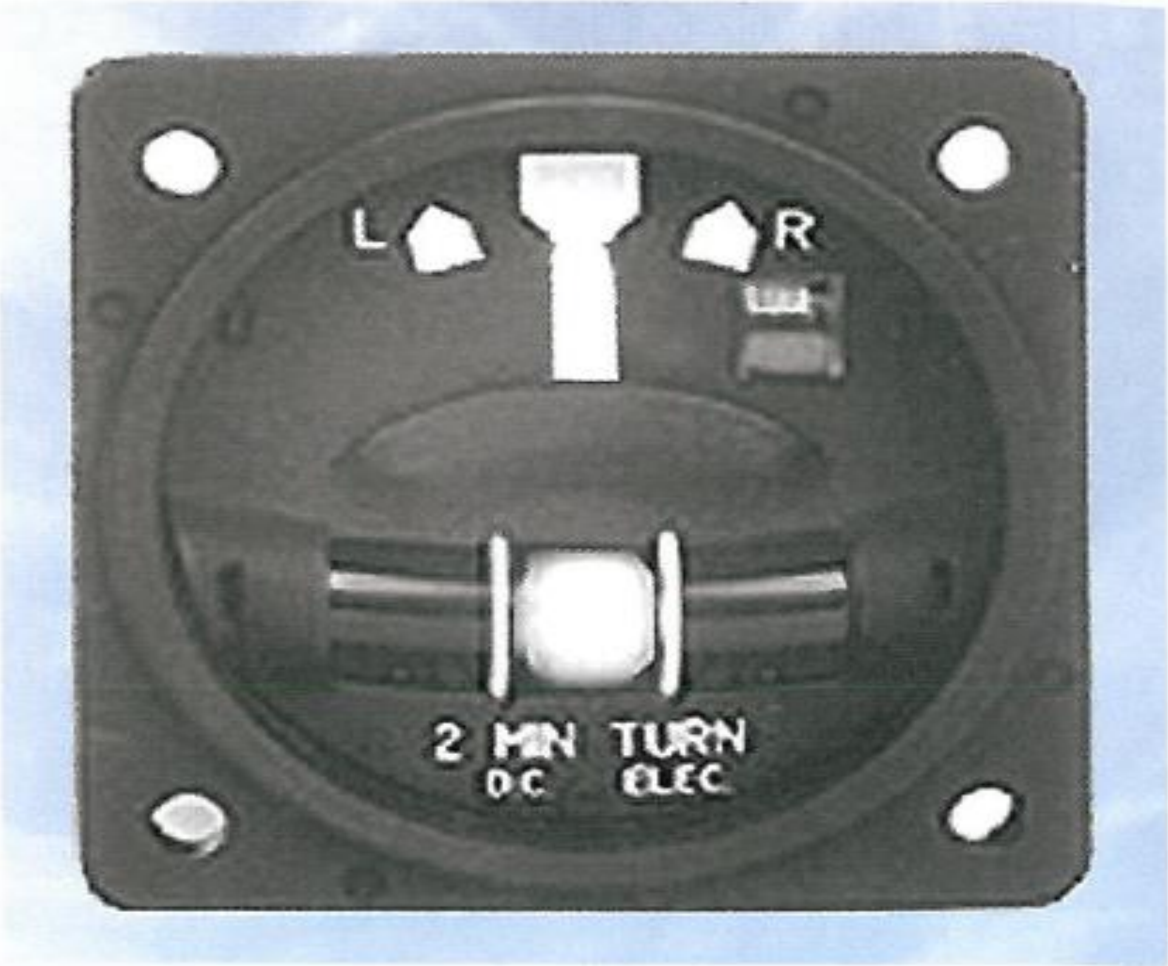


Figure 12.6 The rudder is primarily used to keep the aircraft in balanced flight with the ball "in the middle".

Other uses of the rudder include:

- The holding of a sideslip in specialist manoeuvres.
- To balance a coordinated turn, especially to eliminate adverse yaw on entering a turn.
- To steer the aircraft during taxying.
- In the recovery from a spin.
- To overcome asymmetric power effects in the event of engine failure on a multi-engined aircraft.

Longitudinal Control about the Lateral Axis (Pitch).

The **elevator** or **stabilator** (**all-flying tailplane**) gives the pilot **longitudinal control** in the **pitching plane** about the **lateral axis** *(See Figure 12.7)*.

Fore and aft movement of the control column or control wheel operate the **elevator** in such a way as to produce a **pitching movement** in the natural and logical sense.

If the pilot moves the **control column aft**, the **elevator** or **stabilator** is deflected **upwards**. This will generate an **aerodynamic force** acting **downwards** at the tailplane which will **pitch** the aircraft's nose up. Likewise, if the **control column is moved forward** an **aerodynamic force** is generated which will **pitch** the aircraft nose **downwards**.

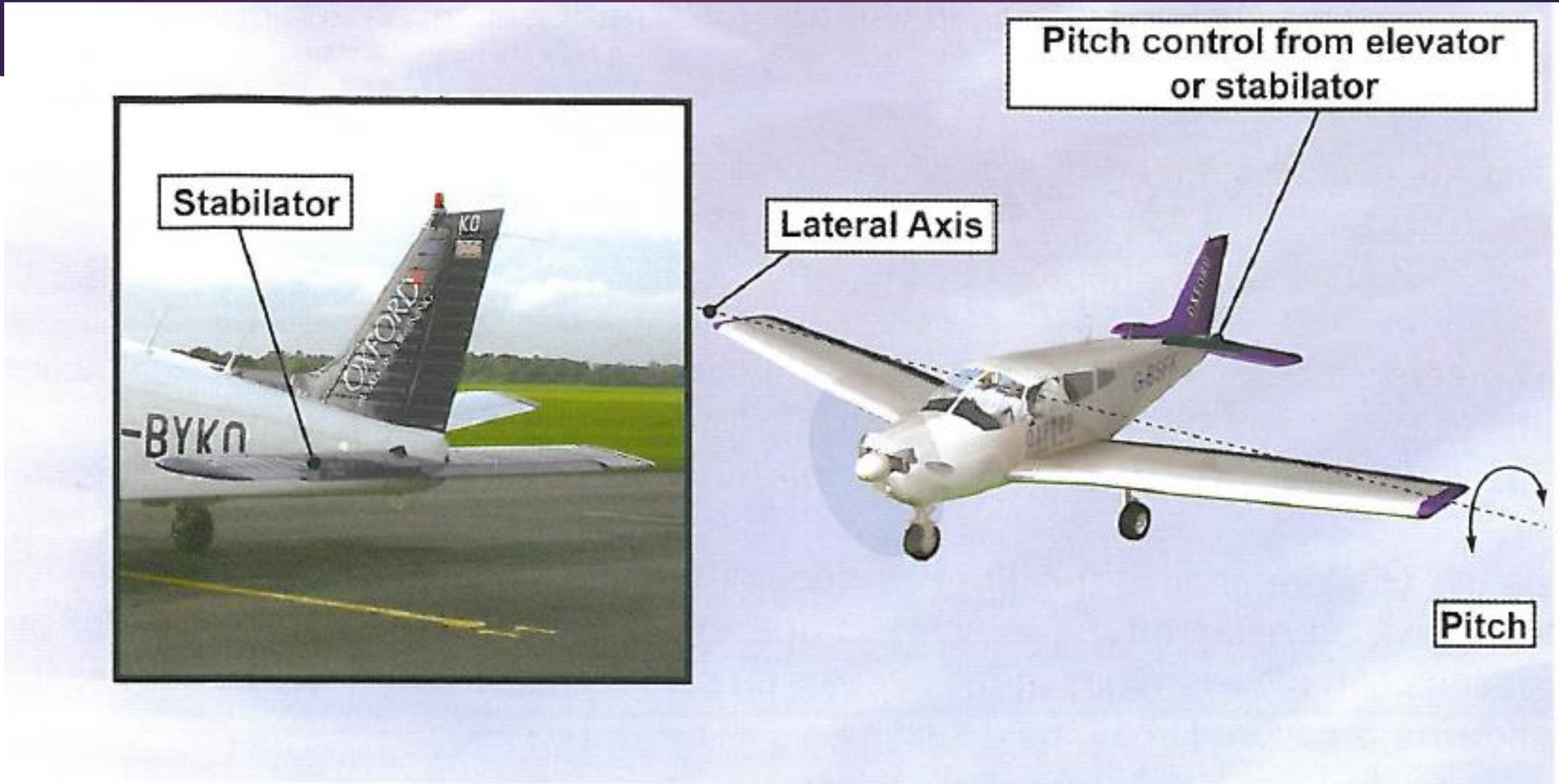


Figure 12.7 The elevator controls the aircraft in pitch.

Lateral Control about the Longitudinal Axis (Roll).

The **ailerons** give the pilot **lateral control** in the **rolling plane** about the **longitudinal axis**. The **ailerons** are located outboard at the trailing edge of each wing. Control of the **ailerons**, or **roll** control, is achieved by **lateral movements** of the control column or control wheel in the logical and instinctive sense.

To **roll** the aircraft to the **left** requires the **control wheel** to be **rotated anticlockwise** or the **control column to be moved to the left**. Movement of the **control column or control wheel** in the opposite sense will cause the aircraft to **roll** to the **right**.

Figure 12.8 Control in roll is achieved with the ailerons.

SECONDARY OR FURTHER EFFECT OF CONTROLS.

The **flying control surfaces** have both **primary** and **secondary effects**. You have just learnt about the primary effects of the controls; here, we deal with the **secondary effects**.

The Elevator.

There is no **secondary effect** of the **elevator** or **stabilator**, although a change in the aircraft's pitch attitude will induce a change of airspeed.

The Secondary Effect of Rudder.

In the chapter on Stability, you learned that an aircraft's rotation about its normal axis (yaw) and its longitudinal axis (roll) are not independent of each other.

A displacement in the yawing plane will always influence an aircraft's motion in the rolling plane and vice versa.

You have learnt that the **primary effect** of rudder is **yaw**. The **secondary effect** of rudder is **roll in the direction of yaw**.

The secondary effect of rudder, then, is roll in the direction of the initial yaw.

The Secondary Effect of Aileron.

You have learnt that the **primary effect** of **aileron** is **roll**. The **secondary effect** of **aileron** is **yaw** in the direction of **roll**.

If a pilot selects an angle of bank, to the left, say, without making any further control movements, the aircraft will respond by **rolling** to the left, about the **longitudinal axis**. The aircraft, then, will enter a **slip** to the left, towards the lower wing and the side component of the relative airflow will, consequently, strike the aircraft's keel surfaces. Because the keel surface area behind the **C of G** is greater than the area of the keel surfaces forward of the **C of G**, the aircraft will **yaw** in the direction of the lower wing. For the reasons given above, the **yaw** will induce further **roll**, which will lead to further **yaw** and so on, until the aircraft enters a **spiral dive** to the left, if the pilot does not intervene.

The secondary effect of aileron, then, is yaw in the direction of the initial roll.

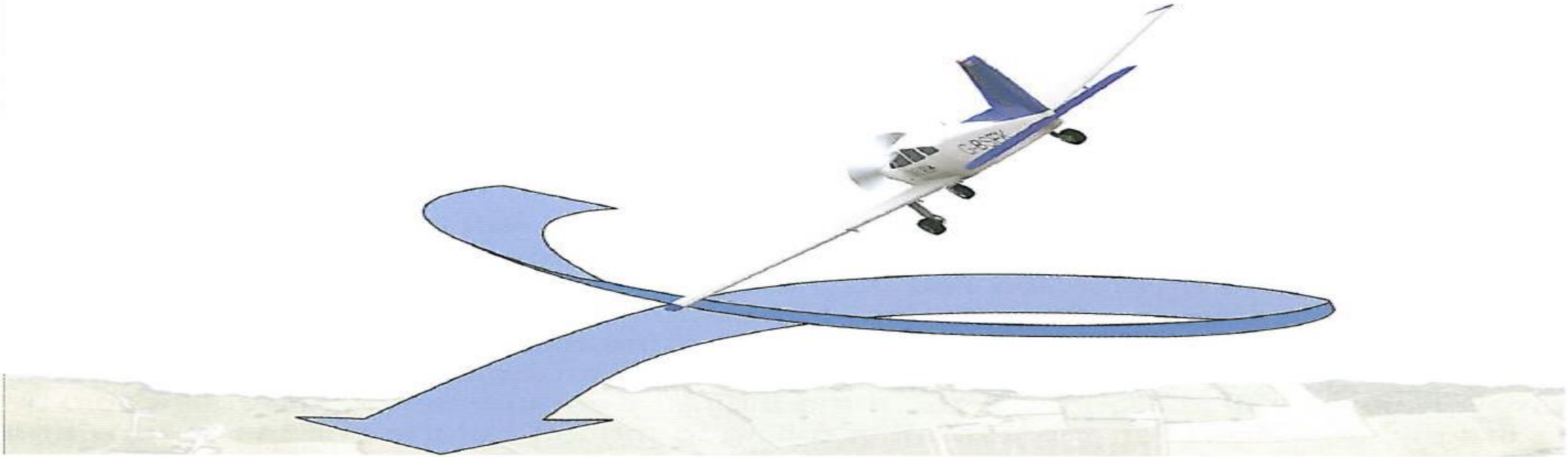


Figure 12.9 The secondary effects of both rudder and ailerons induce rolling and yawing actions, in the same direction, which mutually reinforce each other and lead to a spiral dive.

THE EFFECT OF AIRSPEED ON THE EFFECTIVENESS OF THE FLYING CONTROL SURFACES.

We have already mentioned that the **effectiveness** of the **flying control surfaces increases** with increasing **airspeed**. In this section, we look a little more closely at this aspect of control.

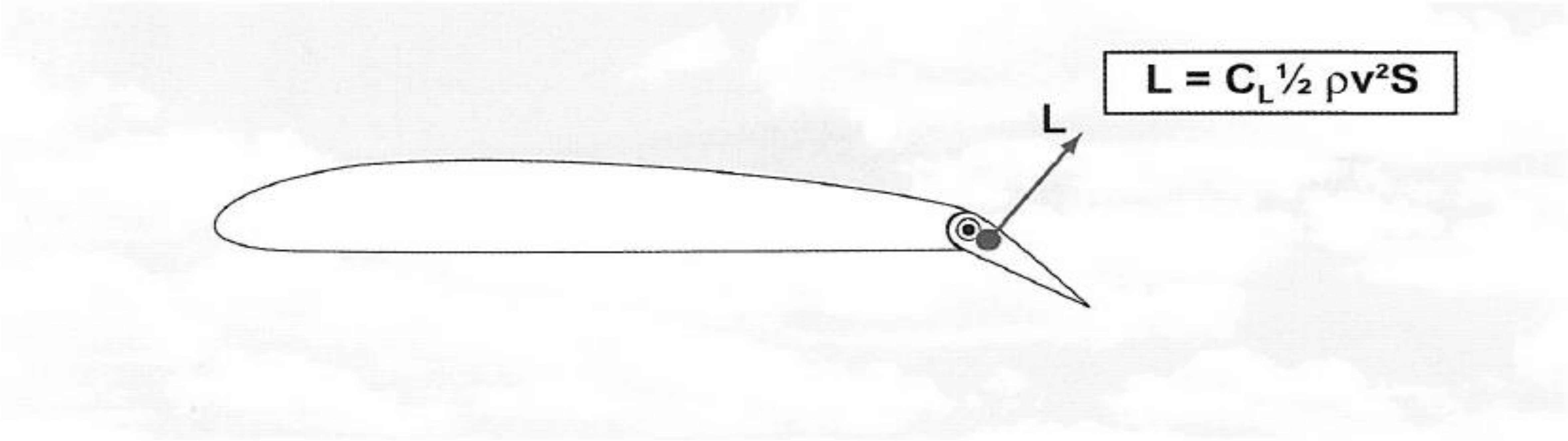


Figure 12.18 The increased effectiveness of a control surface is proportional to the square of the airspeed.

THE EFFECT OF PROPELLER SLIPSTREAM ON CONTROLS.

An aircraft on the approach to land, as in *Figure 12.19*, will be flying at relatively low airspeed. It follows, then, that the effectiveness of the controls would normally be reduced compared to cruising flight. But, with flaps deployed and undercarriage lowered, drag will be high requiring appropriately high levels of **thrust** in order to maintain airspeed. The resulting **propeller slipstream** over the tail will help, therefore, to maintain the effectiveness of the rudder and elevator by energising the airflow across those control surfaces. But the ailerons, which are outside the **slipstream**, will not derive this benefit and, so, will be less effective on the approach than in cruising flight.

Figure 12.19 Only the rudder and elevator benefit from the propeller slipstream effect.

Great care, should, therefore, be exercised by the pilot to retain control over the aircraft in roll, when landing in gusty or cross-wind conditions.

AERODYNAMIC BALANCING.

Although the forces required from the pilot to move the controls of a light aircraft are generally small, the continuous effort to hold, say, a given pitch altitude can become tiring on a long flight at high cruise speeds, particularly in conditions of persistent turbulence. For this reason, flying control surfaces are often **balanced aerodynamically**. **Aerodynamic balancing** is the most common and simplest form of **balance** on light aircraft. **Aerodynamic balancing** involves using the aerodynamic forces generated by the control surface, itself, and can be achieved without reducing control effectiveness.

The Inset Hinge.

One method of **aerodynamic balancing** is the **inset hinge**. *Figure 12.20* on Page 269 represents the **normal hinge** located near to the leading edge of the control, creating a **large hinge moment**. In *Figure 12.24*, however, the control surface **hinge** has been moved aft closer to the centre of pressure of the control surface so that the **hinge moment** is reduced. In addition, the airflow strikes the control surface in front of the **hinge** at $\mathbf{F_1}$, providing a turning moment which further reduces the **hinge moment**. This arrangement helps the pilot to move the controls by reducing the required stick force.

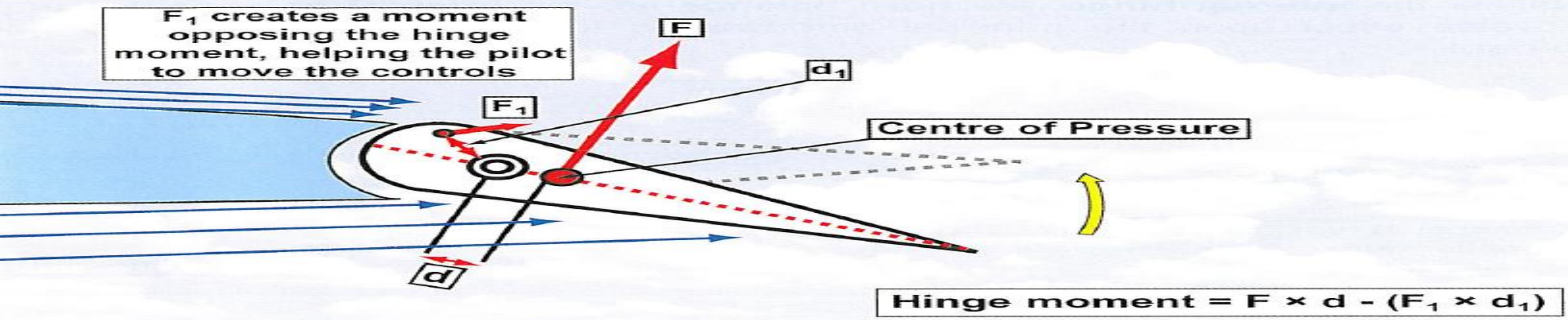


Figure 12.24 The inset hinge, produces a smaller hinge moment than the normal hinge.

The Horn Balance.

Similar in operation to the inset hinge is the **horn balance**, shown in *Figure 12.25*. The **horn** is the part of the flying control surface located forward of the **hinge**. In flight, when the control surface is displaced, aerodynamic forces will be generated both forward and aft of the **hinge** line. The moment generated by the aerodynamic force forward of the hinge counters the main control surface **hinge moment**, and assists the pilot to move the control surface. A disadvantage of the **horn balance** is that it produces an increase in overall drag.

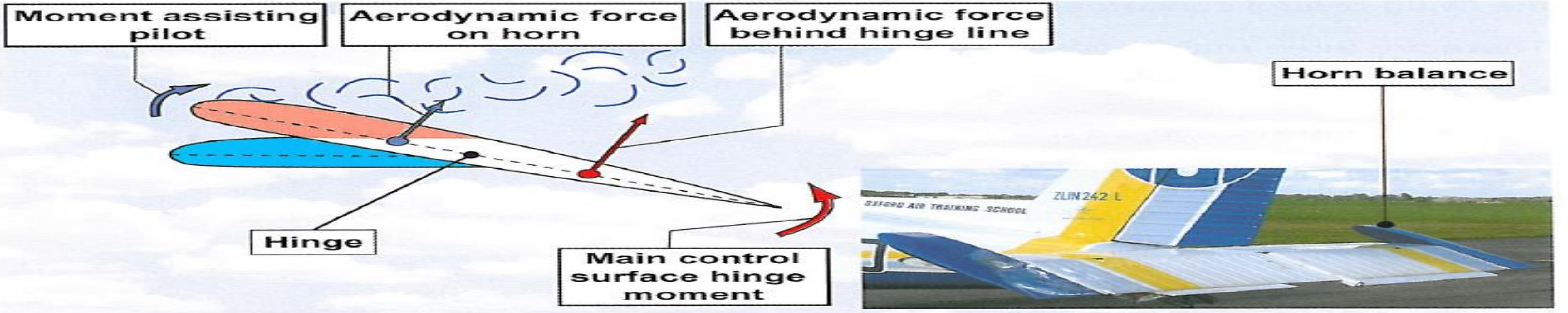


Figure 12.25 A horn balance system on a Zlin.

The Internal Balance.

The same principle as the horn balance is employed, without leading to an increase in drag, in the **internal balance**. The **internal balance** mechanism is enclosed inside the rear of the main aerofoil section, as depicted in *Figure 12.26*. The **internal balance** takes the form of a chamber which senses the same changes in pressure as those produced by the deflection of the control surface, itself. The pressure differential inside the chamber produces **moment** in opposition to the **hinge moment**.

Neither the **internal hinge**, the **horn balance** nor the **internal balance** has any adverse effect upon the principal aerodynamic force produced at the control surface.

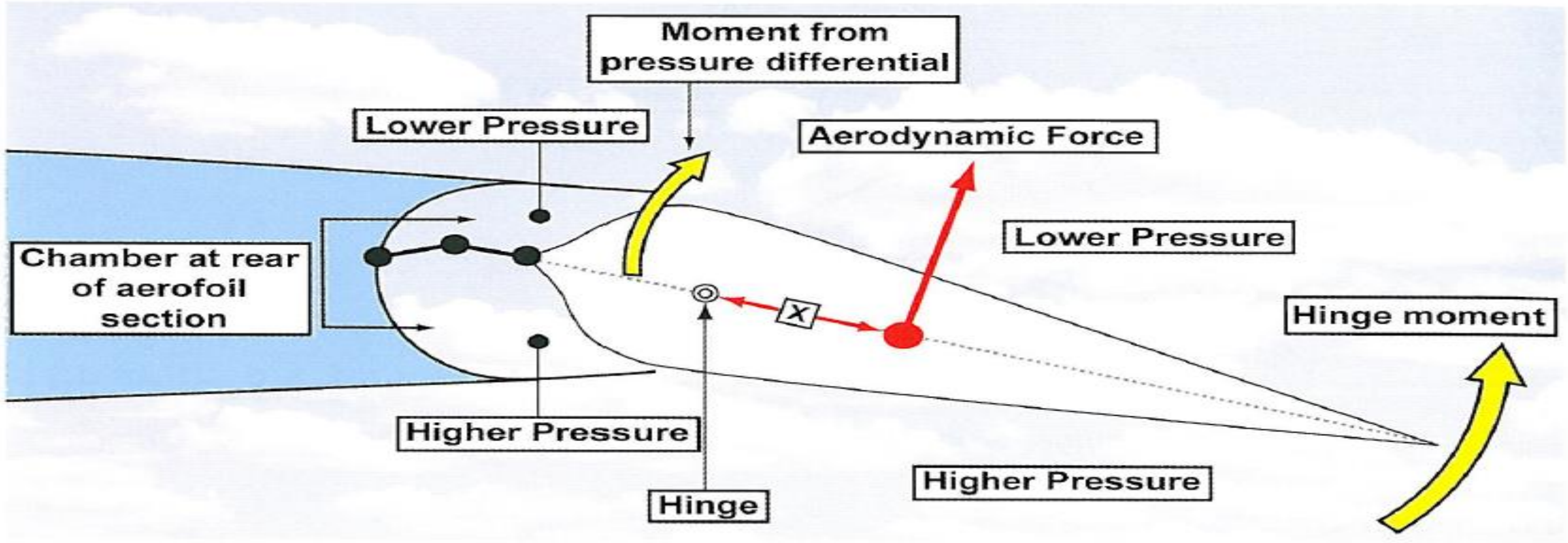


Figure 12.26 The Internal Balance.

TRAILING-EDGE TABS.

The **stick force** required from the pilot to move the flying control surfaces can also be reduced by small aerofoil tabs, known as **trailing-edge tabs**, positioned at the rear of the control surface. Trailing-edge tabs do, however, alter the effectiveness of the flying control concerned.

There are three main types of **trailing-edge tab** device. They are:

- the **balance tab**.
- the **anti-balance tab**.
- the **servo tab**.

The Balance Tab.

The **balance tab** aids the pilot in moving the control surface. With the **balance tab** system, the pilot has no direct control over tab movement. Input to the main flying control is transmitted to a linkage which moves the **balance tab** in the opposite direction to the flying control surface, as depicted in *Figure 12.28*.

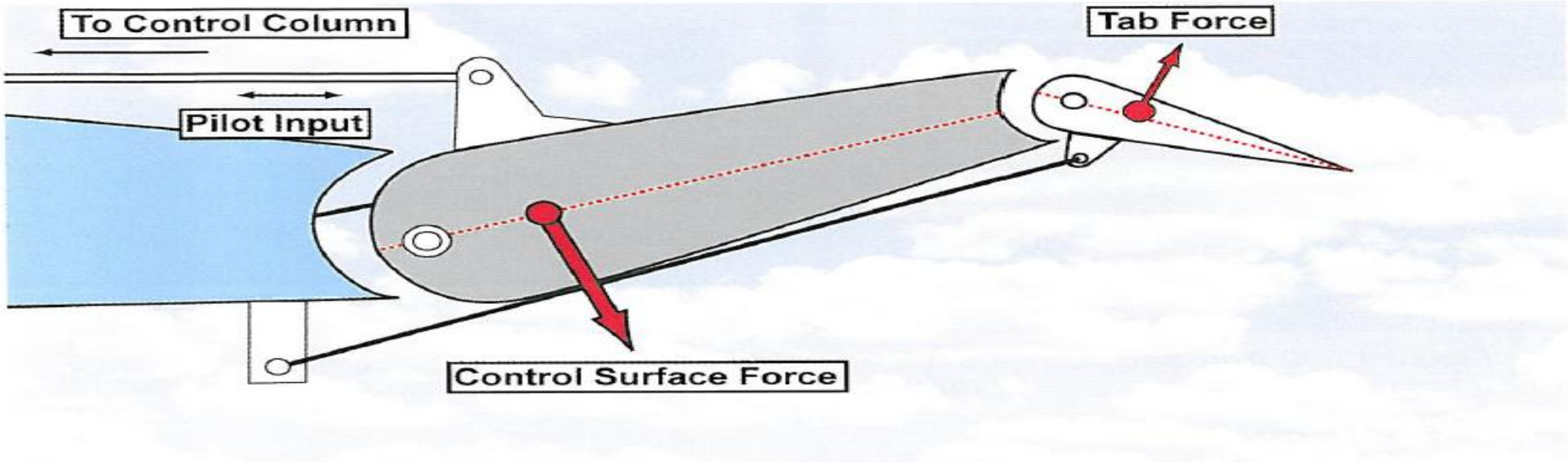


Figure 12.28 A balance tab. The balance tab aids the pilot in moving the control surface.

The pilot moves the control surface through a control rod and, in turn, the control surface movement actuates the **balance tab** movement. The **balance tab** generates a force in the opposite direction to that generated by the main flying control surface. The **balance tab** force reduces the control surface **hinge moment** and, thereby, the stick force required from the pilot. The **balance tab** does, however, cause a slight reduction in control effectiveness.

The Anti-Balance Tab.

Anti-balance tabs increase the stick force required from the pilot in order to provide him with "**feel**". Aircraft fitted with large elevators, and especially aircraft fitted with all-flying tailplanes, are capable of producing very significant aerodynamic forces as a result of their large surface area and their principle of operation. The danger exists, therefore, especially at high speed, that the pilot may over-control and, consequently, over-stress the aircraft. It is, therefore, desirable to increase the stick force and provide the pilot with "**feel**". This objective is achieved by the **anti-balance tab**. *(See Figure 12.29.)* The **anti-balance tab** operates in the <u>same</u> direction as the flying control surface and, thus, increases the stick force required to displace the control surface. This arrangement increases the effectiveness of the control surface itself.

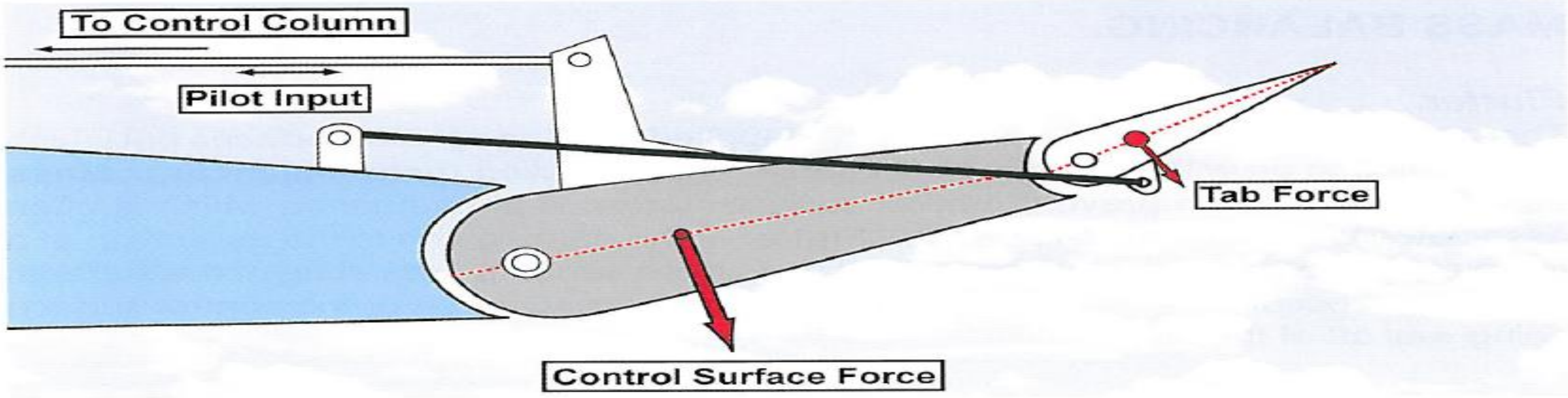


Figure 12.29 The anti-balance tab moves in the same direction as the control surface to increase stick force and provide the pilot with "feel".

Figure 12.30 **Anti-balance** tabs are most commonly found on aircraft with **all-flying tailplanes** or **stabilators**.

The Servo Tab.

The mechanism of the **servo tab** differs from the other types of tabs in that the pilot's control input is to the **servo tab** and not to the flying control surface. Movement of the **servo tab** creates an aerodynamic force which moves the main flying control surface. For instance, if the pilot selects a nose-up pitch attitude, his input to the control column moves the **servo tab** downwards which, in turn, generates an aerodynamic force which displaces the main flying control upwards.

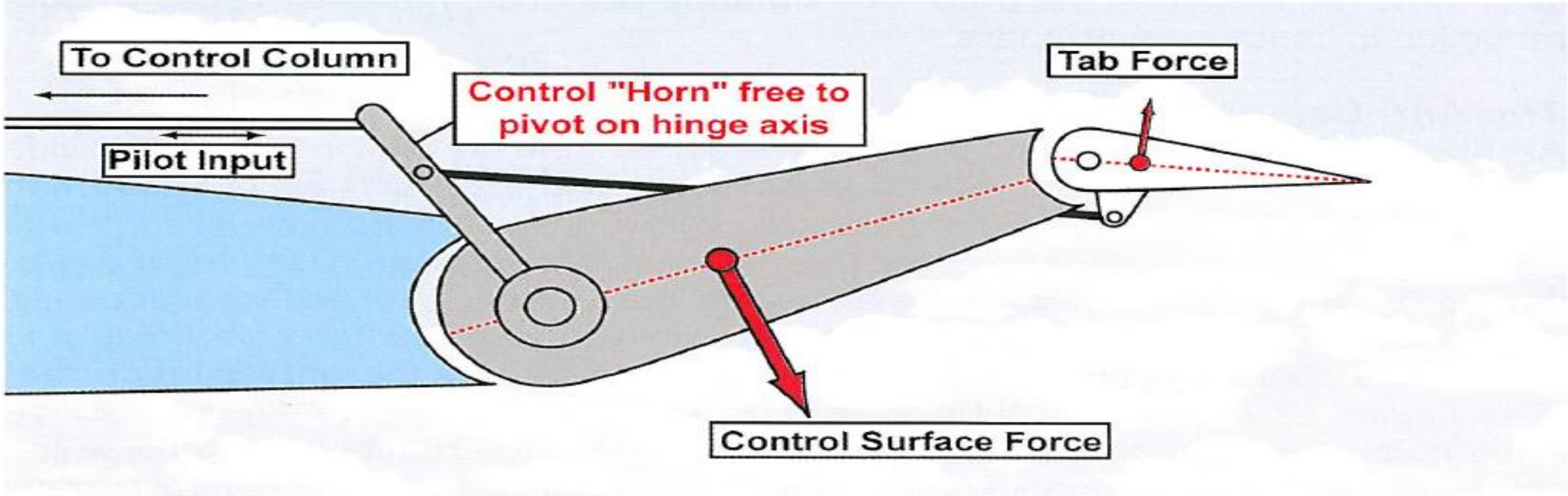


Figure 12.31 The servo tab provides the force which displaces the flying control surface.

MASS BALANCING.

Flutter.

There is one method of balancing which is applied to flying control surfaces but which has nothing to do with alleviating stick force. This is called **mass balancing**. **Mass balancing** is used to prevent control surface **flutter**, a phenomenon which is often associated with high aircraft speeds. **Flutter** is the name given to the oscillation of a flying control surface at high speed, and can cause bending or twisting of the surface. **Flutter** can occur as a result of the **centre of gravity (C of G)** of the control surface being well aft of the hinge.

Figure 12.34 The mass balance fitted to the ailerons of a Zlin.

TRIMMING.

Introduction.

An aircraft is said to be **trimmed,** or **in trim,** when it is able to maintain its selected attitude without the pilot applying any force to the control column.

When an aircraft is **in trim,** the stick force is zero. Flying **in trim**, therefore, means that the pilot is less susceptible to fatigue and is also free to attend to other required tasks, such as navigation.

Your very first flying lesson will have made you aware of the varying magnitude of the force that you have to apply to the control wheel and rudder pedals in order to select and maintain an attitude, other than the attitude for which the aircraft is trimmed. The design of an aircraft is such that, in still air, at a given airspeed, power setting and configuration, the aircraft will be **trimmed** to adopt **one attitude only**. If the pilot changes power-setting or aircraft configuration (by selecting flap, for instance), or selects and maintains any other attitude, he has, once again, to apply a force to the controls to hold the attitude.

But by using the aircraft's **trimming control system** the pilot can **trim out** the need to apply a force to the control wheel to maintain the new attitude.

Most simple light aircraft can be **trimmed**, in flight, to remove stick force in the pitching plane only **(elevator trim)**, though **directional trim (rudder trim)** is fitted to some light aircraft.

The three most common methods of **trimming** a light aircraft are:

- The fixed **trim tab**.
- The adjustable **trim tab**.
- Spring-bias **trimming**.

Fixed Trim Tabs.

The most basic method of achieving trimmed flight is with a **fixed trim tab**. The **fixed trim tab** is a narrow metal plate attached to the trailing edge of a control surface, usually the aileron *(See Figure 12.35)*.

Fixed trim tabs are generally found on low performance aircraft, only. You should note that there can be only one speed, normally the cruise speed, at which the **fixed trim tab** will hold the aircraft in trim.

The Adjustable Trim Tab.

The greatest changes in stick force with speed tend to occur in **pitch**. The elevator or stabilator is, therefore, invariably fitted with **trim tabs** which can be adjusted in flight. A typical **adjustable elevator trim tab** is shown in *Figure 12.36*.

Figure 12.36 An adjustable trim tab fitted to the elevator of a Cessna.

If, for instance, a pilot were to ease back on the control column to raise the nose of the aircraft *(See Figure 12.37)*.and wished to maintain this new attitude, he would have to continue to apply a **rearwards force** to the control column, unless he **re-trims** the aircraft.

In order to remove the **stick force**, the pilot must **re-trim** the aircraft for the higher nose attitude. The trimming system is so designed that the pilot moves the cockpit trim controls in the instinctive sense: rearwards to trim for a nose-high altitude, and forwards to trim for a lower nose altitude *(See Figure 12.38)*.

Figure 12.38 Two methods of pilot trim control.

In this case, by moving his cockpit trim control rearwards, the pilot causes the adjustable **trim tab** to move in the opposite direction to the direction of elevator displacement *(See Figure 12.39)*, thus creating a balancing force which holds the elevator in its new position and maintains the new nose-high altitude, without the pilot having to apply any further force to the control column.

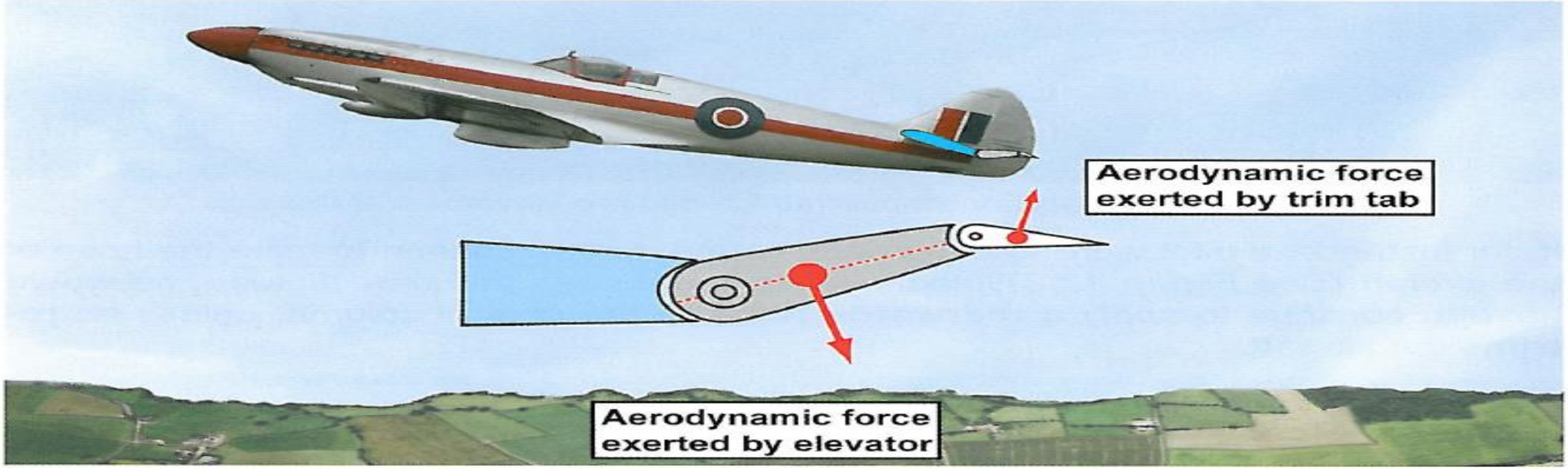


Figure 12.39 The balancing aerodynamic force from the trim tab holds the elevator in the new position. The aircraft is now trimmed for the new nose-high altitude.

Once the aircraft has been trimmed for a given flight attitude, the position of the simple trim tab relative to the control surface will remain fixed, whatever the subsequent displacement of the control surface. However, some **adjustable trim tabs** also serve as **balance tabs**, in which case the **adjustable trim tab** will move about the mean trimmed position as the control surface moves.

Disadvantages of Trim Tabs.

There are three principal disadvantages to using a tab type control to trim an aircraft. Firstly, there is a slight reduction in control effectiveness due to the tab force being in opposition to the force generated by the main flying control surface. Secondly, the deflection of the tab will increase drag. Thirdly, **trim tabs** can reduce the effective range of the control surface.

The Spring Bias Trimming System.

The **spring bias trimming system** works on the principle of an adjustable spring force opposing and, thus, decreasing the stick force applied by the pilot. **Spring bias trimming** has none of the disadvantages associated with the **trim tab system**.

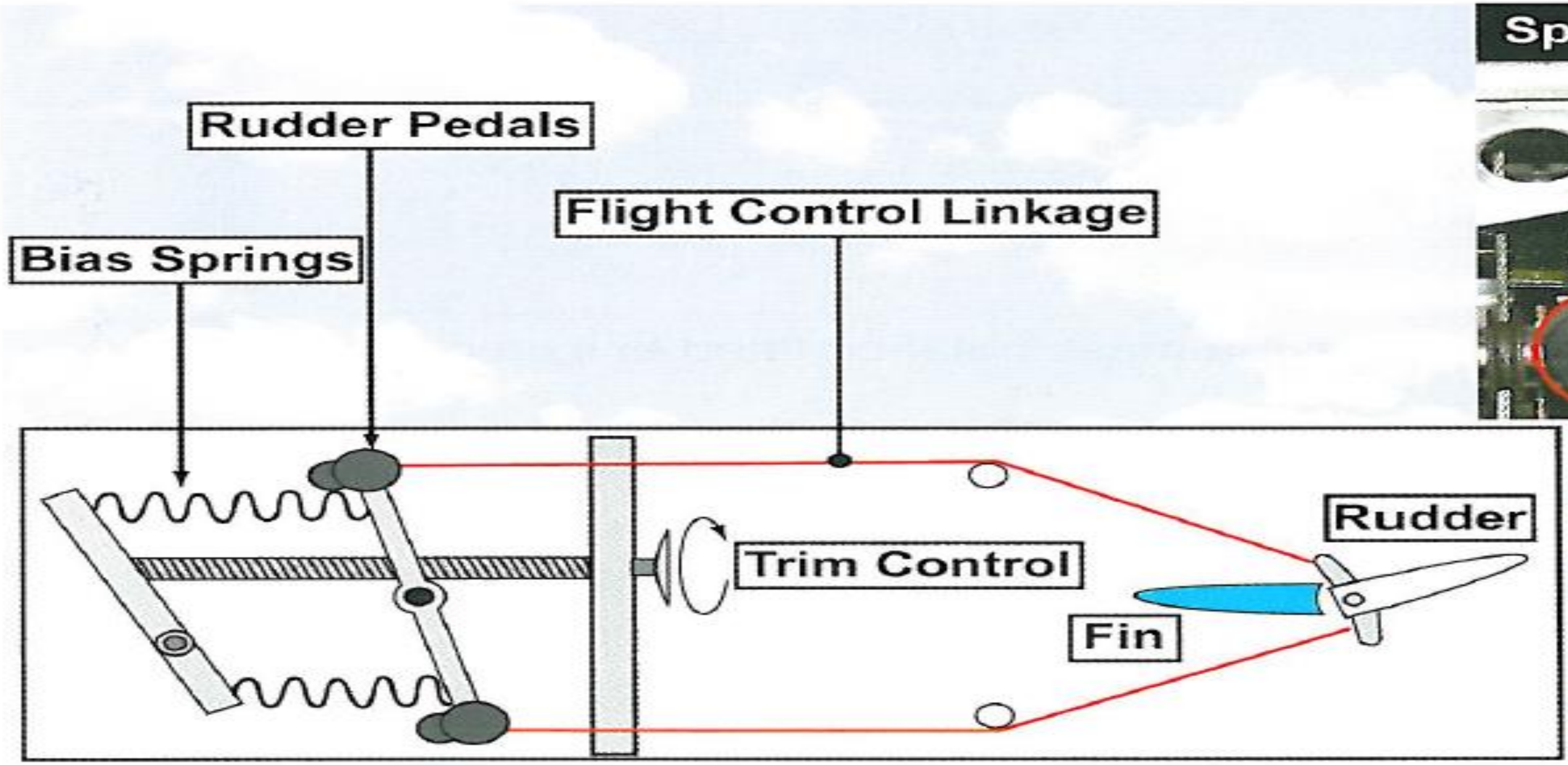


Figure 12.40 The spring bias system.

The **spring bias system** differs from the **trim tab system** in that the trim control system is not linked to the flying control surface but to the associated control linkage. As illustrated in *Figure 12.40*, in the **spring bias system**, the trim control applies a force to the control linkage, to remove **stick force**.

The Variable Incidence Tailplane.

A further method of achieving trim in pitch is the **variable incidence tailplane**. This system, because it adjusts the angle of incidence of the complete tailplane, is very powerful and has the ability to trim for large changes in speed, aircraft configuration and centre of gravity position, while keeping trim drag to a minimum.

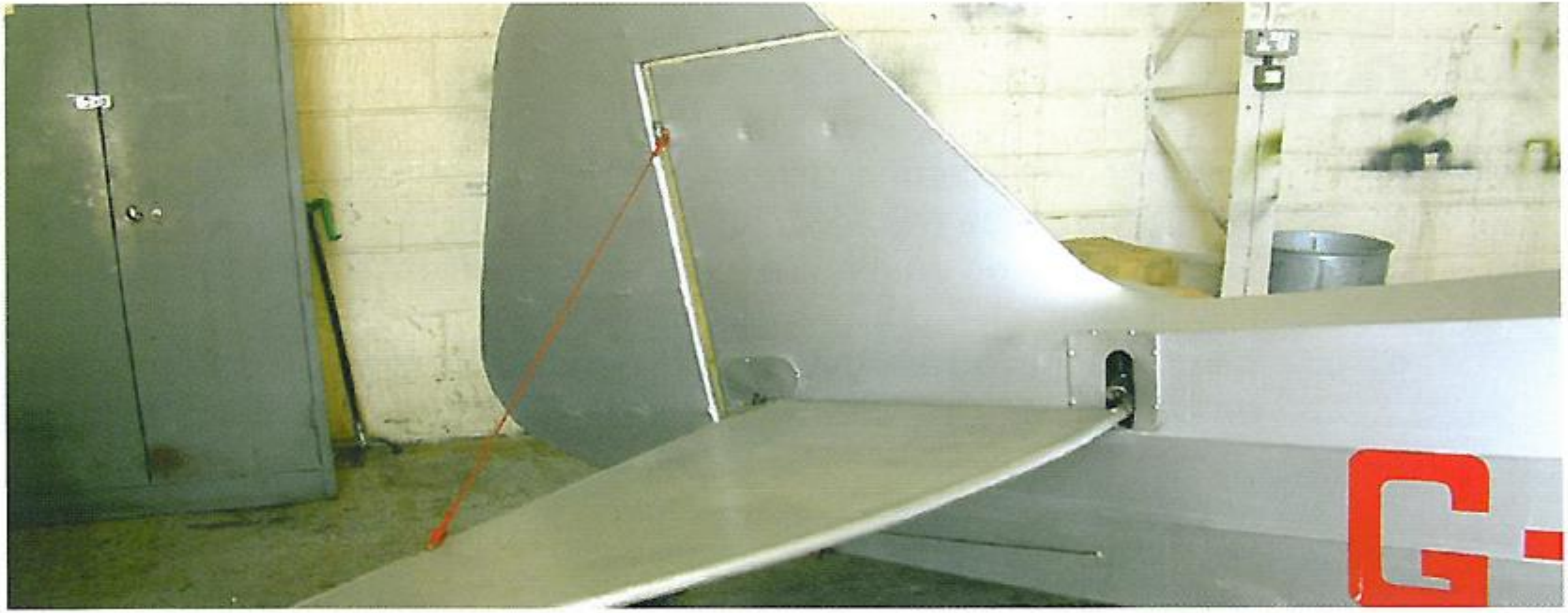


Figure 12.41 A variable incidence tailplane.

CHAPTER 13
THE STALL AND SPIN

STALLING.

The Stalling Angle of Attack.
You learnt in the chapter on **Lift**, that the **coefficient of lift**, C_L, increases with increasing angle of attack, until C_L reaches a maximum, at about **16° angle of attack** for the type of wing used on most light aircraft. Above this angle, C_L decreases sharply. This situation is illustrated by the red C_L line in the graph at *Figure 13.1*.

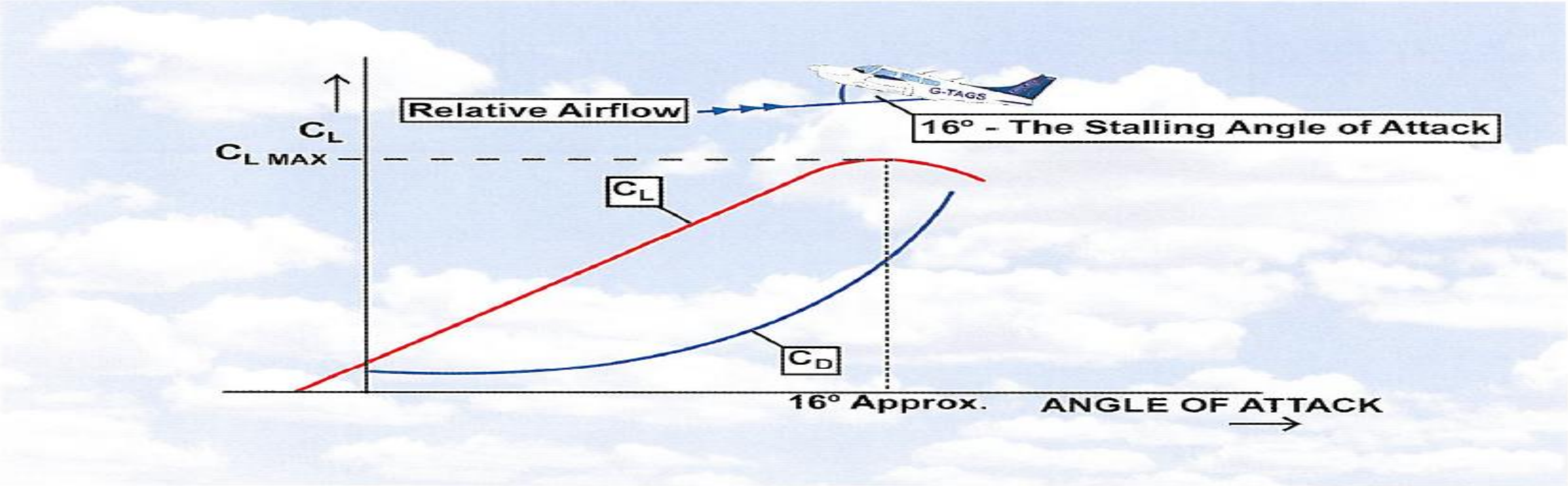


Figure 13.1 At the stalling angle of attack, C_L decreases sharply but C_D carries on increasing.

As the lift force developed by a wing is directly proportional to $\mathbf{C_L}$, (**Lift =** $\mathbf{C_L \frac{1}{2} \rho v^2 S}$), we can see from *Figure 13.1* that, whereas for small angles of attack any increases in angle of attack will produce an increase in lift force, when a certain angle is reached (16° in the diagram), any further increase in angle of attack will result in a reduction in the lift force. This angle is called the **stalling angle of attack.** (Note that *Figure 13.1* shows that the **coefficient of drag**, $\mathbf{C_D}$, **continues to rise**, beyond the **stalling angle of attack**.)

It is important to realise that the speed at which a wing is moving through the air makes no difference to the angle of attack at which the wing stalls. An aerofoil stalls at a given angle of attack, not at a given speed.

The Straight Flight Stalling Speed.

In straight flight, the stall occurs at an indicated airspeed which is defined in the Pilot's Operating Handbook (POH) as the **stalling speed**. But we have just established that a wing stalls at a given angle of attack, not at a given airspeed. So what is meant by the stalling speed contained in the POH?

In order to answer this question, we will assume that an aircraft whose wing stalls at an **angle of attack** of 16° is flying straight and level at 90 knots, with the relative airflow meeting the wing at a typical cruising angle of attack of 4°. As the aircraft is in straight flight, the lift produced by the wings balances the aircraft's weight exactly. Now, you will recall from the **lift formula**, $\mathbf{Lift = C_L \tfrac{1}{2} \rho v^2 S}$, that the factors contributing to the generation of this lift force, which just balances the aircraft's weight, are: the density of the air, ρ, the area of the lifting surfaces, **S**, the aircraft's airspeed, **v**, and the coefficient of lift, $\mathbf{C_L}$, which represents wing camber and configuration, as well as angle of attack.

FACTORS AFFECTING THE STALL.

The Effect of Weight on the Stall.

We have established that a given wing will always stall at the same **angle of attack**, which is approximately **16°** for a typical light aircraft aerofoil cross section. The **stalling angle of attack** can be defined as that **angle of attack** at which the **lift coefficient**, C_L, reaches a maximum, and beyond which C_L will decrease sharply. We may represent this maximum value of C_L at the point of the stall as $C_{L\,MAX}$. *(See Figure 13.1).*

$$\text{Weight} = \text{Lift} = C_{L\,MAX}\,\tfrac{1}{2}\,\rho\,(v_{stall})^2\,S$$

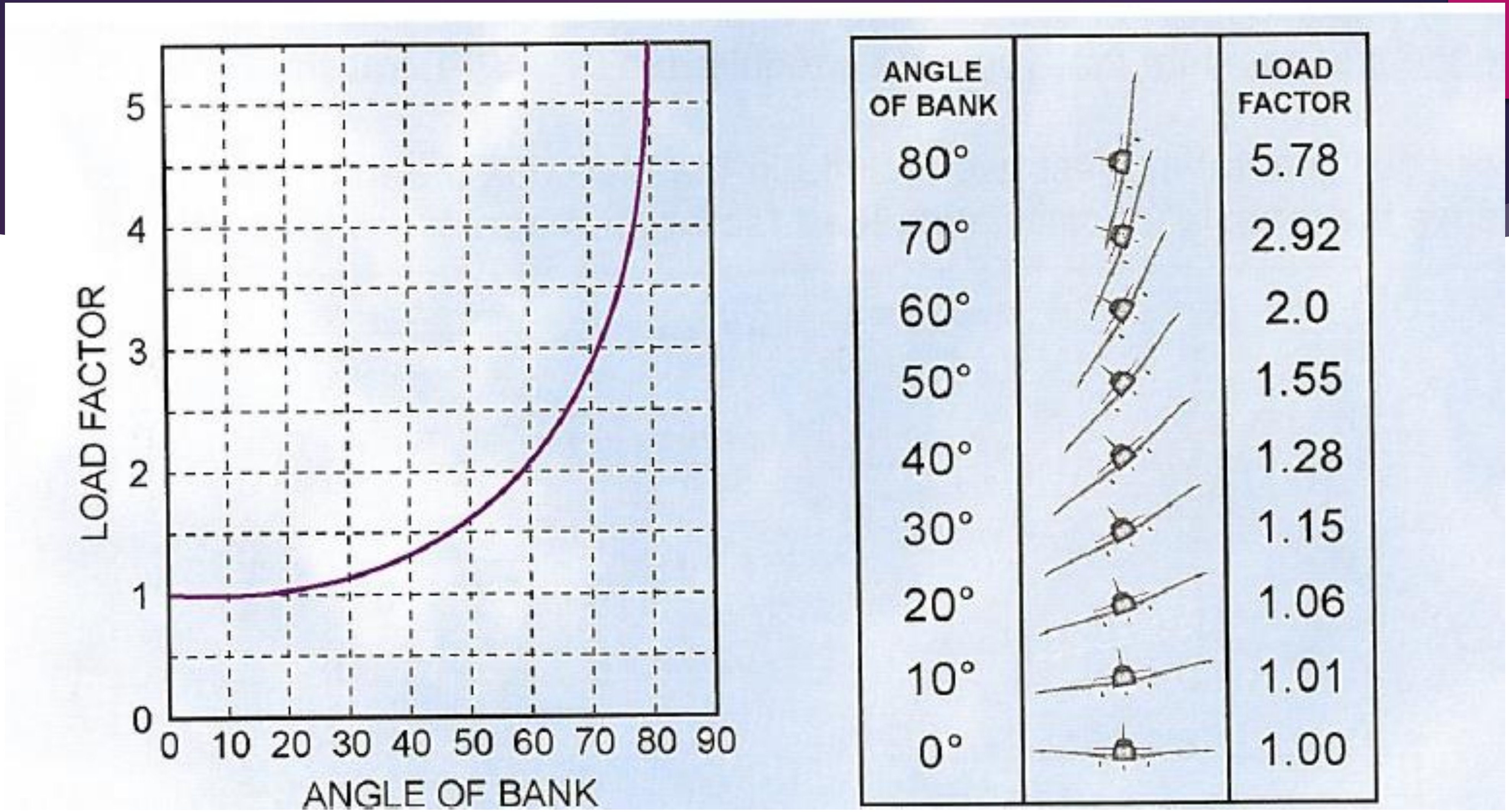
It follows, then, from the lift equation, that a heavier aircraft will stall at a higher airspeed than a more lightly loaded aircraft.

Manoeuvring with Varying Load Factors.

We have seen that the **lift equation** applied to the point of stall, from straight and level flight, can be written as:

Weight = Lift = $\mathbf{C_{L\,MAX}\,\frac{1}{2}\,\rho\,(v_{stall})^2\,S}$ where $\mathbf{v_{stall}}$ is the aircraft's straight and level stall speed.

But, as you learnt in the chapter on '**Flight Forces**', in manoeuvres such as turning flight, lift needs to be greater than the weight of the aircraft.



$$V_{stall(m)} = V_{stall(SF)} \times \sqrt{\text{Load Factor}}$$

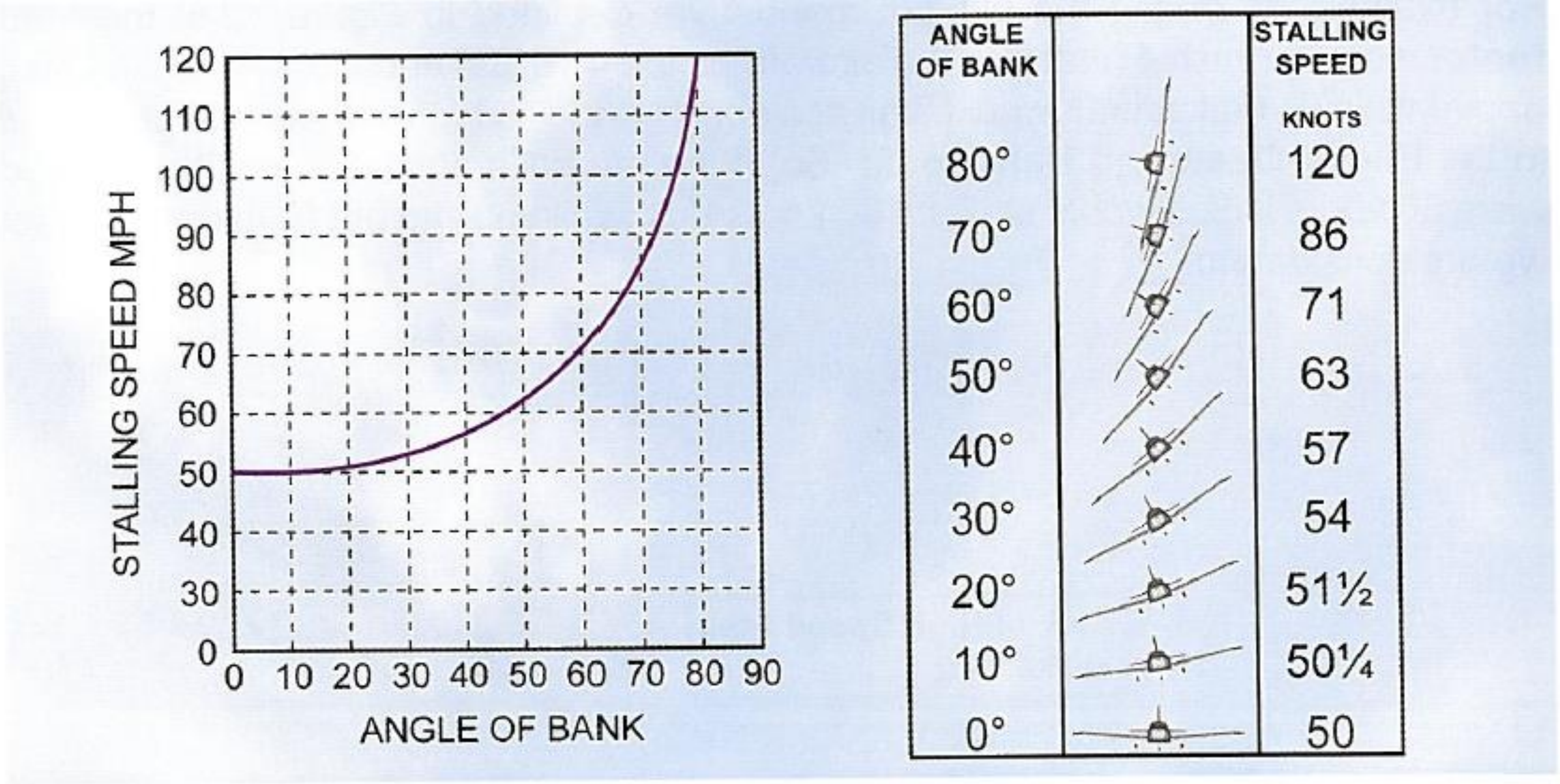


Figure 13.8 Stalling speeds for various angles of bank based on a straight-flight stalling speed of 50 knots.

The Effect of the Position of Centre of Gravity on the Stall.

You learnt in the **Mass and Balance** section of this series of text books that if the aircraft's **centre of gravity (C of G)** is at its most forward limit, the tailplane or stabilator has to produce a greater downforce in order to balance the lift-weight couple *(See Figure 13.16 overleaf)*. This greater tailplane force acting in the same direction as weight, effectively increases the weight of the aircraft. Consequently, for the reasons you have already learnt, the stalling speed increases. As the **C of G** moves aft, less tailplane downforce is required. This condition decreases the total weight of the aircraft and, consequently, decreases the stalling speed, too. *(See Figure 13.17 overleaf)*. During flight testing, the stalling speed is calculated for the worst case scenario, i.e. maximum weight, with the **C of G** at its most forward position.

The Effect of Flaps on the Stall .

Chapter 10, **Lift Augmentation**, considers in detail the effect which the deployment of **flaps** has on the stall. As you have learnt from Chapter 10, deploying **flaps** alters the shape and camber of the wing's aerofoil section and increases $\mathbf{C_{L\,MAX}}$. So, from the **lift equation** for the point of stall, we see that $\mathbf{(v_{stall})}$ must decrease to keep the equation balanced.

$$\textbf{Weight} = \textbf{Lift} = \mathbf{C_{L\,MAX}}\ \tfrac{1}{2}\,\rho\,(\mathbf{v_{stall}})^2\,\mathbf{S}$$

You have also learnt that lowering flaps, while increasing $\mathbf{C_{L\,MAX}}$, reduces the angle of attack at which the aircraft stalls. **This means that if the aircraft stalls from straight and level flight, the nose attitude, with flaps deployed, will be lower than for an equivalent stall exercise with flaps raised.**

Wing Contamination.

Stalling speed may be increased significantly if the wing is **contaminated** *(See Figure 13.18)*. Snow, frost, and ice deposits on the wing, and even heavy rain, can reduce the value of $\mathbf{C_{L\,MAX}}$ by as much as 30% because of their modifying effect on wing profile. Deposits on the airframe will also increase aircraft weight, causing a further increase in stalling speed. Any **contamination** (ice, raindrops, squashed insects, etc.) must be removed from the wings before flight, especially from the leading edge.

Figure 13.18 Frost, snow and ice on the wings increase stall speed.

The Effect of Power, on the Stall.

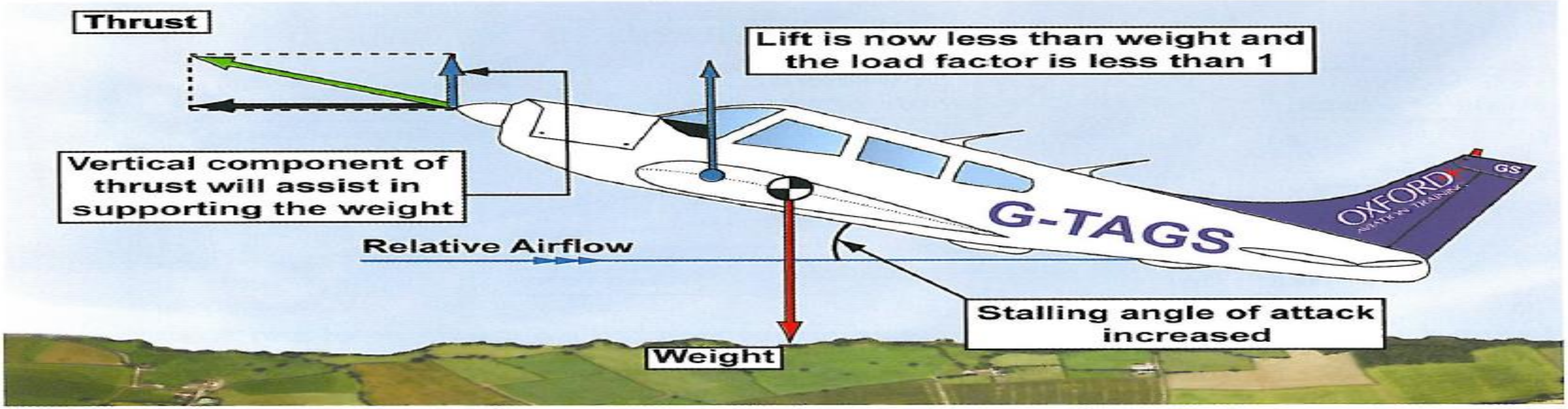


Figure 13.19 When stalling under power, thrust contributes to the Lift, and so the Load Factor is less than 1. Stall speed is, thus, reduced.

When the propeller is producing significant **thrust**, for instance, in cruising flight, the aircraft's stalling speed will be lower than with the engine throttled back. The reasons for this are twofold:

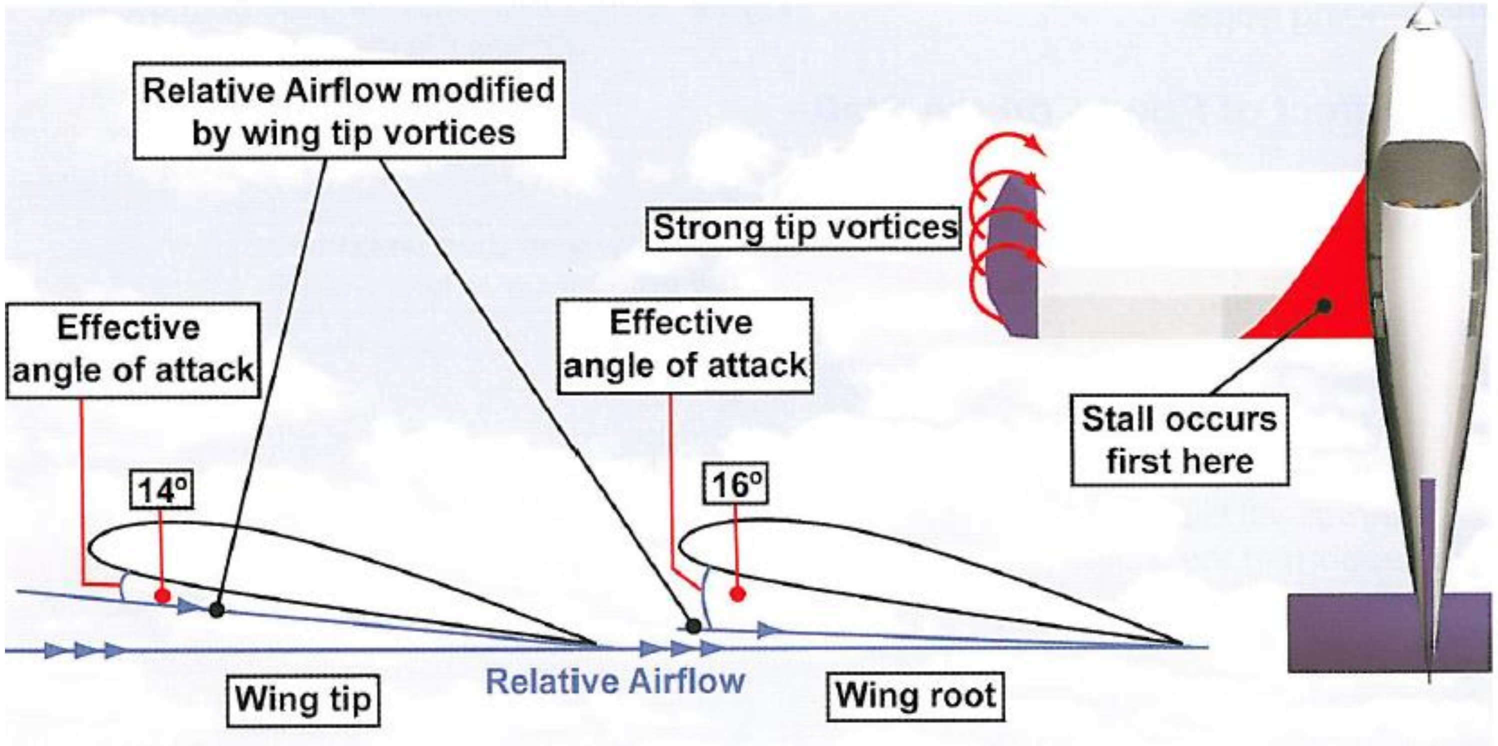
- The propeller **slipstream** energises the airflow over the inner region of the wings and, thereby delays separation. This action increases the value of $\mathbf{C_{L\,MAX}}$ and, thus, decreases the stalling speed.

- The nose high attitude required to induce a stall under power means that the **thrust** force has a vertical component which helps to balance the aircraft's weight. Consequently, the lift force which must be generated by the wing to support the aircraft's weight is now less than the weight, and, so, **load factor** is less than **1**. As you learnt earlier in this chapter, reducing **load factor** reduces stall speed. *(See Figure 13.19 overleaf).*

The Effect of Wing Plan Form on the Stall.

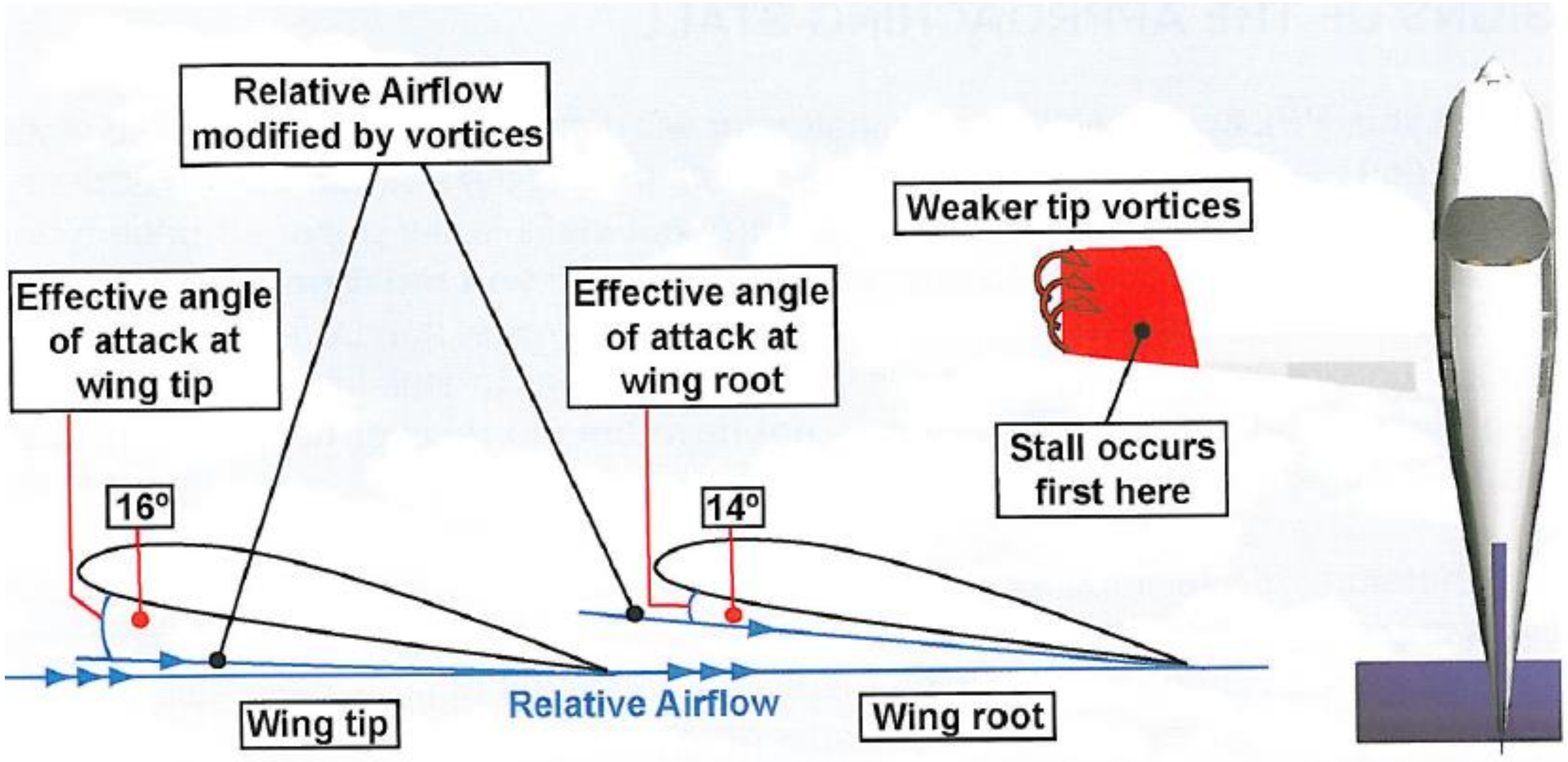
Rectangular Wings.

The separation of the airflow over a wing, which is the essential cause of the stall, does not necessarily occur simultaneously across the whole span of the wing. With a wing of rectangular **planform** (*see Figure 13.20*), separation tends to occur near the wing root and then progress outwards towards the wing tips.



Tapered Wings.

With wings of tapered **planform**, separation tends to occur first of all at the wing tips, and then spreads inboard. It follows, then, that if one wing stalls before the other, there will be pronounced wing drop at the stall.



SIGNS OF THE APPROACHING STALL.

- Possibly, **a high nose attitude, though this is not an essential sign** because, as you have learnt, a stall can occur at any attitude and at any speed. The stall occurs when the wing reaches the stalling angle of attack. **The stalling speed will vary**, among other things, **with the load factor** acting on the aircraft. If the stall occurs from straight and level flight, however, **nose attitude** will be high.

- **Decreasing airspeed**. When the stall is approached from level flight or the glide, the higher-than-normal nose attitude will be accompanied by decreasing airspeed.

- **Sloppiness and decreasing effectiveness of the controls**. Again, if the stall is approached from level flight, nose attitude will be high, speed will be decreasing and, consequently, the controls become noticeably less effective, feeling **sloppy** instead of firm.

- **Airframe buffeting**. As you have learnt, as the angle of attack increases in the approach to the stall, the airflow begins to separate and break away from the wing surface. Airflow in this condition is turbulent and gives rise to airframe **buffeting**. As the turbulence strikes the elevator, it is felt through the control column as vibration.

- **Stall warning device**. At the point of the stall (at $\mathbf{C_{L\,MAX}}$) airframe buffeting becomes more severe. On some aircraft, such as the PA28 Warrior, **a stall warning horn operates at a preset angle of attack,** just before the onset of the stall.

THE SPIN.

When an aircraft **spins**, it is in **a state of stalled flight**, and is losing height rapidly in a steep helical descent, **yawing**, **rolling and pitching**, **at the same time**. Both wings are stalled, and the aircraft is **auto-rotating** under the influence of yawing and rolling moments.

Figure 13.27 The spin is a state of stalled flight with the aircraft in a steep descent, yawing, rolling and pitching at the same time.

Now we can make a further fundamental statement about the **spin. For a spin to develop, yaw must be present at the point of the stall**. This **yaw** is very often caused by one wing stalling first and dropping.

In order better to understand how yaw may be present at the stall, we need to look at the drag situation if wing drop does occur at the stall.

At **low speeds** and **high angles of attack**, **total drag** consists almost exclusively of **induced drag**. When both wings are stalled, both wings experience high levels of **induced drag**. But if a wing drops at the stall, the up-going wing is less stalled than the down-going wing *(See Figure 13.28)*. The drag on the up-going wing is, therefore, less than that on the down-going wing, while its lift is greater. This state of affairs is depicted in *Figure 13.29* where $\mathbf{C_L}$ and $\mathbf{C_D}$ curves are plotted against **angle of attack**.

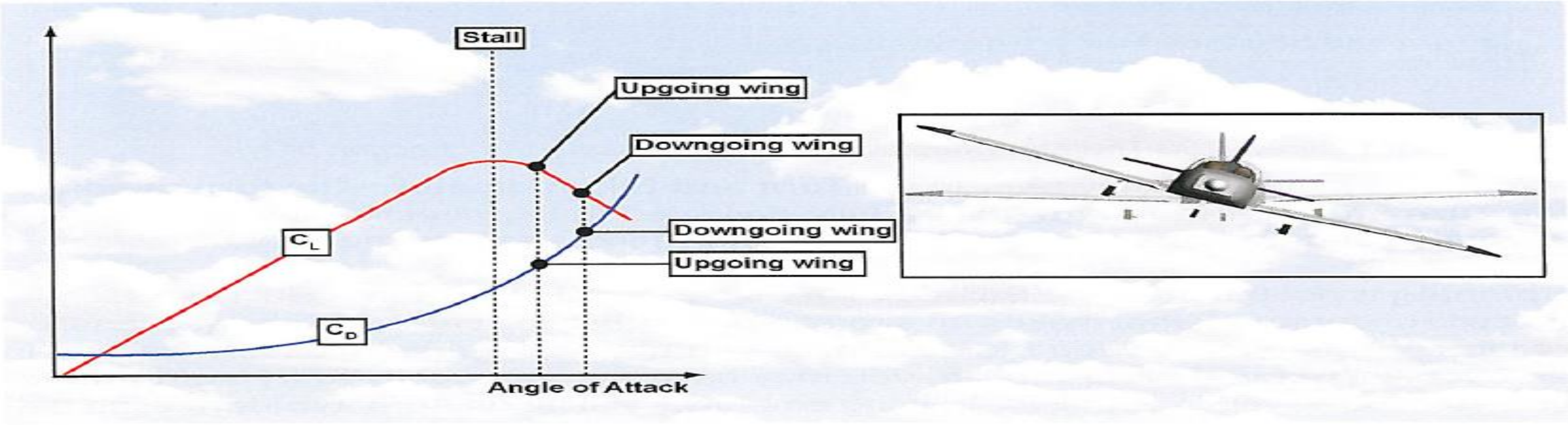


Figure 13.29 Wing-drop at the stall - $\mathbf{C_L}$ and $\mathbf{C_D}$ curves for the up-going and down-going wings.

Determining Direction of the Spin.

There are basically two ways to determine the **direction of spin**. In good visual flight conditions the **direction of spin** can be established by looking along the nose of the aircraft to the ground.

Figure 13.30 The turn needle will always indicate the direction of spin.

Alternatively, the Pilot may refer to the **Turn and Slip Indicator**. The **turn needle** of the **Turn and Slip Indicator** will be fully deflected in the direction of the spin. The **Turn and Slip Indicator** in *Figure 13.30* is indicating a spin to the right.

٣. Frost covering the upper surface of an airplane wing usually will cause

A. The airplane to stall at an angle of attack that is higher than normal.
B. The airplane to stall at an angle of attack that is lower than normal.
C. Drag factors so large that sufficient speed cannot be obtained for take-off

٥. The angle of attack at which a wing stalls remains constant regardless of

A. Weight, dynamic pressure, bank angle, or pitch attitude.
B. Dynamic pressure, but varies with weight, bank angle, and pitch attitude.
C. Weight and pitch attitude, but varies with dynamic pressure and bank angle.

٧. An airplane will stall at the same

A. Angle of attack regardless of the attitude with relation to the horizon.
B. Airspeed regardless of the attitude with relation to the horizon.
C. Angle of attack and attitude with relation to the horizon.

٨. In a rapid recovery from a dive, the effects of load factor would causes the stall speed to

A. Increase.
B. Decrease.
C. Not vary.

٩. The stalling speed of an airplane is most affected by

A. Changes in air density
B. Variations in flight altitude.
C. Variations in airplane loading.

١٠. Recovery from a stall in any airplane becomes more difficult when its

A. Centre of gravity moves aft.
B. Centre of gravity moves forward.
C. Elevator trim is adjusted nose down.

١١. In small airplanes, normal recovery from spins may become difficult if the

A. CG is too far rearward, and rotation is around the longitudinal axis.
B. CG is too far rearward, and rotation is around the CG.
C. Spin is entered before the stall is fully developed.

٤٠. The ratio between the total air load imposed on the wing and the gross weight of an aircraft in flight is known as

A. Load factor and directly affects stall speed.
B. Aspect load and directly affects stall speed.
C. Load factor and has no relation with stall speed.

٤٢. For a given angle of bank, in any airplane, the load factor imposed in a coordinated constant altitude turn

A. Is constant and the stall speed increases.
B. Varies with the rate of turn.
C. Is constant and the stall speed decreases.

٥٧. An airplane has been loaded in such a manner that the CG is located aft of the aft CG limit. One undesirable flight characteristic a pilot might experience with this airplane would be.

A. A longer take off run.
B. Difficulty in recovering from a stalled condition.
C. Stalling at higher-than-normal airspeed.

٦٥. During an approach to a stall, an increased load factor will cause the airplane to

A. Stall at a higher airspeed.
B. Have a tendency to spin.
C. Be more difficult to control.

٦٧. In what flight condition must an aircraft be placed in order to spin ?

A. Partially stalled with one wing low.
B. In a steep diving spiral.
C. Stalled.

٦٨. During a spin to the left, which wing(s) is/are stalled ?

A. Both wings are stalled.
B. Neither wing is stalled.
C. Only the left wing is stalled

٦٩. The angle of attack at which an airp lane wing stalls will

A. Increase if the CG is move forward.
B. Change with an increase in gross weight.
C. Remain the same regardless of gross weight.

١٠٢. During a sp in to the left which wing(s) is/are stalled ?

A. Both wings are stalled.
B. Neither wing is stalled.
C. Only the left wing is stalled.

CHAPTER 14
FLIGHT AND GROUND LIMITATIONS

LIMITATIONS.

The designed structural strength of an aircraft is determined by the magnitude and direction of the **loads** that the designer expects to be imposed on the aircraft, in flight and on the ground. The word **load** is just another name for **force**. You have already learnt a considerable amount about the main **loads** acting on an aircraft: **lift**, **weight**, **thrust** and **drag**.

Airspeed.

in the lift equation which determines the magnitude of the **lift**, <u>and</u> also a factor which can be read directly by the pilot from the ASI as indicated airspeed, **<u>all speed limitations published by the manufacturer are indicated airspeeds</u>**.

REPRESENTATIVE LIMITATIONS FOR A LIGHT TRAINING AIRCRAFT	
Velocity Never to Exceed (V_{NE})	155 knots
Normal Operating Speed (V_{NO})	124 knots
Normal Manoeuvring Speed (V_A)	109 knots
Maximum Velocity Flaps Extended (V_{FE})	101 knots
Take-Off Safety Speed	65 knots
Stall Speed (flaps extended)	46 knots
Stall Speed (clean)	52 knots
Maximum Take-Off Weight (or Mass) (MTOW)/ (MTOM) - Normal Category	2150 lbs 975 kg
MTOW/MTOM – Utility Category	1950 lbs 884 kg
Maximum Demonstrated Crosswind	17 knots
Maximum Load Factor (Normal Category)	+3.8
Maximum Load Factor (Utility Category)	+4.4
No Negative Load Factors Approved	-

Figure 14.5 Table of representative general limitations for a typical, general aviation training aircraft.

THE END